IEEE Conference on Factory Communication

Simulating Time-Sensitive Networking using OMNeT++/INET Framework

WFCS – June 10-13, 2025

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Introduction to OMNeT++

- Simulator for communication networks
- Modular and C++-based
- Open source model libraries
- Widely used in research
- Free for academic use
- Commercial version: OMNEST

omnetpp.org
omnest.com

Introduction to INET Framework

- Model library for wired and wireless networks
  - Internet protocols, routing protocols, etc.
  - Applications, queueing models, clock, etc.
  - Mobility, power consumption, physical environment, etc.
- Open source
- Well-documented
- Built for experimentation

Relevance to Factory Automation

- Support for Time-Sensitive Networking (IEEE)
  - **802.3br** Frame Preemption
  - **802.1Qbv** Time-Aware Traffic Shaping
  - **802.1Qav** Credit-Based Shaper
  - **802.1Qcr** Asynchronous Traffic Shaping
  - **802.1Qci** Per-Stream Filtering and Policing
  - **802.1AS** Time Synchronization
  - **802.1CB** Frame Replication and Elimination
  - **802.1cg** 10BASE-T1S
- Extensible with Profinet, EtherCAT, etc.
- Allows analyzing custom and diverse industrial networks

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

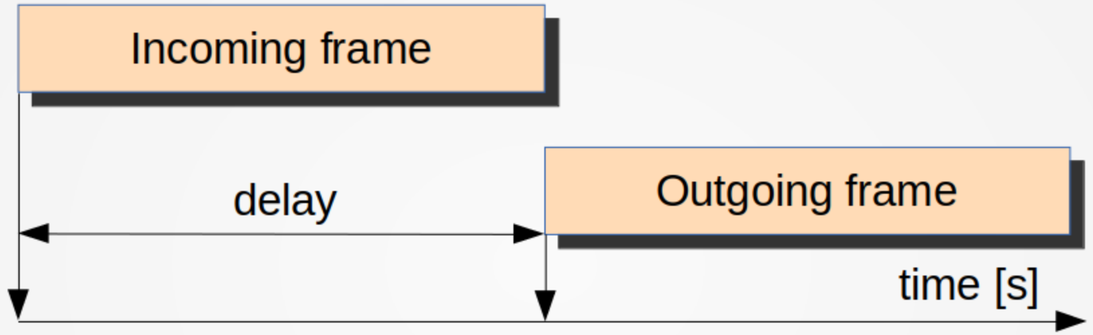
Automatic gate schedule configuration

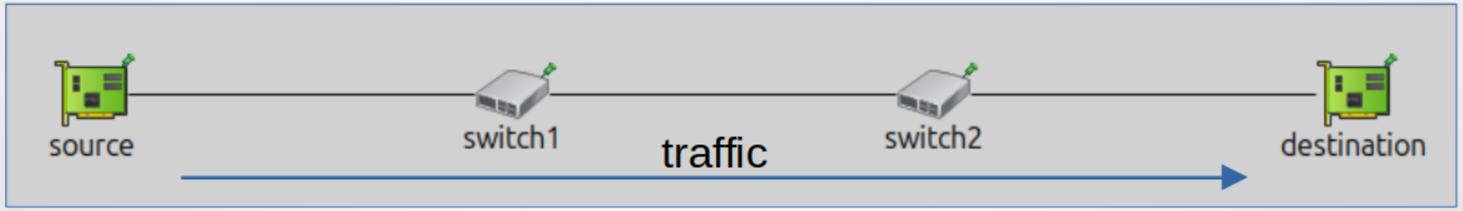
Time synchronization

Frame replication and elimination for reliability

Store-and-forward Switching

- Receive whole frame before forwarding



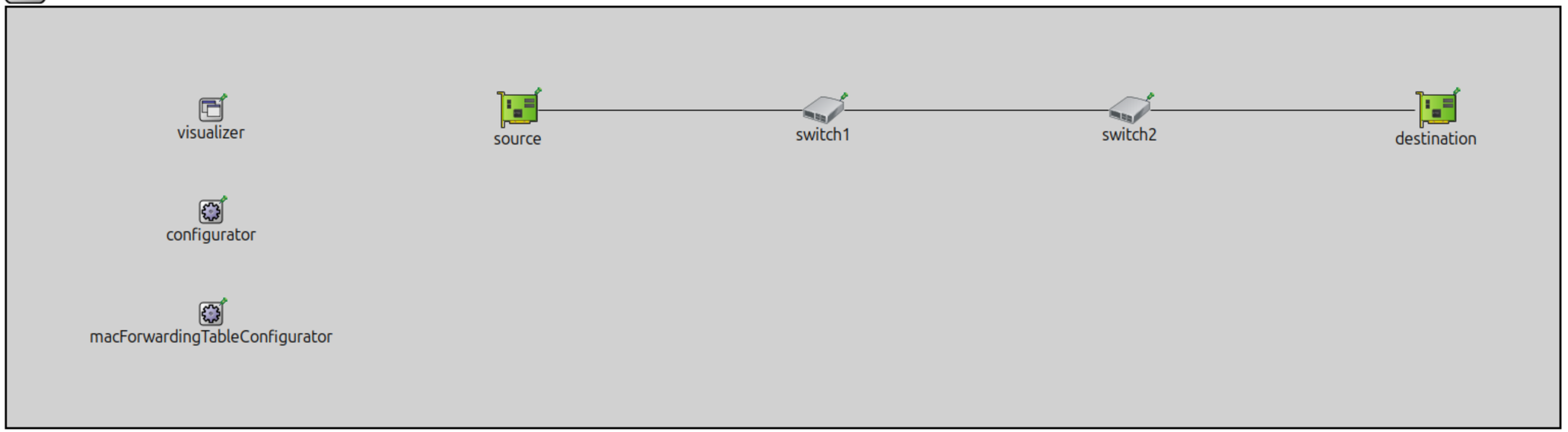


File Edit Source View Navigate Search Project Run Window Help

CutthroughSwitching.ned

package step1_cutthrough_switching

CutthroughSwitchingShowcase



Palette
Selector
Connection
Types
Submodules
TsnDevice (inet.node.tsn)
TsnSwitch (inet.node.tsn)
AdhocHost (inet.node.inet)
AodvRouter (inet.node.aodv)
ApplicationLayerNodeBase (inet.node.base)
BgpRouter (inet.node.bgp)
BurstHost (inet.examples.inet.routerperf)
CorrespondentNode6 (inet.node.xmipv6)
DsdvRouter (inet.node.dsdv)
DymoRouter (inet.node.dymo)
EigrpRouter (inet.node.eigrp)
EthernetPlcaHost (inet.node.ethernet)
GpsrRouter (inet.examples.seaport)
GpsrRouter (inet.node.gpsr)
GpsrStandardHost (inet.examples.seaport)
GpsrWirelessHost (inet.examples.seaport)
GptpEndstation (inet.linklayer.ieee8021as)
GptpMaster (inet.linklayer.

Design Source

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CutthroughSwitching.ned

```
1  package step1_cutthrough_switching;
2
3  import Wfcs2025NetworkBase;
4  import inet.node.ethernet.EthernetLink;
5  import inet.node.tsn.TsnDevice;
6  import inet.node.tsn.TsnSwitch;
7
8  network CutthroughSwitchingShowcase extends Wfcs2025NetworkBase
9  {
10     submodules:
11         source: TsnDevice {
12             @display("p=500,100");
13         }
14         switch1: TsnSwitch {
15             @display("p=800,100");
16         }
17         switch2: TsnSwitch {
18             @display("p=1100,100");
19         }
20         destination: TsnDevice {
21             @display("p=1400,100");
22         }
23     connections:
24         source.ethg++ <--> EthernetLink <--> switch1.ethg++;
25         switch1.ethg++ <--> EthernetLink <--> switch2.ethg++;
26         switch2.ethg++ <--> EthernetLink <--> destination.ethg++;
27 }
28
29
```

Design Source

File Edit Source Navigate Search Project Run Window Help

CutthroughSwitching.ned | CutthroughSwitching.ini

```
[General]
abstract = true
network = CutthroughSwitchingShowcase
sim-time-limit = 10ms
record-eventlog = true
result-dir = "results/wip"

# configure Ethernet speed
*.*.eth[*].bitrate = 1Gbps

# configure source applications
*.source.numApps = 1
*.source.app[0].typename = "UdpSourceApp"
*.source.app[0].io.destAddress = "destination"
*.source.app[0].io.destPort = 1000
*.source.app[0].source.packetLength = 1200B # ~10us transmission duration
*.source.app[0].source.productionInterval = truncnormal(200us, 50us) # 3 hops without cut-through would fill up the queues

# configure destination applications
*.destination.numApps = 1
*.destination.app[0].typename = "UdpSinkApp"
*.destination.app[0].io.localPort = 1000

[StoreAndForward]
description = "Ethernet switches completely receive incoming frames before forwarding them"

# no configuration required

[CutthroughSwitching]
```

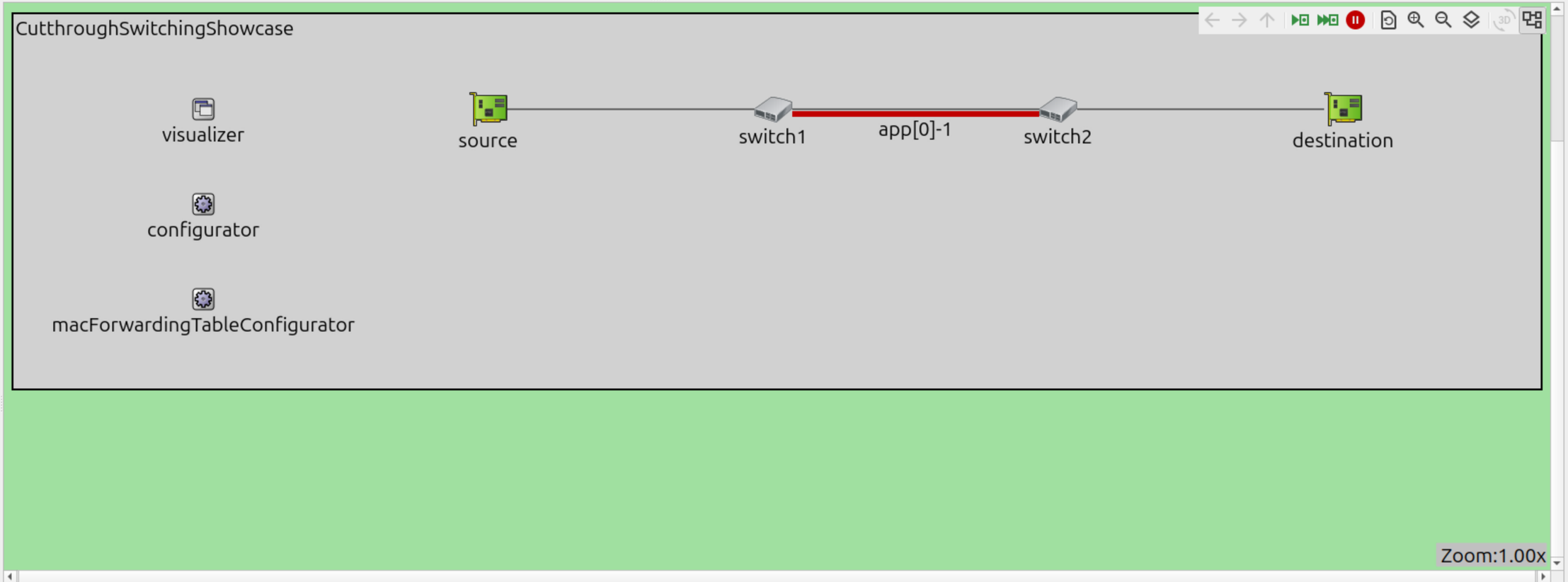
Form Source

OMNeT++/Qtenv (release) - StoreAndForward #0 - CutthroughSwitching.ini - /home/levy/workspace/inet/wfcs2025/step1_cutthrough_switching

File Simulate Inspect View Help

next: #45 | 0s 000ms 165us 025ns 796ps

Next: TxEndTimer (inet::ClockEvent, id=40) | In: CutthroughSwitchingShowcase.switch1.eth[1].phyLayer.transmitter (PacketTransmitter, id=239) | At: 0.000167464491s (now+0.000002438695s)



CutthroughSwitchingS
simulation.scheduled-e

CutthroughSwitchingS
displayStringTextFor
hasGlobalArp (cPar)
visualizer (Integratec
configurator (Ipv4Ne
macForwardingTable
source (TsnDevice) ic
switch1 (TsnSwitch) i
switch2 (TsnSwitch) i
destination (TsnDevi
canvas (cCanvas) 25

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#14	0.000	source --> switch1	app[0]-0	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	
#17	0.000'010'082	switch1 --> switch2	app[0]-0	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#22	0.000'020'164	switch2 --> destination	app[0]-0	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#39	0.000'147'350'491	source --> switch1	app[0]-1	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#42	0.000'157'432'491	switch1 --> switch2	app[0]-1	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200

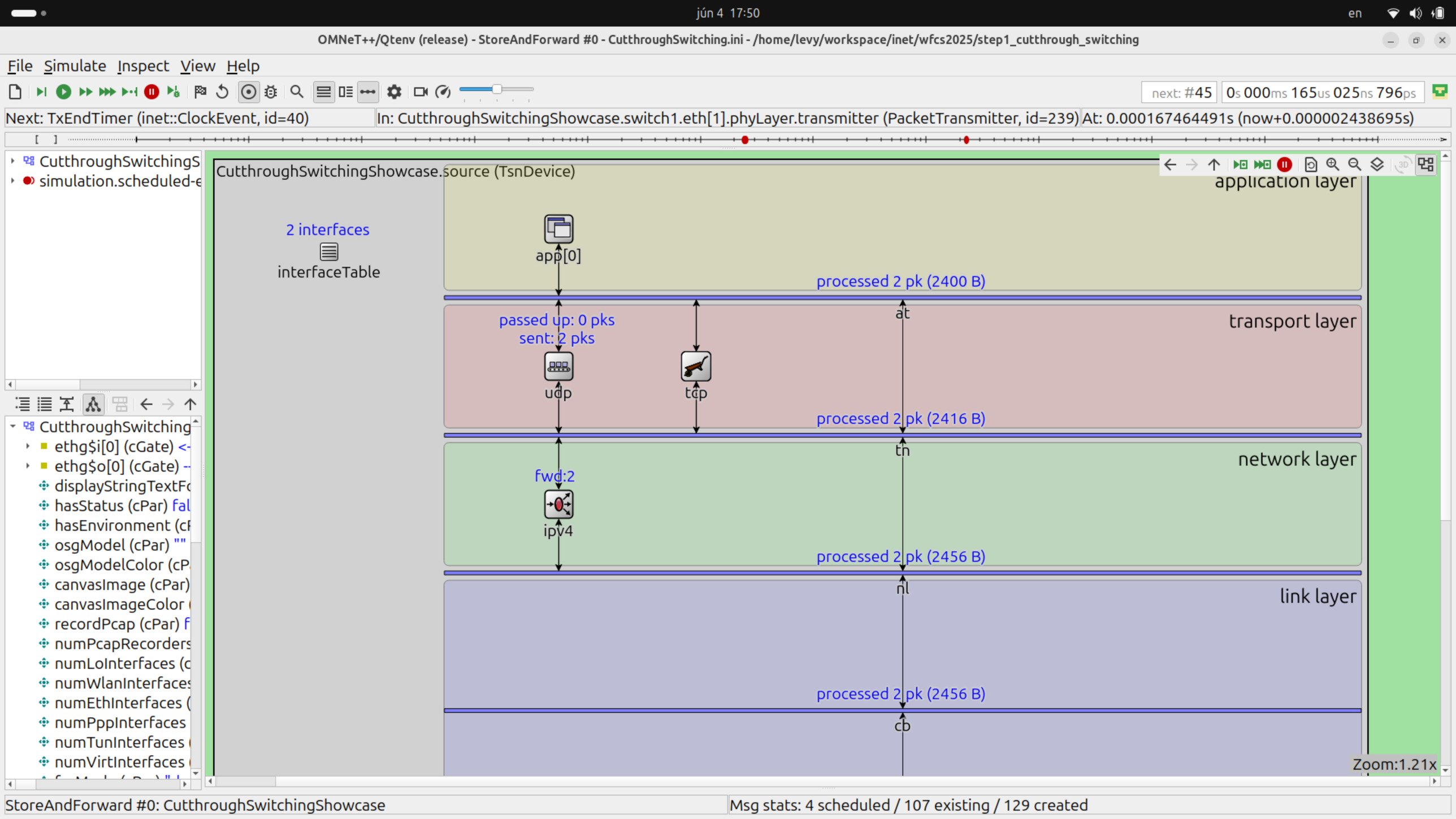
StoreAndForward #0: CutthroughSwitchingShowcase | Msg stats: 4 scheduled / 107 existing / 129 created

OMNeT++/Qtenv (release) - StoreAndForward #0 - CutthroughSwitching.ini - /home/levy/workspace/inet/wfcs2025/step1_cutthrough_switching

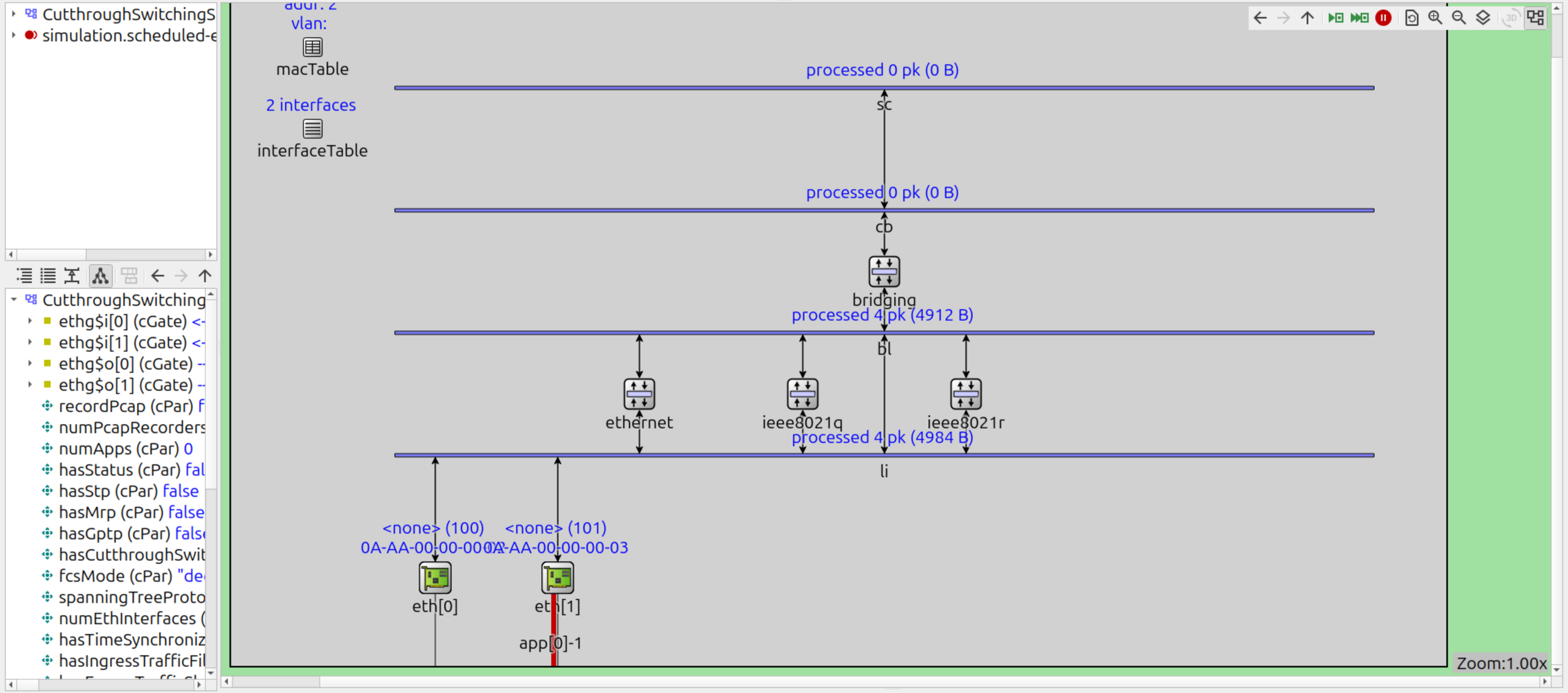
File Simulate Inspect View Help

next: #45 | 0s 000ms 165us 025ns 796ps

Next: TxEndTimer (inet::ClockEvent, id=40) | In: CutthroughSwitchingShowcase.switch1.eth[1].phyLayer.transmitter (PacketTransmitter, id=239) | At: 0.000167464491s (now+0.000002438695s)



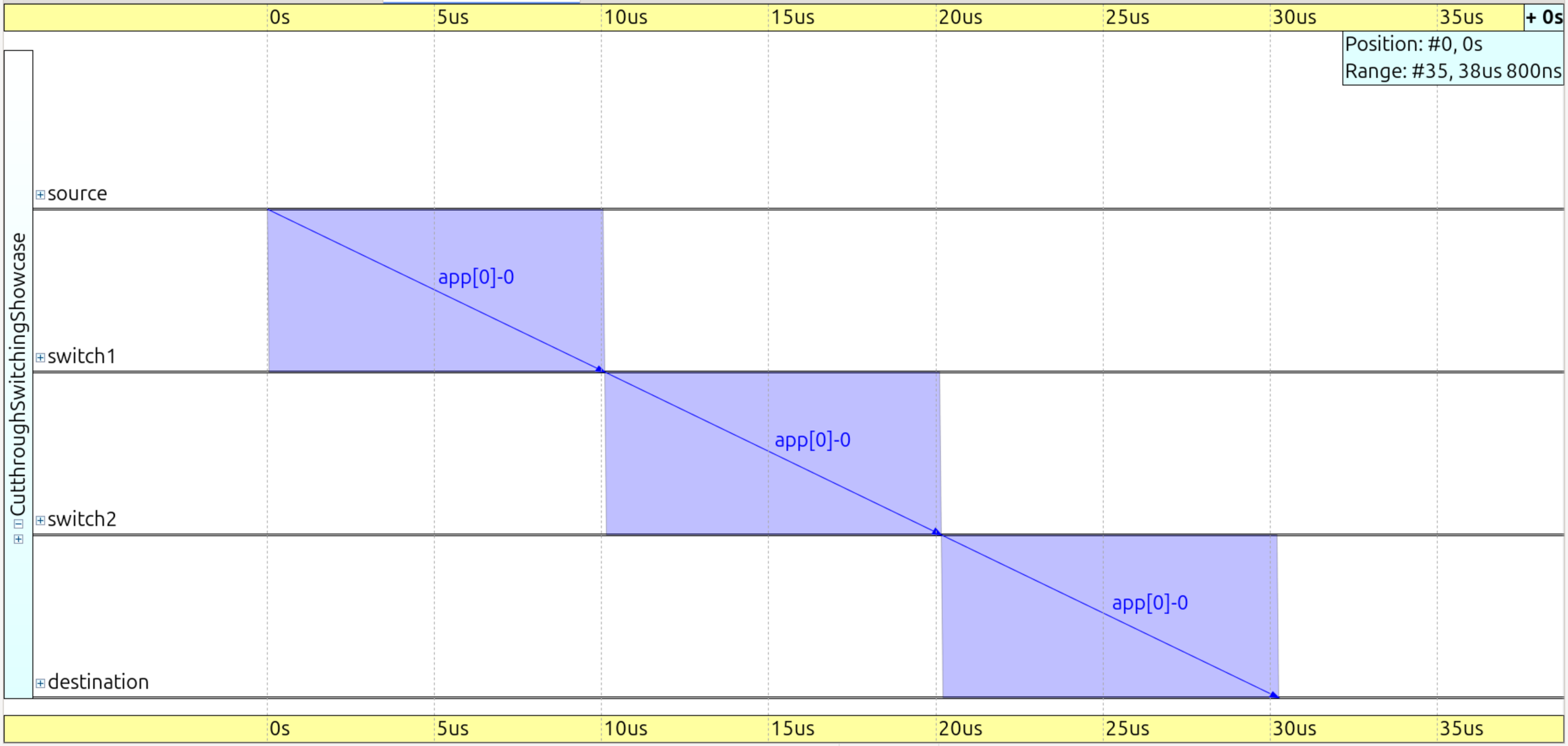
StoreAndForward #0: CutthroughSwitchingShowcase | Msg stats: 4 scheduled / 107 existing / 129 created



ui - inet/wfcs2025/step1_cutthrough_switching/results/StoreAndForward-#0.elog : StoreAndForward-0-20250604-16:04:02-60261 - OMNeT++ IDE

File Edit Navigate Search Project Run Window Help

CutthroughSwitching.ned | CutthroughSwitching.ini | StoreAndForward-#0.elog



Simul... Time | Unfiltered | Codeium: No comple...erated | Show Chat

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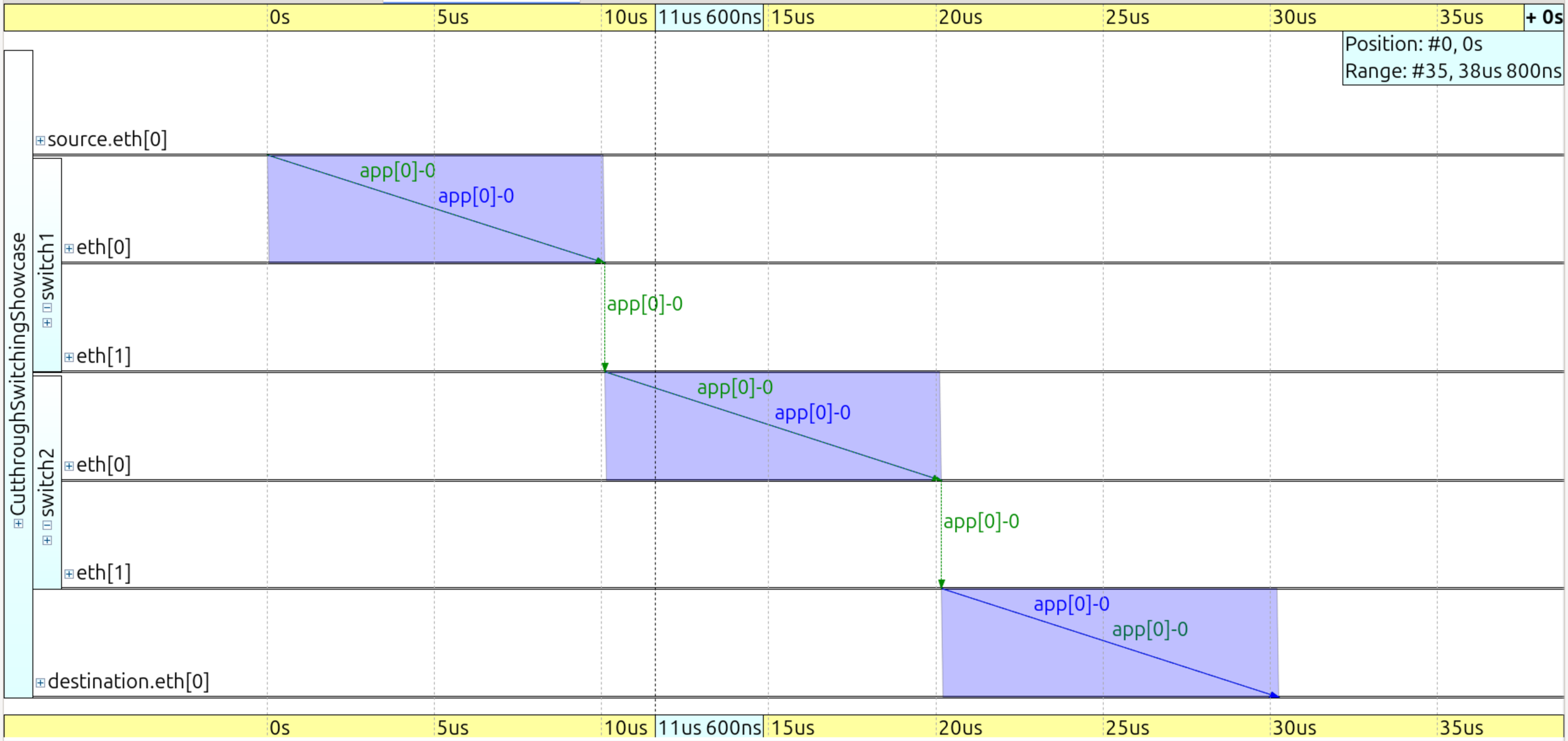
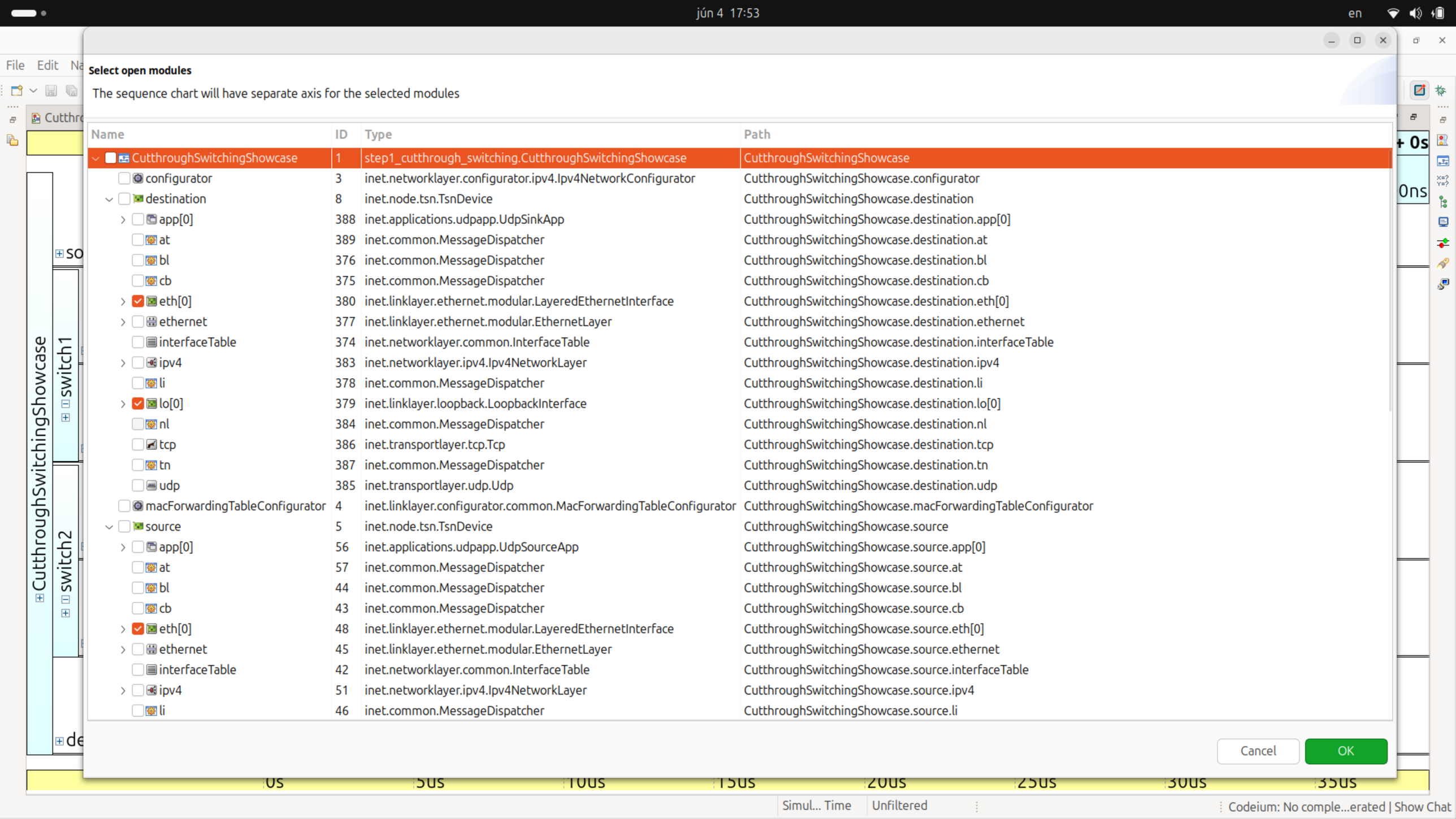
CutthroughSwitching.ned | CutthroughSwitching.ini | StoreAndForward-#0.elog

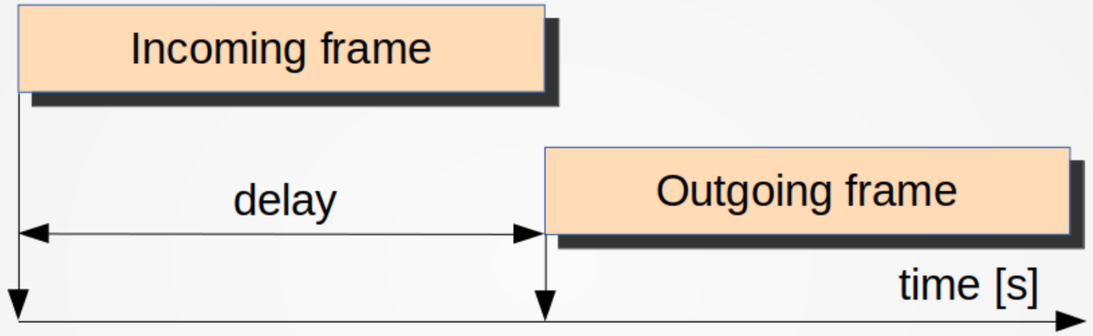


Simul... Time | Unfiltered | Codeium: No comple...erated | Show Chat

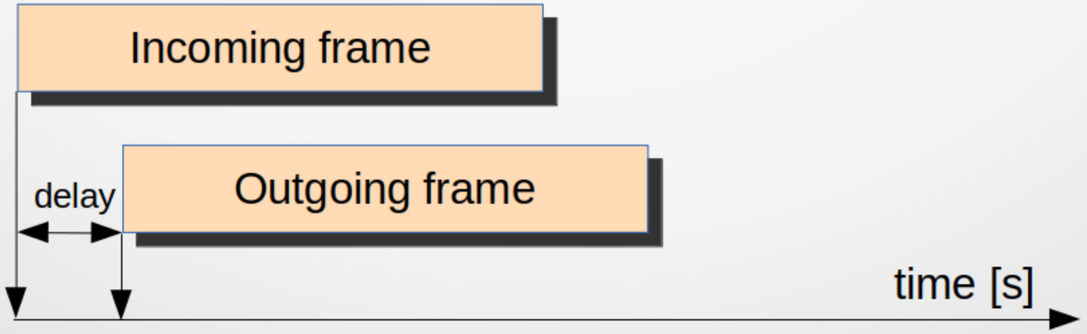

jún 4 17:53
en
File Edit Na
Select open modules
The sequence chart will have separate axis for the selected modules
Name ID Type Path
CutthroughSwitchingShowcase 1 step1_cutthrough_switching.CutthroughSwitchingShowcase CutthroughSwitchingShowcase
configurator 3 inet.networklayer.configurator.ipv4.Ipv4NetworkConfigurator CutthroughSwitchingShowcase.configurator
destination 8 inet.node.tsn.TsnDevice CutthroughSwitchingShowcase.destination
app[0] 388 inet.applications.udpapp.UdpSinkApp CutthroughSwitchingShowcase.destination.app[0]
at 389 inet.common.MessageDispatcher CutthroughSwitchingShowcase.destination.at
bl 376 inet.common.MessageDispatcher CutthroughSwitchingShowcase.destination.bl
cb 375 inet.common.MessageDispatcher CutthroughSwitchingShowcase.destination.cb
eth[0] 380 inet.linklayer.ethernet.modular.LayeredEthernetInterface CutthroughSwitchingShowcase.destination.eth[0]
ethernet 377 inet.linklayer.ethernet.modular.EthernetLayer CutthroughSwitchingShowcase.destination.ethernet
interfaceTable 374 inet.networklayer.common.InterfaceTable CutthroughSwitchingShowcase.destination.interfaceTable
ipv4 383 inet.networklayer.ipv4.Ipv4NetworkLayer CutthroughSwitchingShowcase.destination.ipv4
li 378 inet.common.MessageDispatcher CutthroughSwitchingShowcase.destination.li
lo[0] 379 inet.linklayer.loopback.LoopbackInterface CutthroughSwitchingShowcase.destination.lo[0]
nl 384 inet.common.MessageDispatcher CutthroughSwitchingShowcase.destination.nl
tcp 386 inet.transportlayer.tcp.Tcp CutthroughSwitchingShowcase.destination.tcp
tn 387 inet.common.MessageDispatcher CutthroughSwitchingShowcase.destination.tn
udp 385 inet.transportlayer.udp.Udp CutthroughSwitchingShowcase.destination.udp
macForwardingTableConfigurator 4 inet.linklayer.configurator.common.MacForwardingTableConfigurator CutthroughSwitchingShowcase.macForwardingTableConfigurator
source 5 inet.node.tsn.TsnDevice CutthroughSwitchingShowcase.source
app[0] 56 inet.applications.udpapp.UdpSourceApp CutthroughSwitchingShowcase.source.app[0]
at 57 inet.common.MessageDispatcher CutthroughSwitchingShowcase.source.at
bl 44 inet.common.MessageDispatcher CutthroughSwitchingShowcase.source.bl
cb 43 inet.common.MessageDispatcher CutthroughSwitchingShowcase.source.cb
eth[0] 48 inet.linklayer.ethernet.modular.LayeredEthernetInterface CutthroughSwitchingShowcase.source.eth[0]
ethernet 45 inet.linklayer.ethernet.modular.EthernetLayer CutthroughSwitchingShowcase.source.ethernet
interfaceTable 42 inet.networklayer.common.InterfaceTable CutthroughSwitchingShowcase.source.interfaceTable
ipv4 51 inet.networklayer.ipv4.Ipv4NetworkLayer CutthroughSwitchingShowcase.source.ipv4
li 46 inet.common.MessageDispatcher CutthroughSwitchingShowcase.source.li
Cancel
OK
CutthroughSwitchingShowcase
switch1
switch2
0s 5us 10us 15us 20us 25us 30us 35us
Simul... Time
Unfiltered
Codeium: No comple...erated | Show Chat

Cut-through Switching

- Receive whole frame before forwarding



- Start forwarding as soon as MAC header is received



CutthroughSwitching.ned | CutthroughSwitching.ini | StoreAndForward-#0.elog

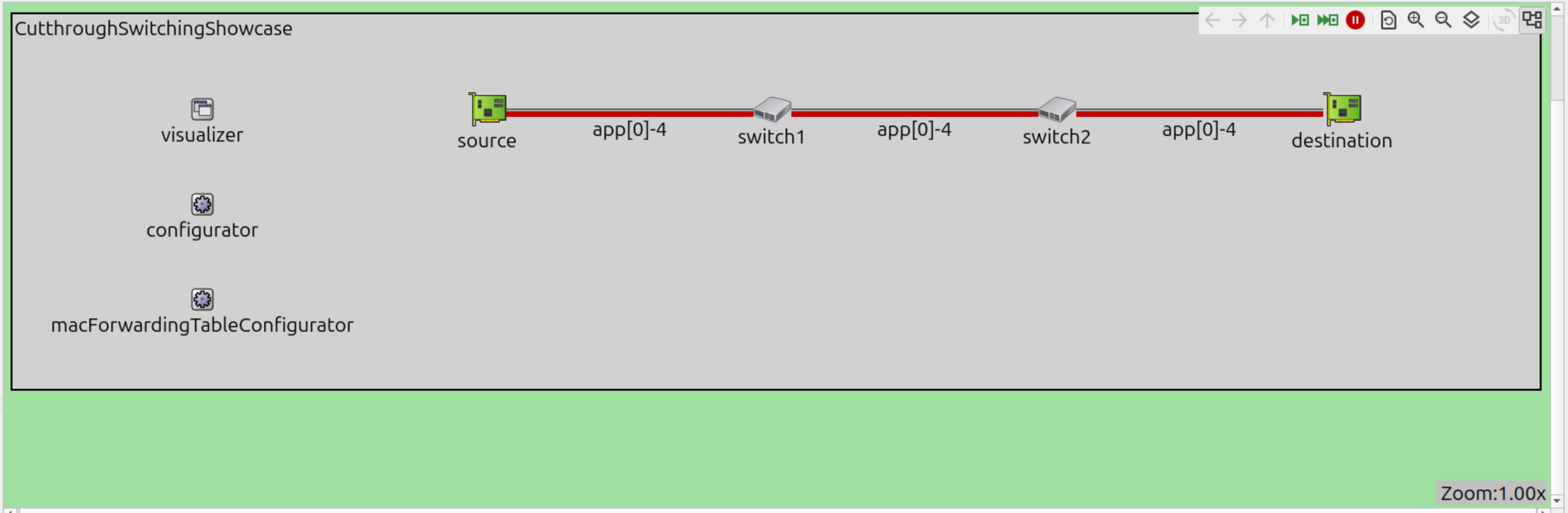
```
result-dir = "results/wip"

# configure Ethernet speed
*.*.eth[*].bitrate = 1Gbps

# configure source applications
*.source.numApps = 1
*.source.app[0].typename = "UdpSourceApp"
*.source.app[0].io.destAddress = "destination"
*.source.app[0].io.destPort = 1000
*.source.app[0].source.packetLength = 1200B # ~10us transmission duration
*.source.app[0].source.productionInterval = truncnormal(200us, 50us) # 3 hops without cut-through would fill up the queues

# configure destination applications
*.destination.numApps = 1
*.destination.app[0].typename = "UdpSinkApp"
*.destination.app[0].io.localPort = 1000

[StoreAndForward]
description = "Ethernet switches completely receive incoming frames before forwarding them"

# no configuration required

[CutthroughSwitching]
description = "Ethernet switches start forwarding incoming frames after the Ethernet MAC header has been received"

# enable cut-through in all network nodes
*.*.hasCutthroughSwitching = true
```

OMNeT++/Qtenv (release) - CutthroughSwitching #0 - CutthroughSwitching.ini - /home/levy/workspace/inet/wfcs2025/step1_cutthrough_switching

File Simulate Inspect View Help

next: #139 | 0s 000ms 872us 134ns 659ps

Next: TxEndTimer (inet::ClockEvent, id=9) | In: CutthroughSwitchingShowcase.source.eth[0].phyLayer.transmitter (StreamingTransmitter, id=94) | At: 0.000880244399s (now+0.00000810974s)



CutthroughSwitchingS
simulation.scheduled-e

CutthroughSwitchingS
displayStringTextFor
hasGlobalArp (cPar)
visualizer (Integratec
configurator (Ipv4Ne
macForwardingTable
source (TsnDevice) ic
switch1 (TsnSwitch) i
switch2 (TsnSwitch) i
destination (TsnDevi
canvas (cCanvas) 25 t

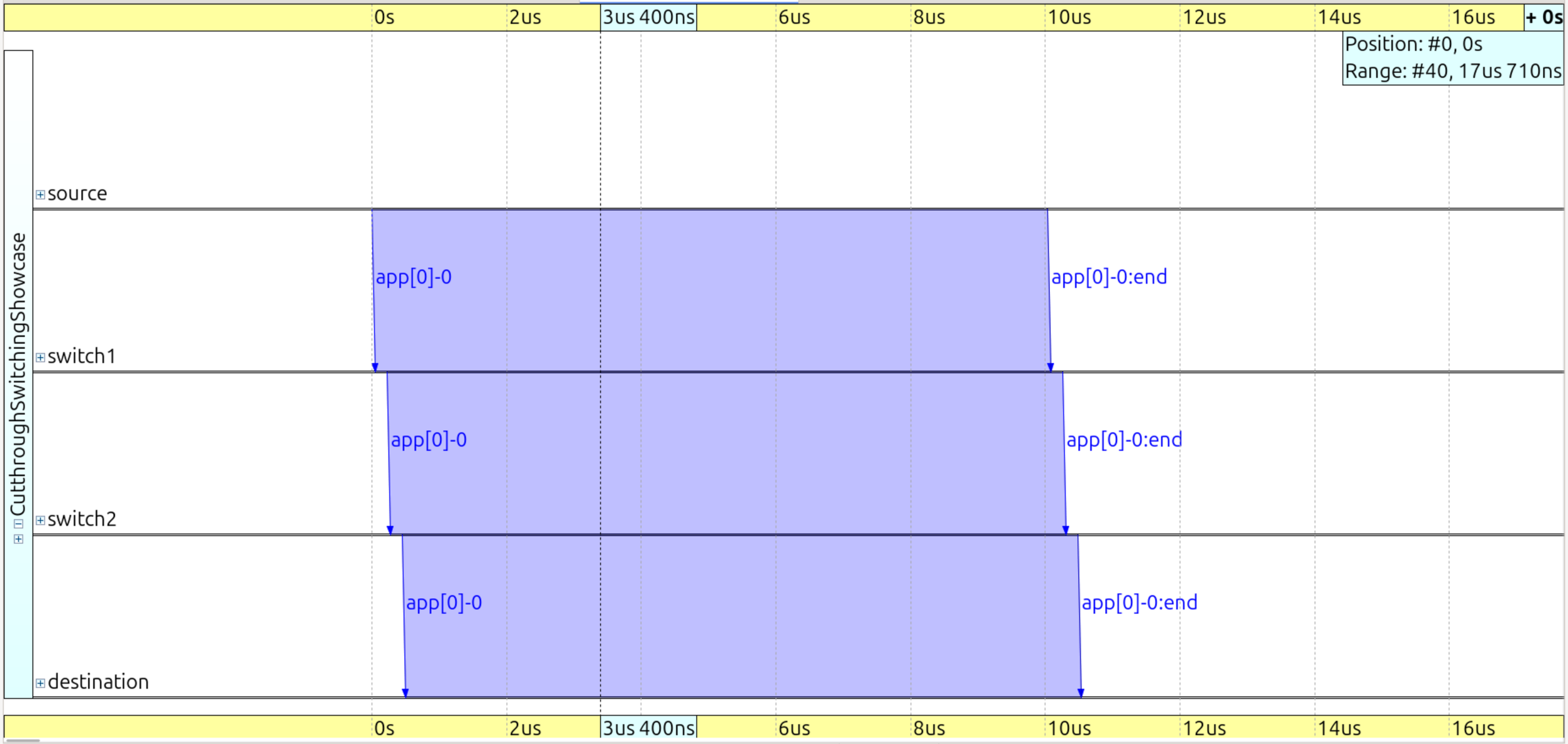
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#105	0.000'634'444'064	switch1 --> switch2 app[0]-3		10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	
#108	0.000'634'670'064	switch2 --> destination app[0]-3		10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 126
#110	0.000'644'250'064	source --> switch1 app[0]-3:end		10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 126
#114	0.000'644'476'064	switch1 --> switch2 app[0]-3:end		10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 126
#118	0.000'644'702'064	switch2 --> destination app[0]-3:end		10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 126
#131	0.000'870'212'399	source --> switch1 app[0]-4		10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 126
#134	0.000'870'438'399	switch1 --> switch2 app[0]-4		10.0.0.1:1025	10.0.0.2:1000	UDP		50 B	1025->1000, p
#137	0.000'870'664'399	switch2 --> destination app[0]-4		10.0.0.1:1025	10.0.0.2:1000	UDP		50 B	1025->1000, p

CutthroughSwitching #0: CutthroughSwitchingShowcase | Msg stats: 7 scheduled / 151 existing / 280 created

ui - inet/wfcs2025/step1_cutthrough_switching/results/CutthroughSwitching-#0.elog : CutthroughSwitching-0-20250604-16:04:02-60259 - OMNeT++ IDE

File Edit Navigate Search Project Run Window Help

CutthroughSwitching.ned | CutthroughSwitching.ini | StoreAndForward-#0.elog | CutthroughSwitching-#0.elog



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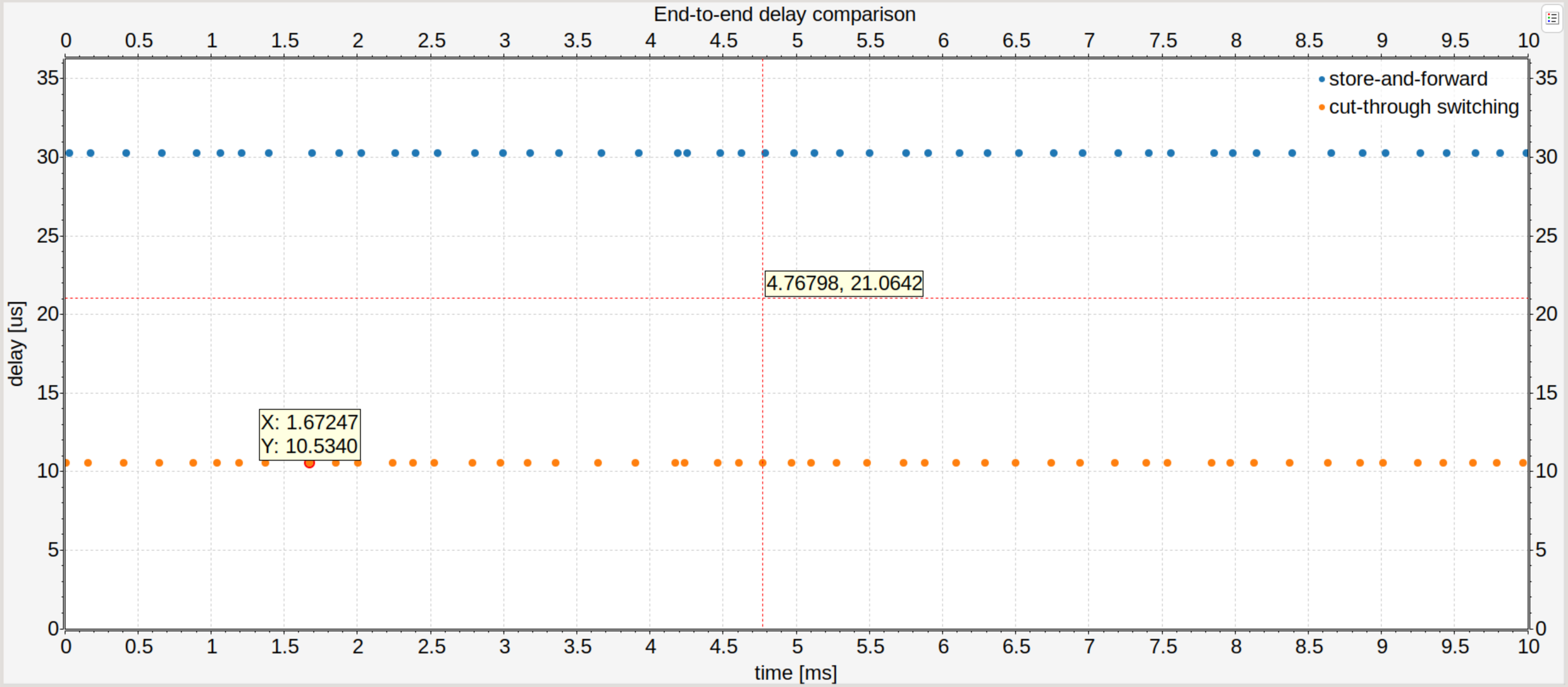


End-to-end Delay Validation

- Propagation time = 50ns
- Transmission time = 1254B * 8 / 1Gbps = 10.032us
- Cut-through delay = 22B * 8 / 1Gbps = 176ns
- Store-and-forward end-to-end delay =

  3 * (Transmission time + Propagation time) = 30.246us
- Cut-through switcing end-to-end delay =

  1 * Transmission time + 3 * Propagation time + 2 * Cut-through delay = 10.534us

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

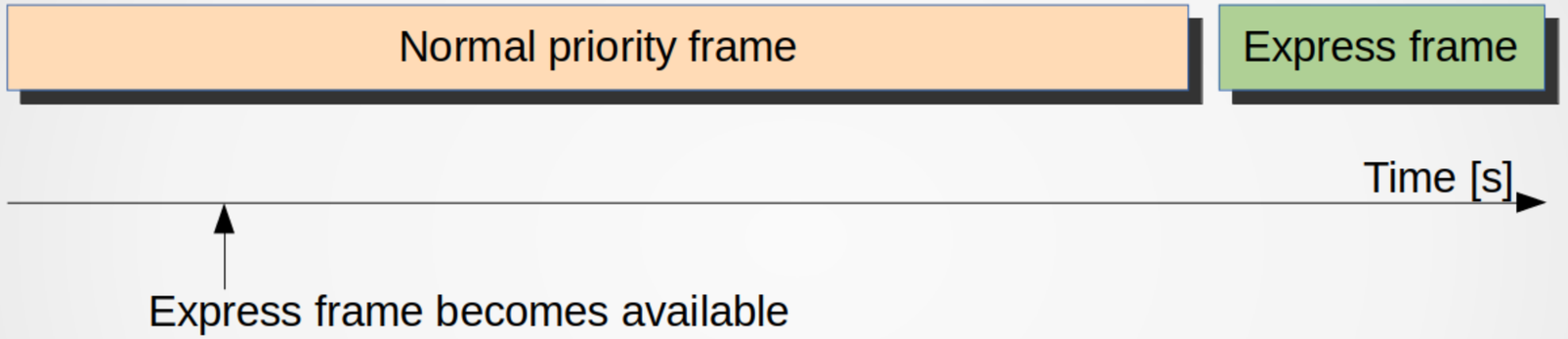
Automatic gate schedule configuration

Time synchronization

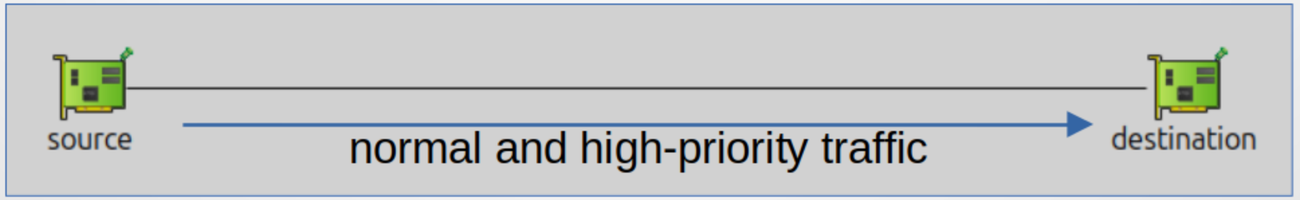
Frame replication and elimination for reliability

Long Frame Problem

- Long frame delays high priority frame



- Express frame waits in the queue

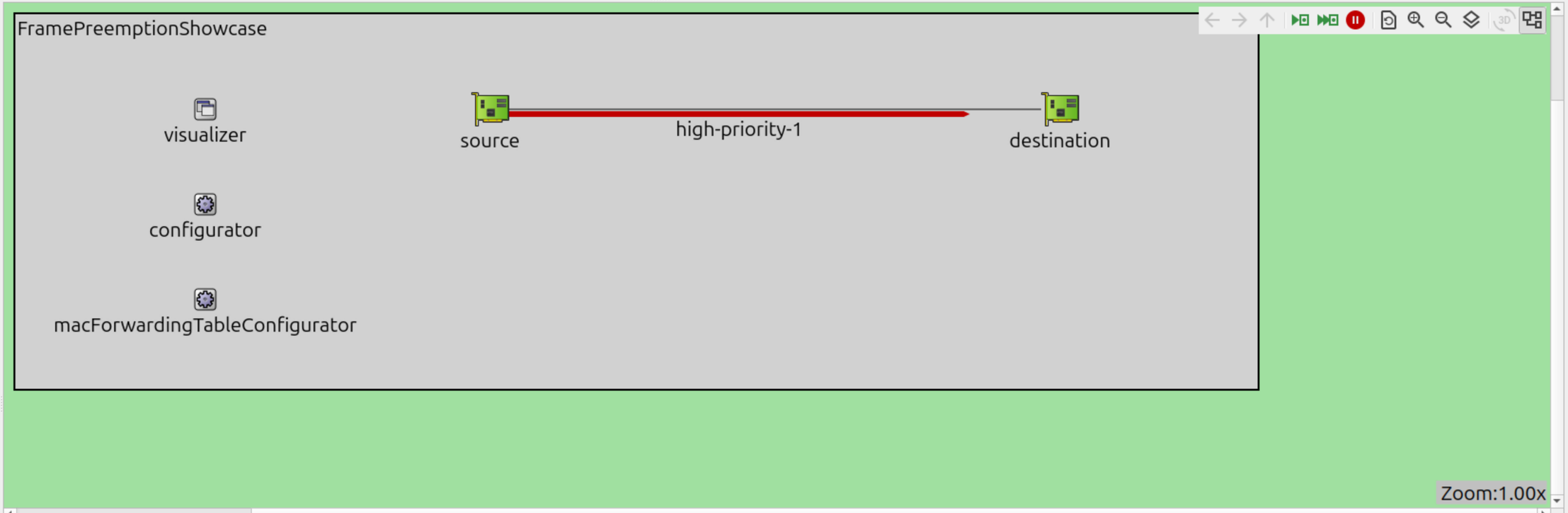


OMNeT++/Qtenv (release) - PriorityQueueing #0 - FramePreemption.ini - /home/levy/workspace/inet/wfcs2025/step2_frame_preemption

File Simulate Inspect View Help

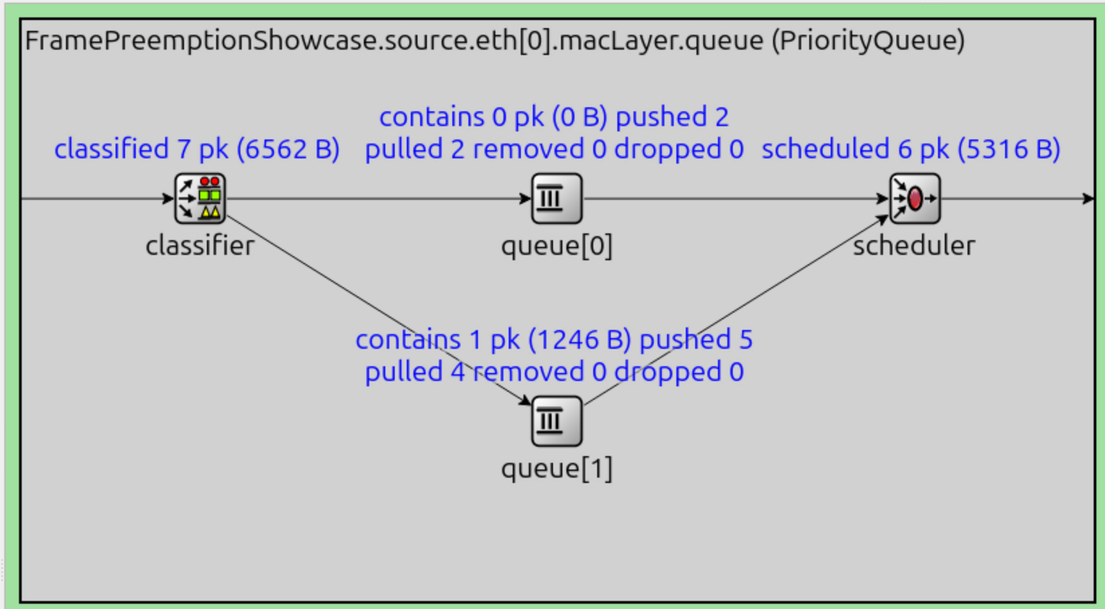
next: #92 | 0s 000ms 529us 185ns 209ps

Next: TxEndTimer (inet::ClockEvent, id=9) | In: FramePreemptionShowcase.source.eth[0].phyLayer.transmitter (PacketTransmitter, id=95) | At: 0.000543061908s (now+0.000013876699s)



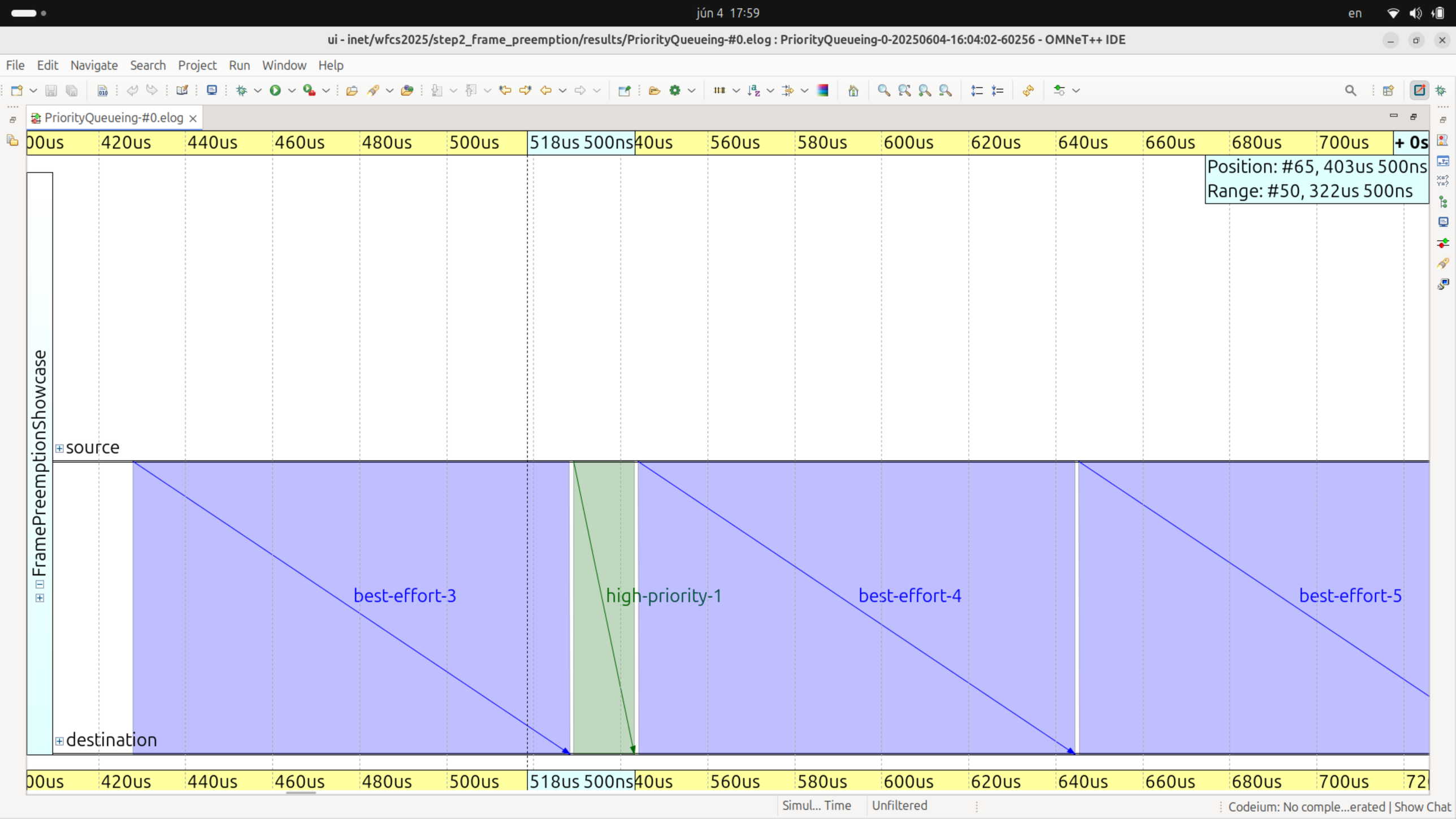
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#13	0.000	source --> destination	high-priority-0	10.0.0.1:1026	10.0.0.2:1001	UDP		174 B	
#28	0.000'014'880	source --> destination	best-effort-0	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#43	0.000'149'239'039	source --> destination	best-effort-1	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#57	0.000'291'867'573	source --> destination	best-effort-2	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#71	0.000'427'861'908	source --> destination	best-effort-3	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN) 1200
#91	0.000'529'141'908	source --> destination	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		174 B	(UNKNOWN) 120

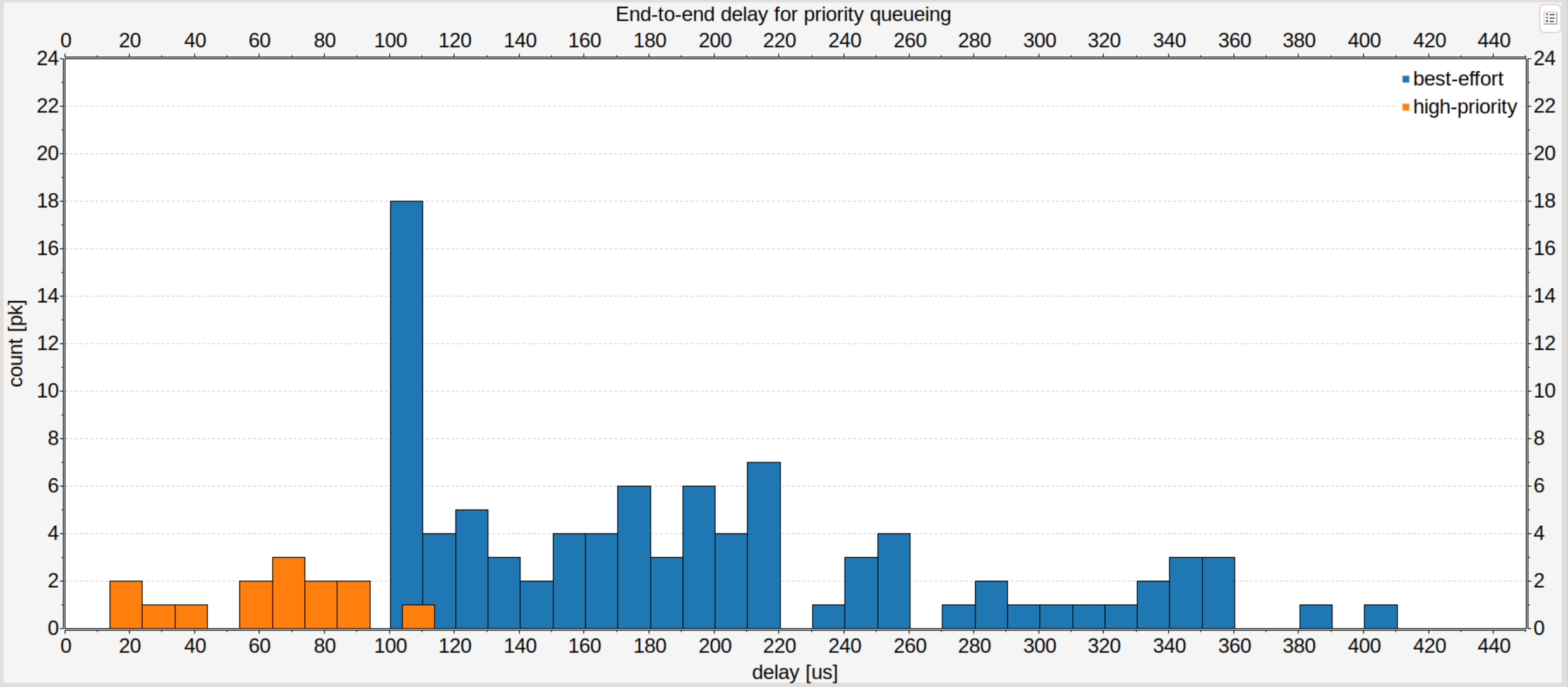
PriorityQueueing #0: FramePreemptionShowcase | Msg stats: 5 scheduled / 67 existing / 111 created



Zoom:1.33x

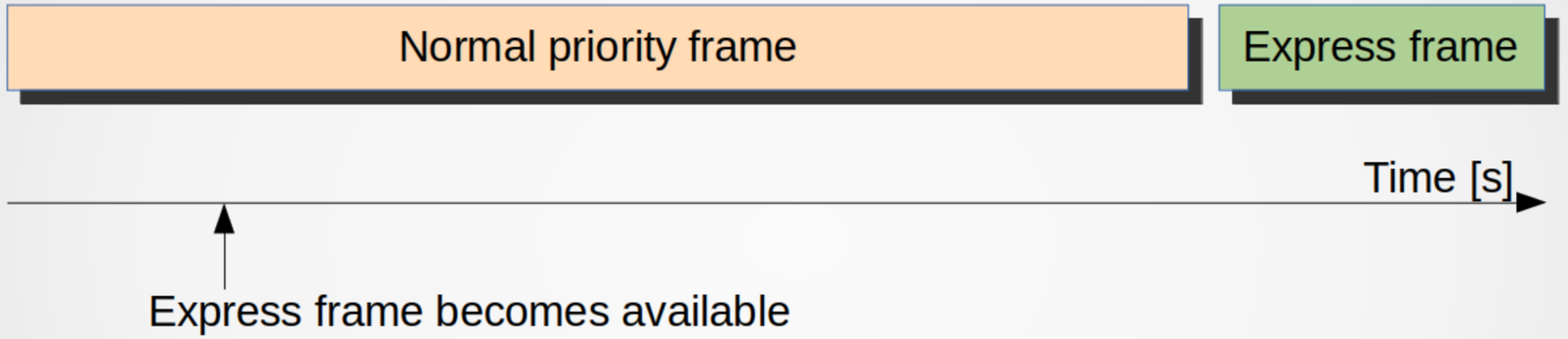
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#76	0.000'473'504'914	^ --> .	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		166 B	
#76	0.000'473'504'914	. --> classifier	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		166 B	(UNKNOWN) 126
#76	0.000'473'504'914	classifier --> queue[0]	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		166 B	(UNKNOWN) 126
#82	0.000'490'412'145	^ --> .	best-effort-4	10.0.0.1:1025	10.0.0.2:1000	UDP		1246 B	(UNKNOWN) 126
#82	0.000'490'412'145	. --> classifier	best-effort-4	10.0.0.1:1025	10.0.0.2:1000	UDP		1246 B	(UNKNOWN) 126
#82	0.000'490'412'145	classifier --> queue[1]	best-effort-4	10.0.0.1:1025	10.0.0.2:1000	UDP		1246 B	(UNKNOWN) 126
#91	0.000'529'141'908	queue[0] --> scheduler	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		166 B	(UNKNOWN) 126
#91	0.000'529'141'908	scheduler --> .	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		166 B	(UNKNOWN) 126


jún 4 17:59
en
ui - inet/wfcs2025/step2_frame_preemption/results/PriorityQueueing-#0.elog : PriorityQueueing-0-20250604-16:04:02-60256 - OMNeT++ IDE
File Edit Navigate Search Project Run Window Help
PriorityQueueing-#0.elog
00us 420us 440us 460us 480us 500us 518us 500ns 40us 560us 580us 600us 620us 640us 660us 680us 700us + 0s
Position: #65, 403us 500ns
Range: #50, 322us 500ns
FramePreemptionShowcase
source
destination
best-effort-3
high-priority-1
best-effort-4
best-effort-5
00us 420us 440us 460us 480us 500us 518us 500ns 40us 560us 580us 600us 620us 640us 660us 680us 700us 72
Simul... Time
Unfiltered
Codeium: No comple...erated | Show Chat



Frame Preemption

- Long frame delays high priority frame



- Reduce latency by interrupting transmission

ui - inet/wfcs2025/step2_frame_preemption/FramePreemption.ini - OMNeT++ IDE

File Edit Source Navigate Search Project Run Window Help

PriorityQueueing-#0.elog FramePreemption.anf FramePreemption.ini

```
31
32 # configure destination applications
33 *.destination.numApps = 2
34 *.destination.app[*].typename = "UdpSinkApp"
35 *.destination.app[0].io.localPort = 1000
36 *.destination.app[1].io.localPort = 1001
37
38 [PriorityQueueing]
39 description = "High-priority frames are transmitted before best-effort frames"
40
41 # configure priority queueing
42 **.macLayer.queue.typename = "PriorityQueue"
43 **.macLayer.queue.numQueues = 2
44 **.macLayer.queue.queue[*].packetCapacity = 4
45 **.macLayer.queue.queue*.typename = "DropTailQueue"
46 **.macLayer.queue.classifier.classifierClass = "inet::PacketVlanReqClassifier"
47
48 [FramePreemption]
49 description = "Transmission of best-effort frames are preempted by high-priority frames"
50
51 # configure Ethernet frame preemption
52 *.*.eth[0].macLayer.typename = "EthernetPreemptingMacLayer"
53 *.*.eth[0].phyLayer.typename = "EthernetPreemptingPhyLayer"
54
55 # configure MAC nested sublayer queueing
56 *.source.eth[0].macLayer.queue.typename = ""
57 *.source.eth[0].macLayer.*MacLayer.queue.typename = "DropTailQueue"
58 *.source.eth[0].macLayer.*MacLayer.queue.packetCapacity = 4
59
```

Form Source

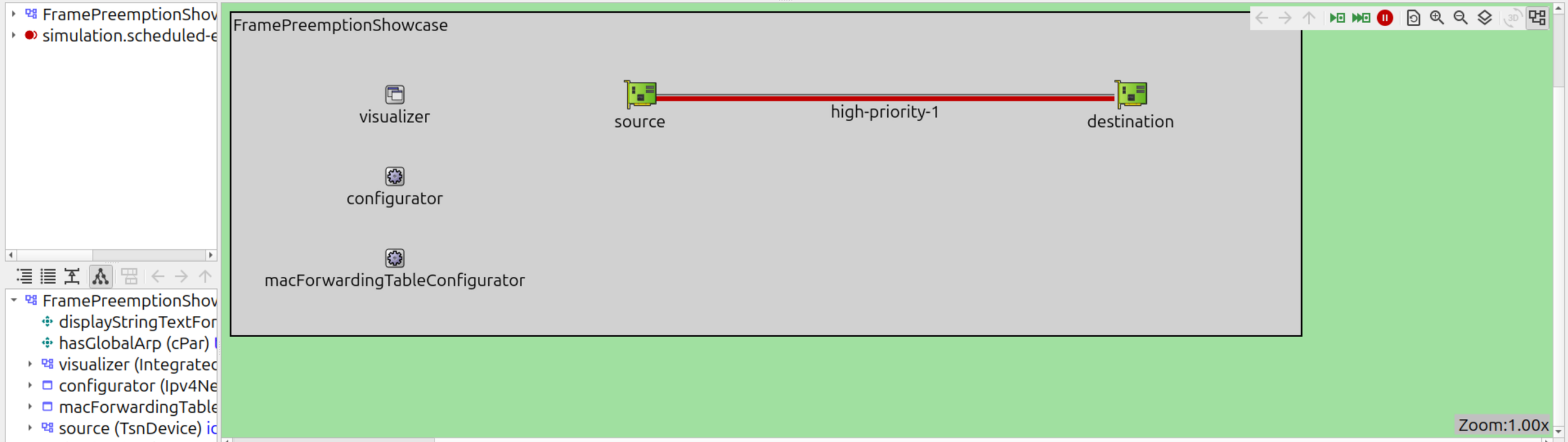
Writable Insert 1 : 1 : 0 Codeium: No comple...erated | Show Chat

OMNeT++/Qtenv (release) - FramePreemption #0 - FramePreemption.ini - /home/levy/workspace/inet/wfcs2025/step2_frame_preemption

File Simulate Inspect View Help

next: #80 | 0s 000ms 476us 260ns 511ps

Next: Timer (inet::ClockEvent, id=6) | In: FramePreemptionShowcase.source.eth[0].macLayer.preemptingServer (PreemptingServer, id=81) | At: 0.000488741908s (now+0.000012481397s)



FramePreemptionShov
simulation.scheduled-e

FramePreemptionShov
displayStringTextFor
hasGlobalArp (cPar)
visualizer (Integratec
configurator (Ipv4Ne
macForwardingTable
source (TsnDevice) ic
destination (TsnDevi
canvas (cCanvas) 19

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#40	0.000'149'239'039	source --> destination	best-effort-1				Ethernet PHY	1254 B	
#43	0.000'249'559'039	source --> destination	best-effort-1:end				Ethernet PHY	1254 B	(UNKNOWN) (ir
#54	0.000'291'867'573	source --> destination	best-effort-2				Ethernet PHY	1254 B	(UNKNOWN) (ir
#57	0.000'392'187'573	source --> destination	best-effort-2:end				Ethernet PHY	1254 B	(UNKNOWN) (ir
#68	0.000'427'861'908	source --> destination	best-effort-3				Ethernet PHY	1254 B	(UNKNOWN) (ir
#74	0.000'473'504'914	source --> destination	best-effort-3-frag0:progress				Ethernet PHY	583 B	(UNKNOWN) (ir
#76	0.000'474'501'908	source --> destination	best-effort-3-frag0:end				Ethernet PHY	583 B	(UNKNOWN) (ir
#78	0.000'475'461'908	source --> destination	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP		174 B	(UNKNOWN) 126

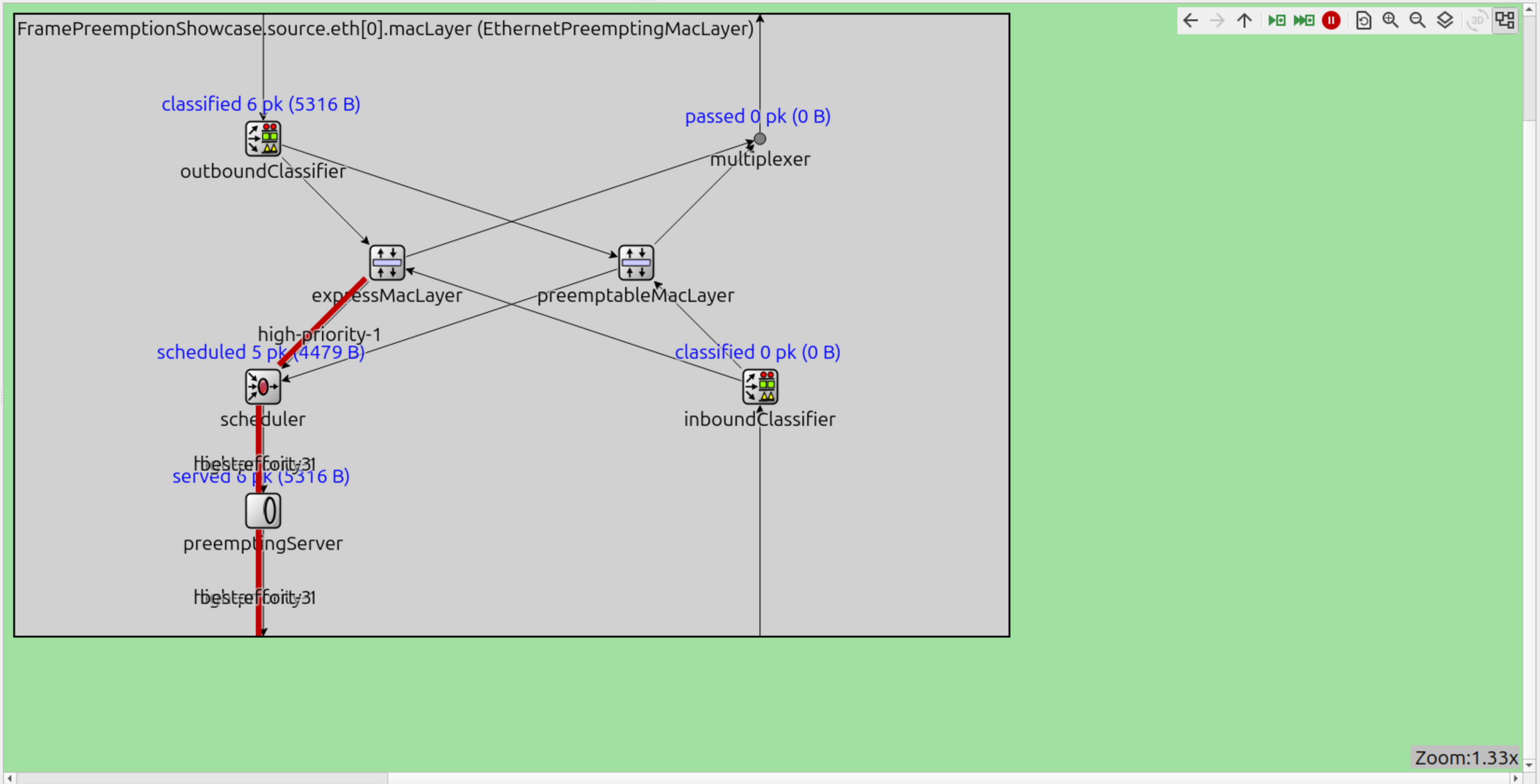
FramePreemption #0: FramePreemptionShowcase | Msg stats: 5 scheduled / 84 existing / 170 created

OMNeT++/Qtenv (release) - FramePreemption #0 - FramePreemption.ini - /home/levy/workspace/inet/wfcs2025/step2_frame_preemption

File Simulate Inspect View Help

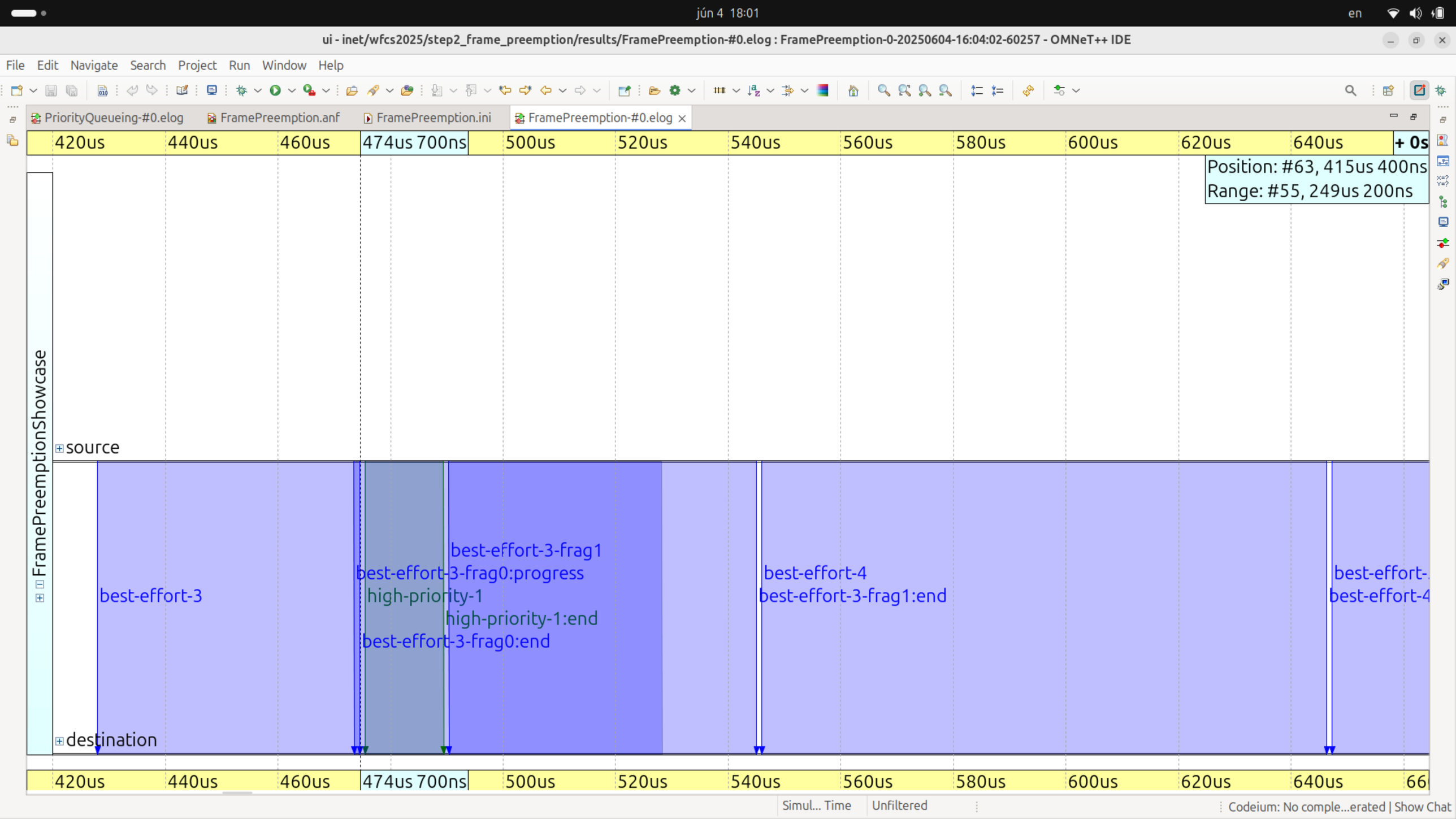
next: #80 | 0s 000ms 476us 260ns 511ps

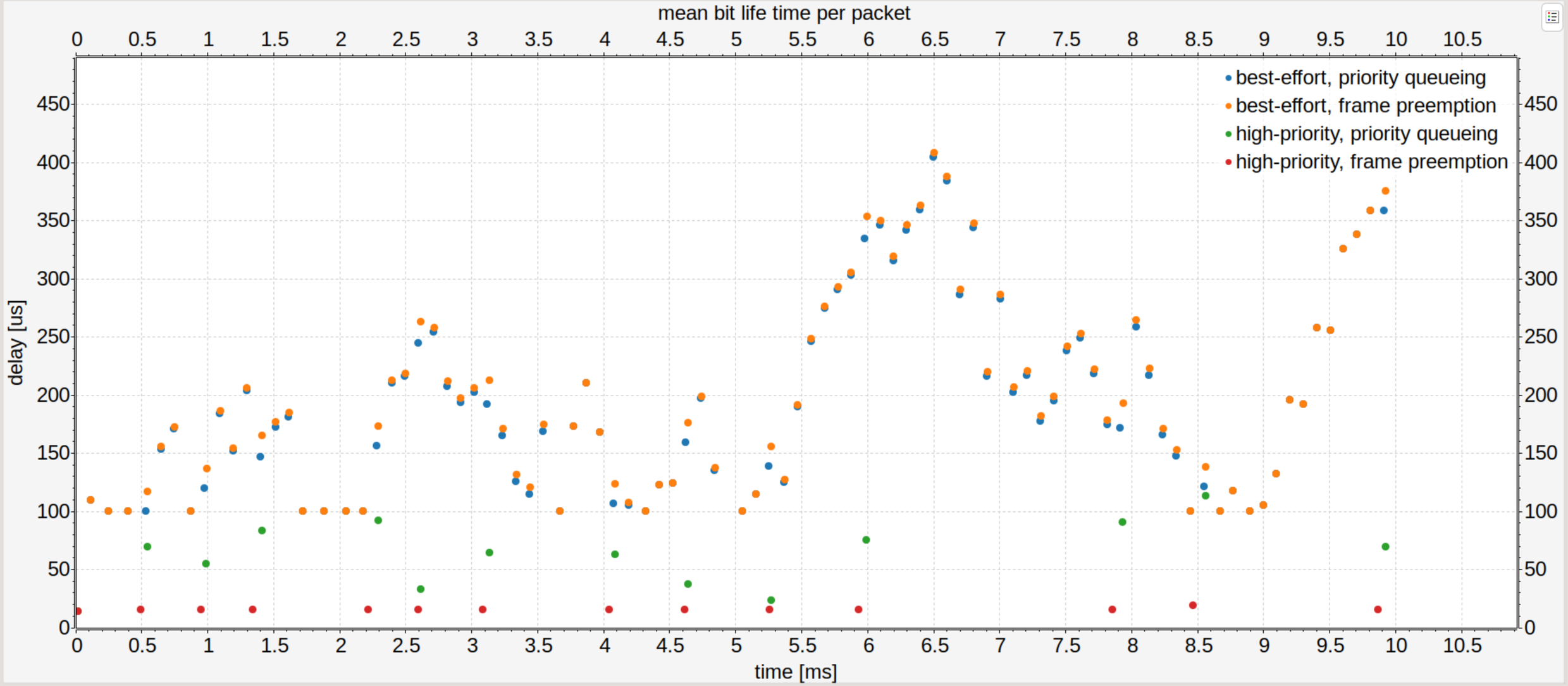
Next: Timer (inet::ClockEvent, id=6) | In: FramePreemptionShowcase.source.eth[0].macLayer.preemptingServer (PreemptingServer, id=81) | At: 0.000488741908s (now+0.000012481397s)



FramePreemption #0: FramePreemptionShowcase

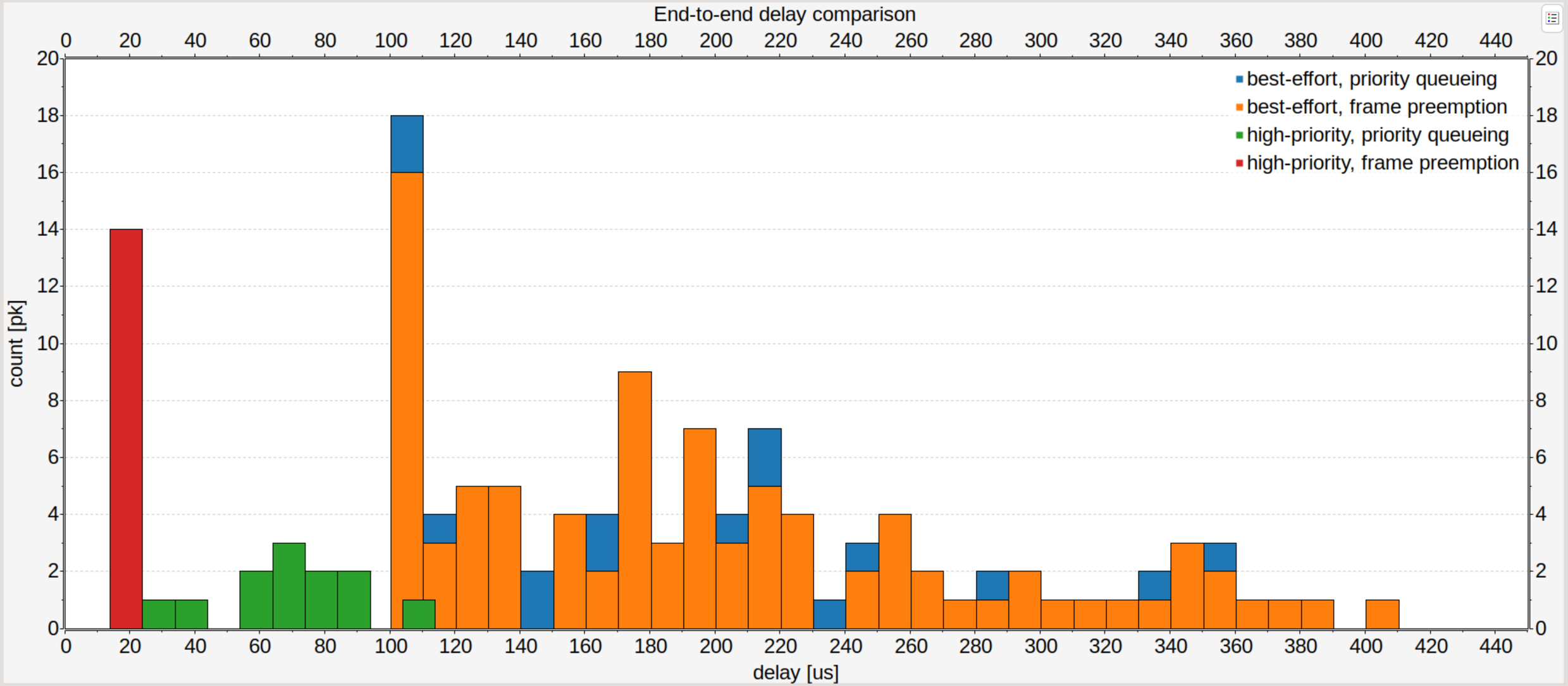
Msg stats: 5 scheduled / 84 existing / 170 created


jún 4 18:01
en
ui - inet/wfcs2025/step2_frame_preemption/results/FramePreemption-#0.elog : FramePreemption-0-20250604-16:04:02-60257 - OMNeT++ IDE
File Edit Navigate Search Project Run Window Help
PriorityQueueing-#0.elog
FramePreemption.anf
FramePreemption.ini
FramePreemption-#0.elog
420us 440us 460us 474us 700ns 500us 520us 540us 560us 580us 600us 620us 640us + 0s
Position: #63, 415us 400ns
Range: #55, 249us 200ns
FramePreemptionShowcase
source
destination
best-effort-3
best-effort-3-frag1
best-effort-3-frag0:progress
high-priority-1
high-priority-1:end
best-effort-3-frag0:end
best-effort-4
best-effort-3-frag1:end
best-effort-
best-effort-4
420us 440us 460us 474us 700ns 500us 520us 540us 560us 580us 600us 620us 640us 66
Simul... Time
Unfiltered
Codeium: No comple...erated | Show Chat



PriorityQueueing-#0.elog | FramePreemption.anf | FramePreemption.ini | FramePreemption-#0.elog

End-to-end delay comparison



Inputs | Browse Data | Charts | End-to-end delay comparison

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

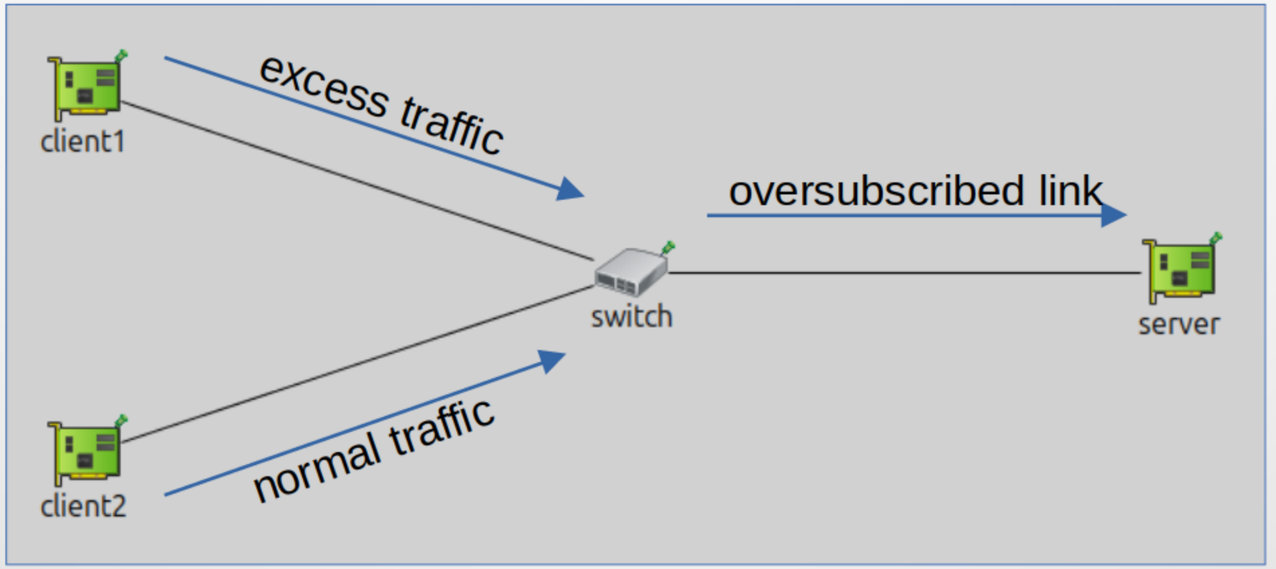
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Incoming Excess Traffic

- Excess traffic contends with other streams
- Introduces unpredicatable latency and jitter
- Violates end-to-end delay guarantees



ui - inet/wfcs2025/step3_stream_filtering/StreamFiltering.ini - OMNeT++ IDE

File Edit Source Navigate Search Project Run Window Help

StreamFiltering.ini

```
[General]
abstract = true
network = StreamFilteringShowcase
sim-time-limit = 1s
result-dir = "results/wip"

# configure Ethernet speed
*.*.eth[*].bitrate = 100Mbps

# configure client applications
*.client*.numApps = 1
*.client*.app[*].typename = "UdpSourceApp"
*.client1.app[0].display-name = "excess traffic"
*.client2.app[0].display-name = "normal traffic"
*.client*.app[*].io.destAddress = "server"
*.client1.app[0].io.destPort = 1000
*.client2.app[0].io.destPort = 1001
*.client1.app[0].io.displayStringTextFormat = "{numSent} excess traffic"
*.client2.app[0].io.displayStringTextFormat = "{numSent} normal traffic"

# configure excess traffic stream from ~40Mbps to ~110Mbps
*.client1.app[0].source.packetLength = 1000B
*.client1.app[0].source.productionInterval = 200us + replaceUnit(sin(dropUnit(simTime() * 10)), "ms") / 8

# configure normal traffic stream ~20Mbps
*.client2.app[0].source.packetLength = 500B
*.client2.app[0].source.productionInterval = 250us

# configure server applications
```

Form Source

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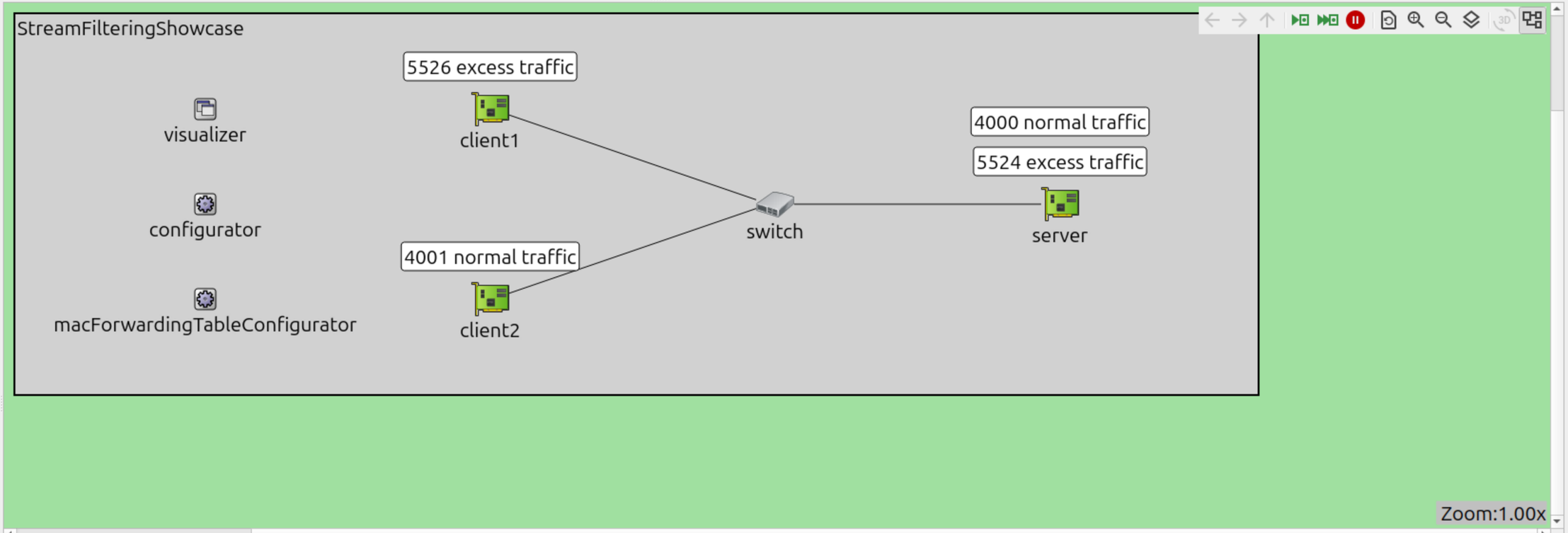
OMNeT++/Qtenv (release) - NoStreamFiltering #0 - StreamFiltering.ini - /home/levy/workspace/inet/wfcs2025/step3_stream_filtering

File Simulate Inspect View Help

next: #180 993 | 1s 000ms 000us 000ns 000ps

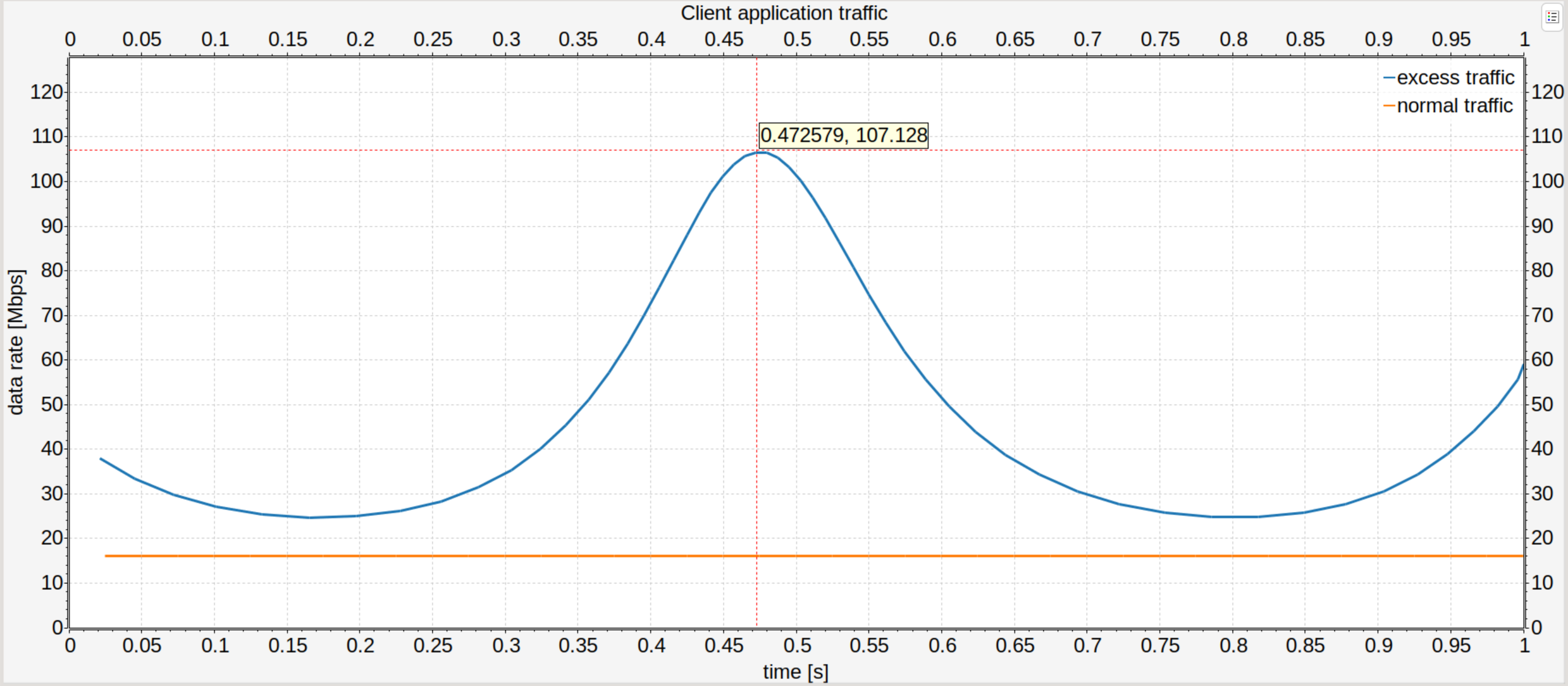
Next: n/a | In: n/a | At: n/a



Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#1720	0.010'099'590'939	client1 --> switch	excess traffic-49	10.0.0.1:1025	10.0.0.3:1000	UDP		1054 B	
#1731	0.010'183'960'939	switch --> server	excess traffic-49	10.0.0.1:1025	10.0.0.3:1000	UDP		1054 B	(UNKNOWN)
#1739	0.010'250	client2 --> switch	normal traffic-41	10.0.0.2:1025	10.0.0.3:1001	UDP		554 B	(UNKNOWN)
#1750	0.010'294'370	switch --> server	normal traffic-41	10.0.0.2:1025	10.0.0.3:1001	UDP		554 B	(UNKNOWN)
#1758	0.010'312'193'977	client1 --> switch	excess traffic-50	10.0.0.1:1025	10.0.0.3:1000	UDP		1054 B	(UNKNOWN)
#1769	0.010'396'563'977	switch --> server	excess traffic-50	10.0.0.1:1025	10.0.0.3:1000	UDP		1054 B	(UNKNOWN)
#1785	0.010'500	client2 --> switch	normal traffic-42	10.0.0.2:1025	10.0.0.3:1001	UDP		554 B	(UNKNOWN)

NoStreamFiltering #0: StreamFilteringShowcase | Msg stats: 8 scheduled / 311 existing / 143178 created

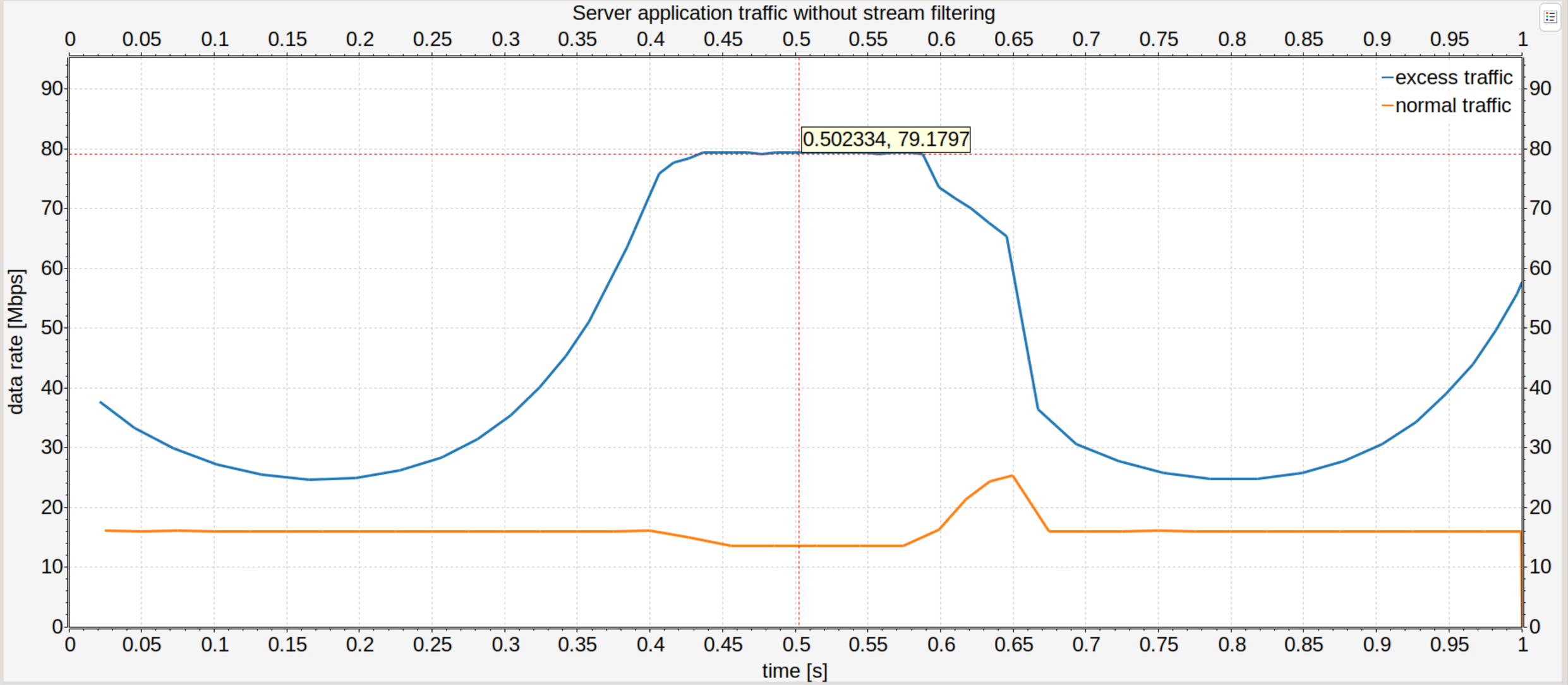
Client application traffic



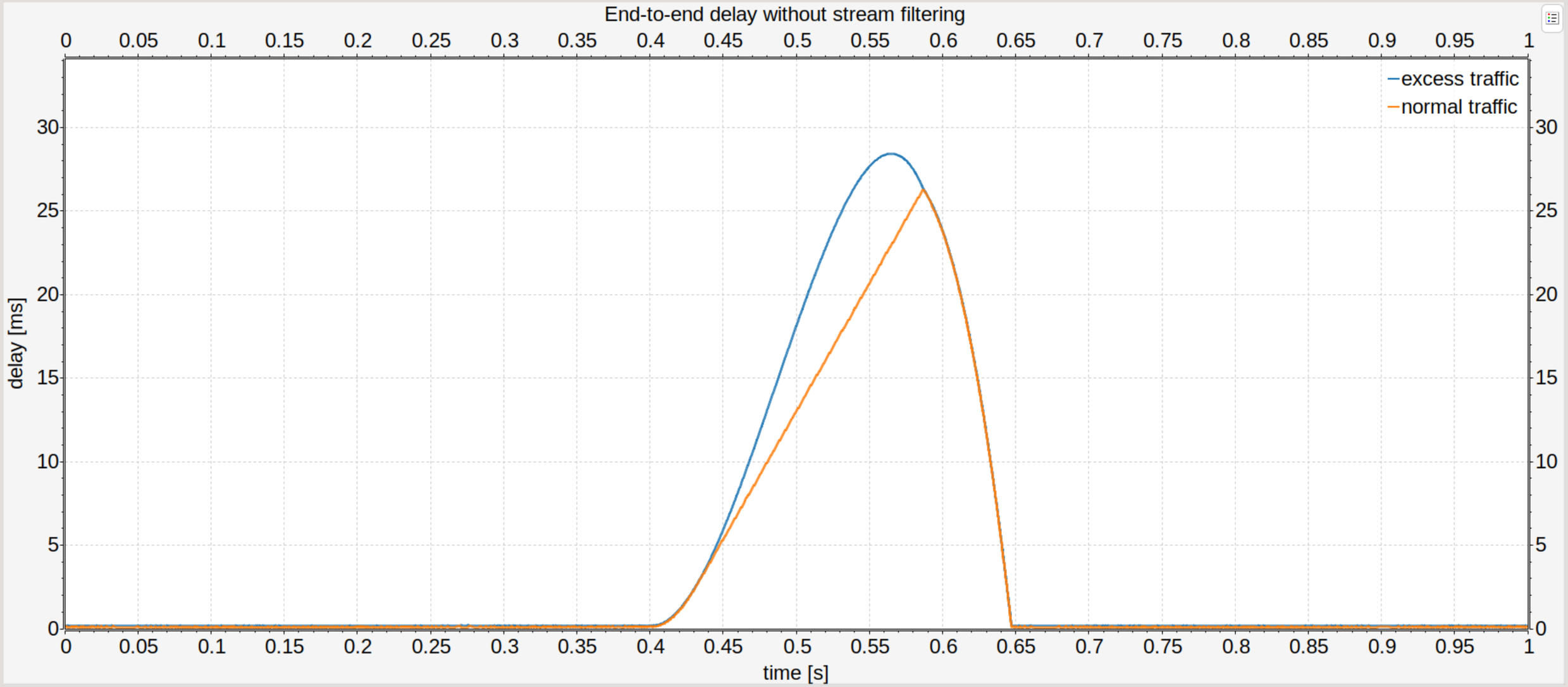
File Edit Navigate Search Project Run Window Help

StreamFiltering.ini StreamFiltering.anf ×

Server application traffic without stream filtering



Inputs | Browse Data | Charts | Client application traffic | Server application traffic without stream filtering ×



Per-Stream Filtering

- Classify packets
- Shape streams with token-bucket coloring
- Enforce policing actions
- Minimizes cross-stream interference

ui - inet/wfcs2025/step3_stream_filtering/StreamFiltering.ini - OMNeT++ IDE

File Edit Source Navigate Search Project Run Window Help

StreamFiltering.ini × StreamFiltering.anf

```
59                                                    {stream: "normal traffic", packetFilter: expr(udp.destPort == 1001)}]
60
61 # configure client stream encoding
62 *.client*.bridging.streamCoder.encoder.mapping = [{stream: "excess traffic", vlan: 0},
63                                                    {stream: "normal traffic", vlan: 4}]
64
65 # disable forwarding IEEE 802.1Q C-Tag
66 *.switch.bridging.directionReverser.reverser.excludeEncapsulationProtocols = ["ieee8021qctag"]
67
68 # configure stream decoding
69 *.switch.bridging.streamCoder.decoder.mapping = [{vlan: 0, stream: "excess traffic"},
70                                                  {vlan: 4, stream: "normal traffic"}]
71
72 # enable ingress per-stream filtering
73 *.switch.hasIngressTrafficFiltering = true
74
75 # configure per-stream filtering
76 *.switch.bridging.streamFilter.ingress.typename = "BareIeee8021qFilter"
77 *.switch.bridging.streamFilter.ingress.numStreams = 2
78 *.switch.bridging.streamFilter.ingress.hasDefaultPath = false
79 *.switch.bridging.streamFilter.ingress.classifier.mapping = {"excess traffic": 0, "normal traffic": 1}
80 *.switch.bridging.streamFilter.ingress.meter[0].display-name = "excess traffic"
81 *.switch.bridging.streamFilter.ingress.meter[1].display-name = "normal traffic"
82 *.switch.bridging.streamFilter.ingress.meter[*].typename = "SingleRateTwoColorMeter"
83 *.switch.bridging.streamFilter.ingress.meter[0].committedInformationRate = 40Mbps
84 *.switch.bridging.streamFilter.ingress.meter[1].committedInformationRate = 20Mbps
85 *.switch.bridging.streamFilter.ingress.meter[0].committedBurstSize = 10kB
86 *.switch.bridging.streamFilter.ingress.meter[1].committedBurstSize = 5kB
87
```

Form Source

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File Edit Source Refactor Navigate Search Project Run Window Help

StreamFiltering.ini | StreamFiltering.anf | TokenBucketMeter.cc | TokenBucketMeter.h

```
7
8  #ifndef __INET_TOKENBUCKETMETER_H
9  #define __INET_TOKENBUCKETMETER_H
10
11 #include "inet/queueing/base/PacketMeterBase.h"
12 #include "inet/queueing/base/TokenBucketMeterMixin.h"
13 #include "inet/queueing/base/TokenBucketMixin.h"
14
15 namespace inet {
16 namespace queueing {
17
18 extern template class TokenBucketMeterMixin<TokenBucketMixin<PacketMeterBase>>;
19
20 class INET_API TokenBucketMeter : public TokenBucketMeterMixin<TokenBucketMixin<PacketMeterBase>>
21 {
22   protected:
23     const char *label = nullptr;
24
25   protected:
26     virtual void initialize(int stage) override;
27
28     virtual void meterPacket(Packet *packet) override;
29 };
30
31 } // namespace queueing
32 } // namespace inet
33
34 #endif
35
36
```

File Edit Source Refactor Navigate Search Project Run Window Help

StreamFiltering.ini | StreamFiltering.anf | TokenBucketMeter.cc | TokenBucketMeter.h

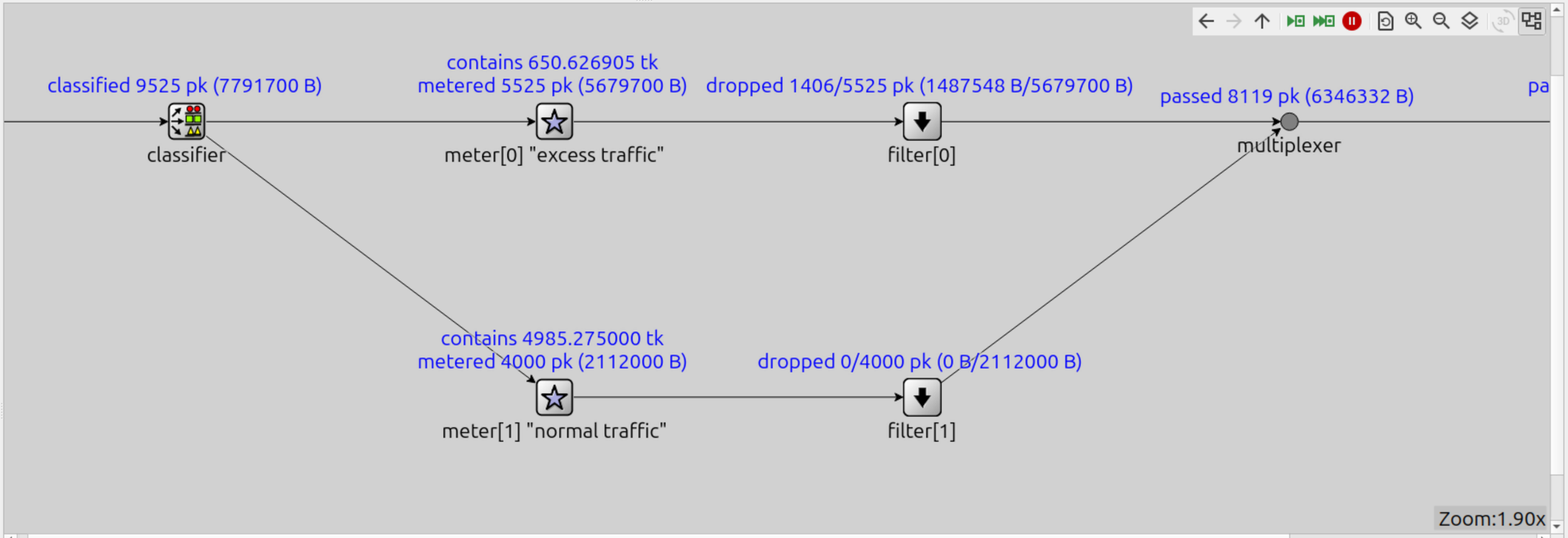
```
15 Define_Module(TokenBucketMeter);
16
17 template class TokenBucketMeterMixin<TokenBucketMixin<PacketMeterBase>>;
18
19 void TokenBucketMeter::initialize(int stage)
20 {
21     TokenBucketMeterMixin<TokenBucketMixin<PacketMeterBase>>::initialize(stage);
22     if (stage == INITSTAGE_LOCAL)
23         label = par("label");
24 }
25
26 void TokenBucketMeter::meterPacket(Packet *packet)
27 {
28     emit(tokensChangedSignal, getNumTokens());
29     auto numTokens = getNumPacketTokens(packet);
30     EV_DEBUG << "Checking tokens for packet" << EV_FIELD(numTokens) << EV_FIELD(tokenBucket) << EV_FIELD(packet) << EV_ENDL;
31     if (tokenBucket.getNumTokens() >= numTokens) {
32         tokenBucket.removeTokens(numTokens);
33         EV_INFO << "Removed tokens, labeling packet" << EV_FIELD(numTokens) << EV_FIELD(tokenBucket) << EV_FIELD(label) << EV_FI
34         labelPacket(packet, label);
35         emit(tokensChangedSignal, tokenBucket.getNumTokens());
36         rescheduleOverflowTimer();
37     }
38     else {
39         EV_INFO << "Insufficient number of tokens for packet" << EV_FIELD(numTokens) << EV_FIELD(tokenBucket) << EV_FIELD(packet
40         if (defaultLabel != nullptr)
41             labelPacket(packet, defaultLabel);
42     }
43 }
```

OMNeT++/Qtenv (release) - StreamFiltering #0 - StreamFiltering.ini - /home/levy/workspace/inet/wfcs2025/step3_stream_filtering

File Simulate Inspect View Help

next: #188 339 | 1s 000ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a

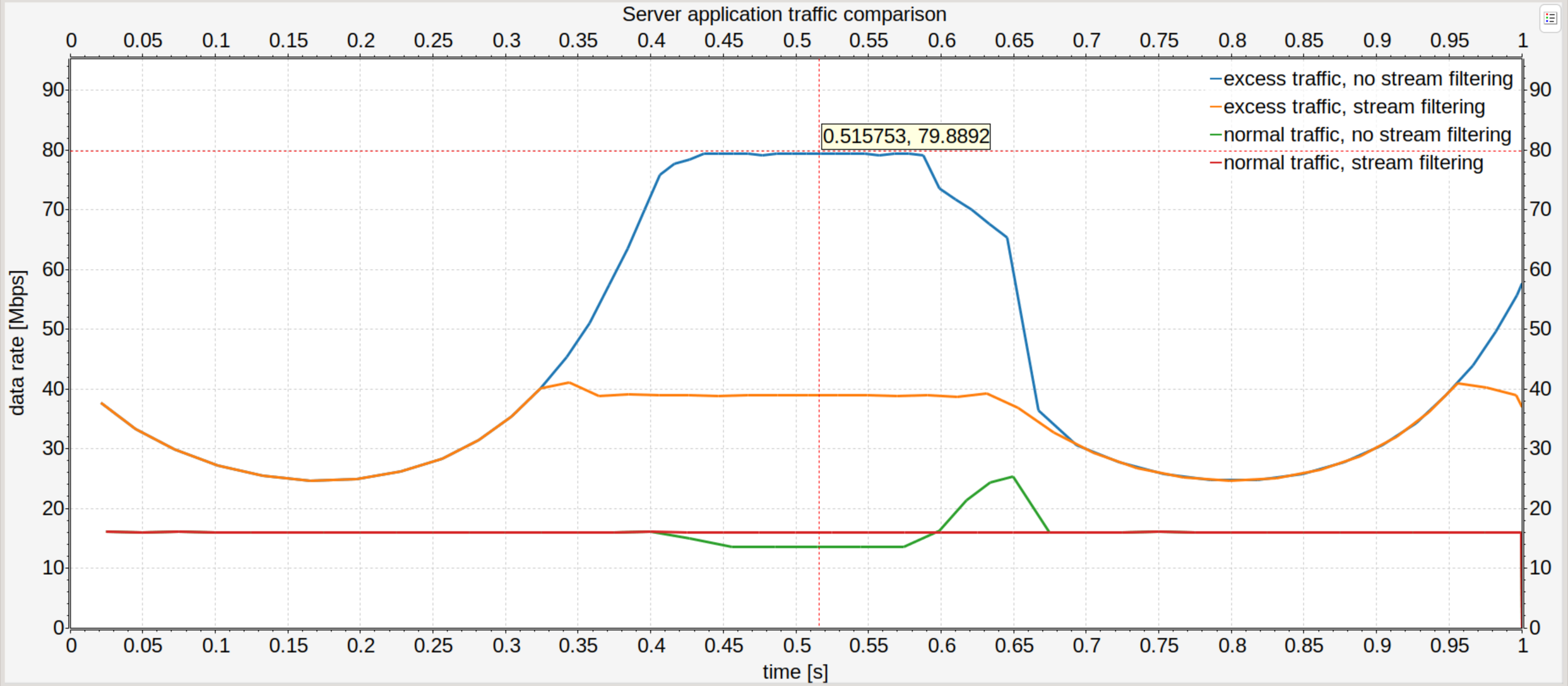


StreamFilteringShowcase
simulation.scheduled-eve

StreamFilteringShowcas
builtinAnimationsAllowe
canvas = nullptr (omnetp
className = 'omnetpp::c
componentType (cDyr
displayName = '' [...] (str
displayString = p=200,10
fullName = 'ingress' (stri
fullPath = 'StreamFilterir
gates[2] (omnetpp::cGat
id = 310 (int)
index = <not a vector> (i
info = 'id=310' (string)
isModule = true (bool)
isSimple = false (bool)
isVector = false (bool)
listenedSignals[0] (omne
name = 'ingress' [...] (stri

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#9269	0.051'794'690	barrier --> .	normal traffic-207	10.0.0.2:1025	10.0.0.3:1001	UDP		528 B	
#9287	0.051'857'734'509	. --> classifier	excess traffic-225	10.0.0.1:1025	10.0.0.3:1000	UDP		1028 B	(UNKNOWN)
#9287	0.051'857'734'509	classifier --> meter[0]	excess traffic-225	10.0.0.1:1025	10.0.0.3:1000	UDP		1028 B	(UNKNOWN)
#9287	0.051'857'734'509	meter[0] --> filter[0]	excess traffic-225	10.0.0.1:1025	10.0.0.3:1000	UDP		1028 B	(UNKNOWN)
#9287	0.051'857'734'509	filter[0] --> multiplexer	excess traffic-225	10.0.0.1:1025	10.0.0.3:1000	UDP		1028 B	(UNKNOWN)
#9287	0.051'857'734'509	multiplexer --> barrier	excess traffic-225	10.0.0.1:1025	10.0.0.3:1000	UDP		1028 B	(UNKNOWN)
#9287	0.051'857'734'509	barrier --> .	excess traffic-225	10.0.0.1:1025	10.0.0.3:1000	UDP		1028 B	(UNKNOWN)

StreamFiltering #0: StreamFilteringShowcase | Msg stats: 8 scheduled / 1207 existing / 170228 created

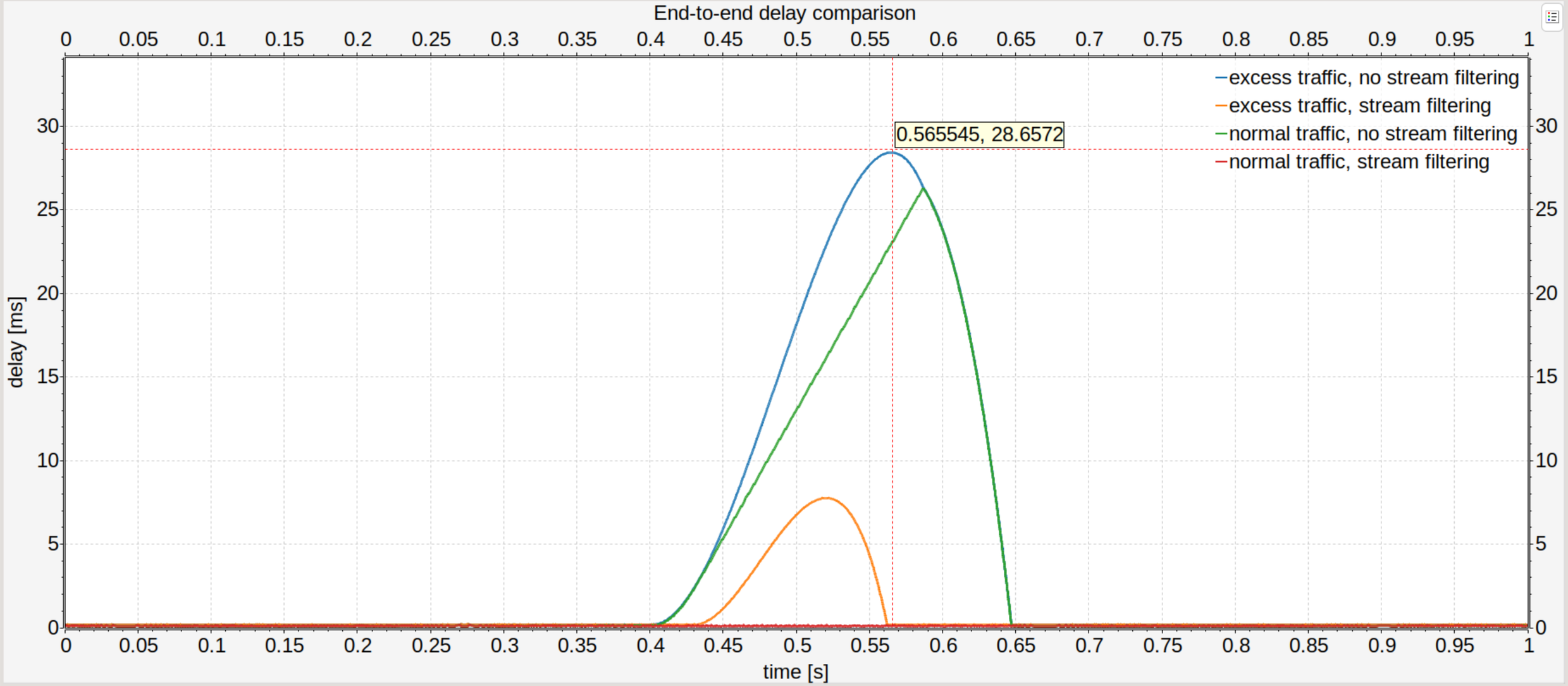


ui - inet/wfcs2025/step3_stream_filtering/StreamFiltering.anf - OMNeT++ IDE

File Edit Navigate Search Project Run Window Help

StreamFiltering.ini | StreamFiltering.anf | TokenBucketMeter.cc | TokenBucketMeter.h

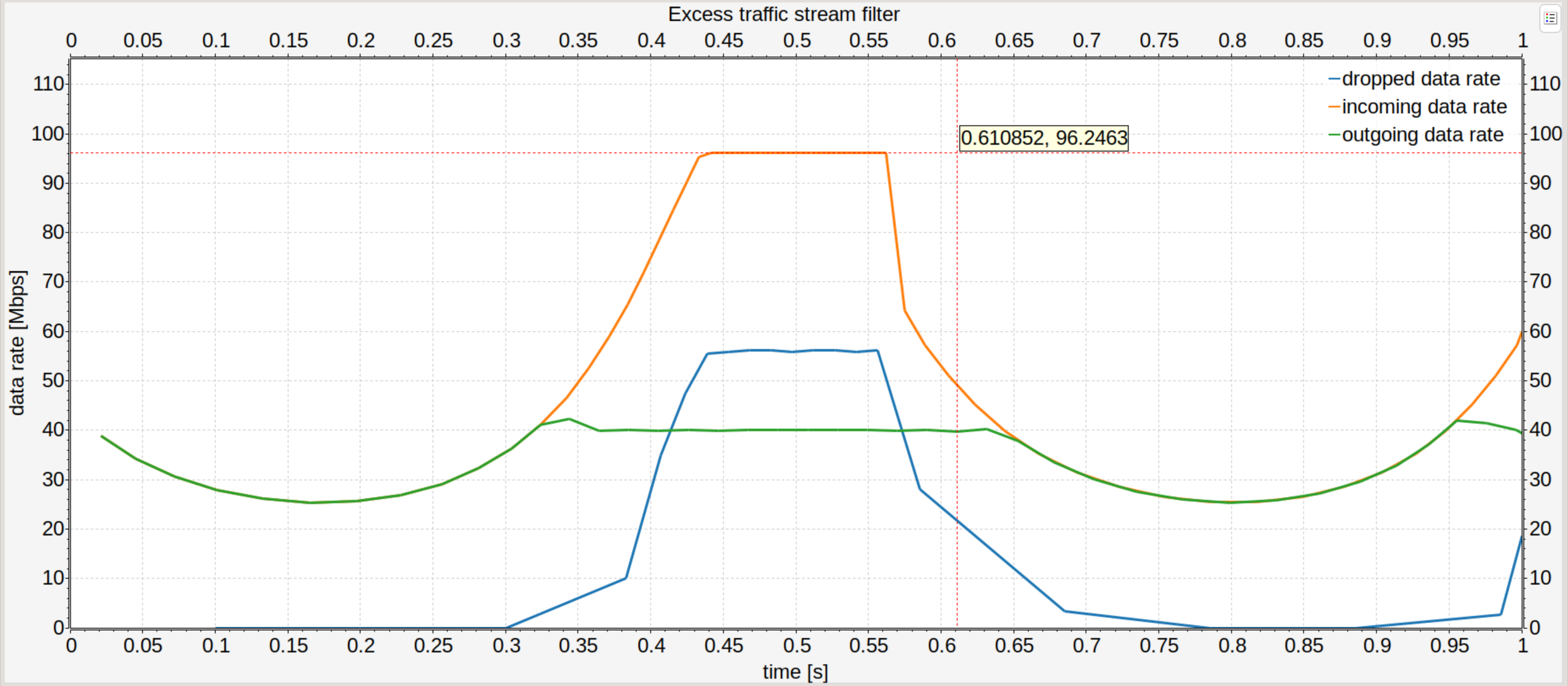
End-to-end delay comparison



Inputs | Browse Data | Charts | Client application traffic | Server application traffic without stream filtering | End-to-end delay without stream filtering | Server application traffic comparison | End-to-end delay comparison

Selected: Chart 'End-to-end delay comparison'

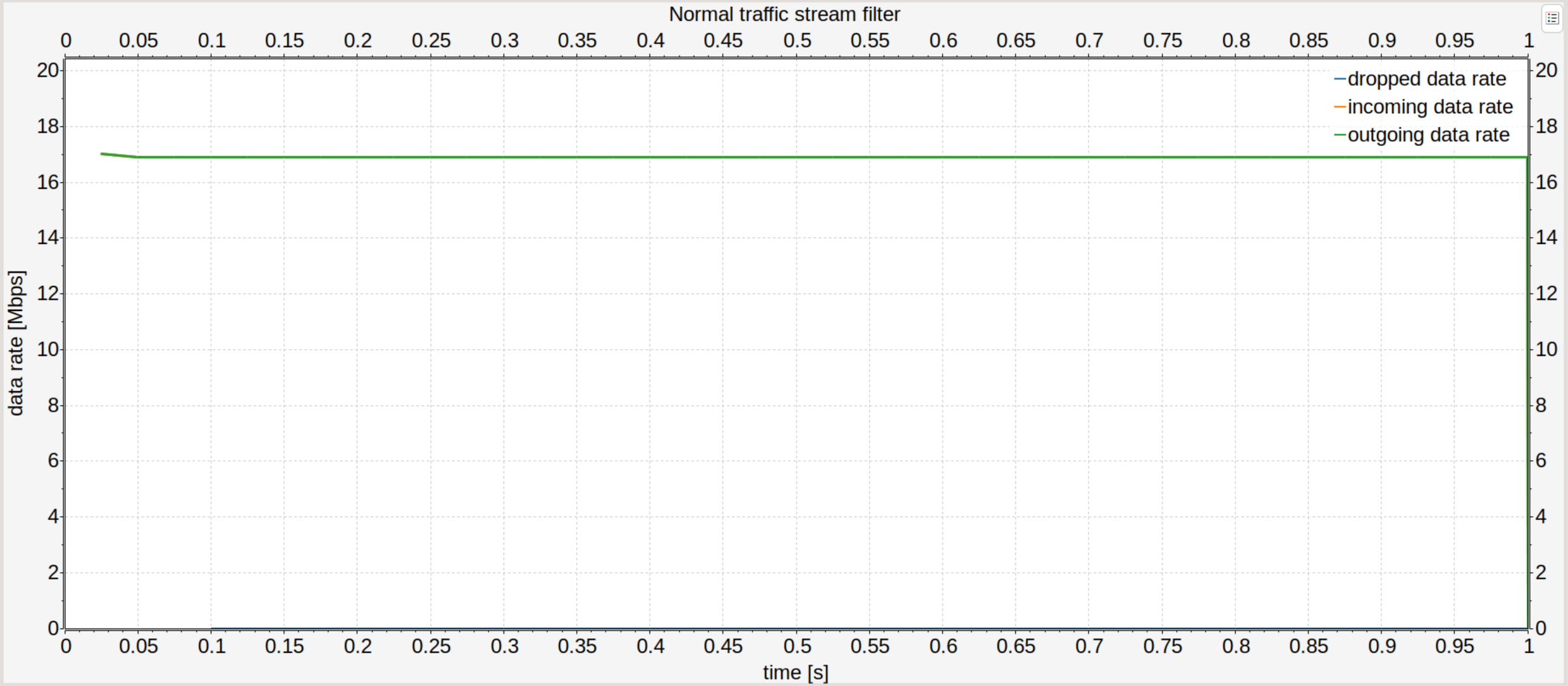
Codeium: No comple...erated | Show Chat


Excess traffic stream filter
dropped data rate
incoming data rate
outgoing data rate
0.610852, 96.2463
data rate [Mbps]
time [s]
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
0 10 20 30 40 50 60 70 80 90 100 110

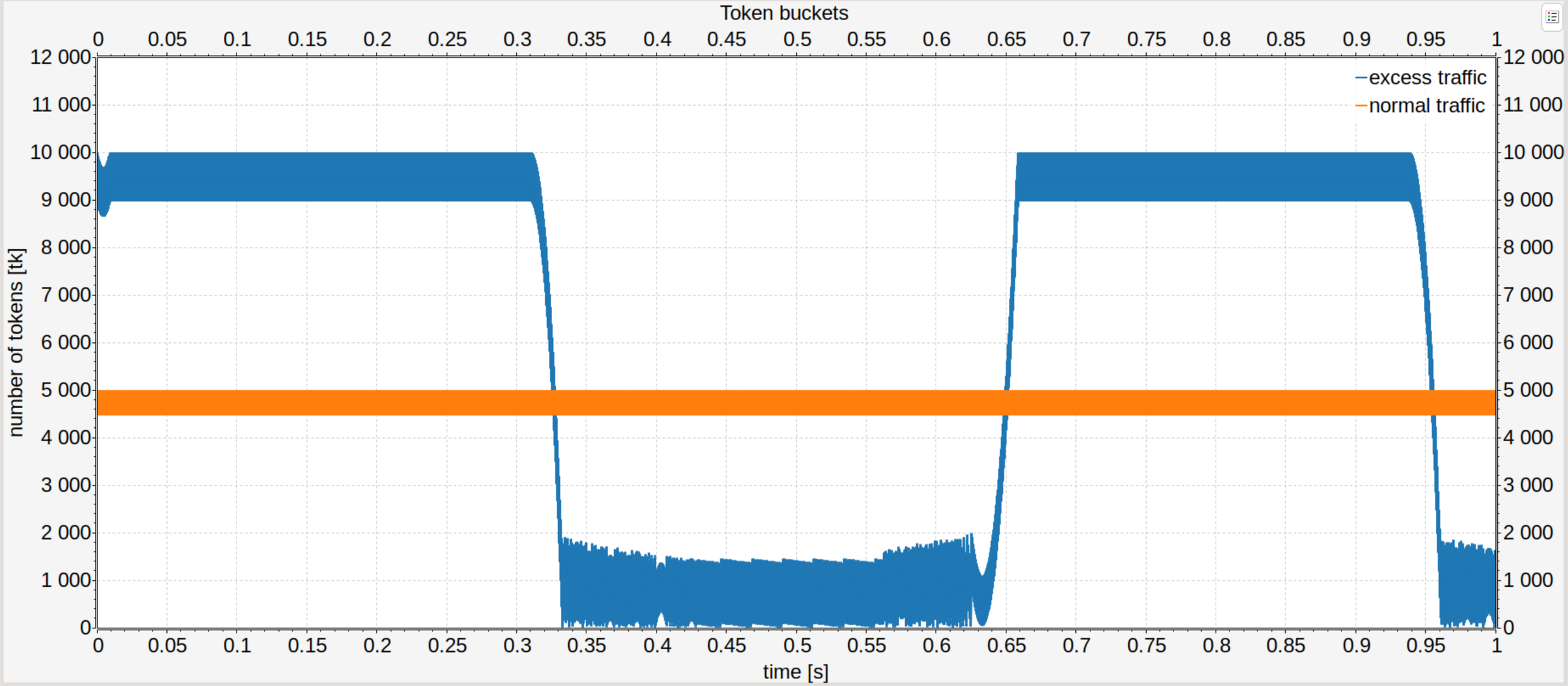
File Edit Navigate Search Project Run Window Help

StreamFiltering.ini | StreamFiltering.anf | TokenBucketMeter.cc | TokenBucketMeter.h

Normal traffic stream filter



Inputs | Browse Data | Charts | Client application traffic | Server application traffic with... | End-to-end delay without stre... | Server application traffic com... | End-to-end delay comparison | Excess traffic stream filter | Normal traffic stream filter


Token buckets
excess traffic
normal traffic
number of tokens [tk]
time [s]
0
1 000
2 000
3 000
4 000
5 000
6 000
7 000
8 000
9 000
10 000
11 000
12 000
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

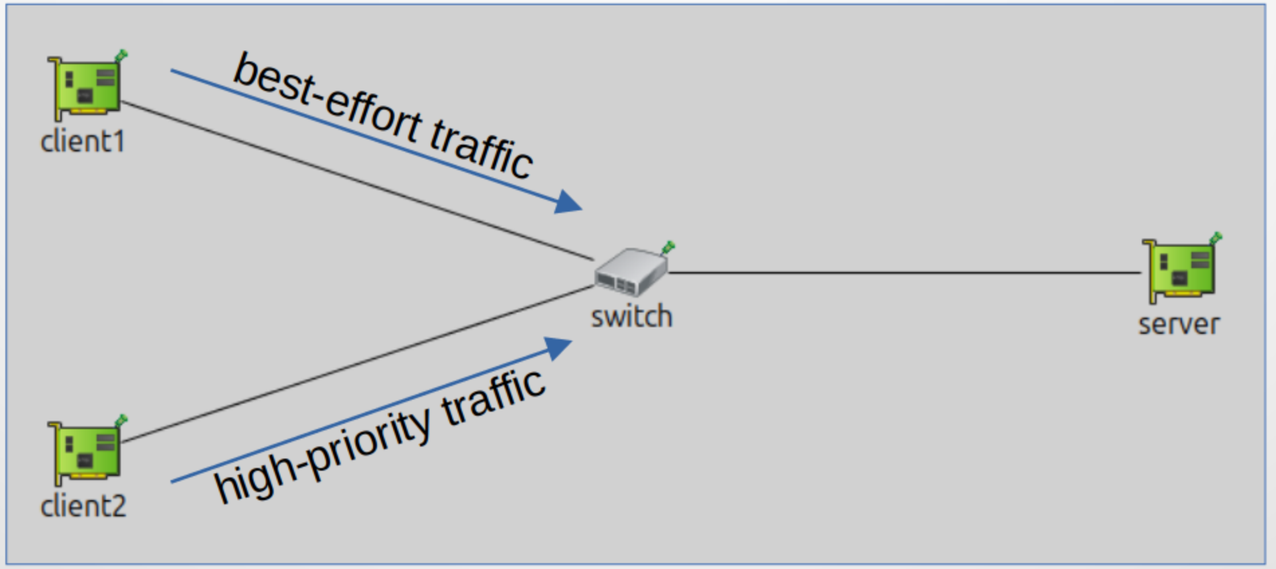
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Outgoing Traffic Contention

- Priority queueing is insufficient
- Time-critical frame must wait ongoing transmission
- Introduces unpredicatable latency and jitter
- Violates end-to-end delay guarantees



ui - inet/wfcs2025/step4_traffic_shaping/TrafficShaping.ini - OMNeT++ IDE

File Edit Source Navigate Search Project Run Window Help

TrafficShaping.ini

```
# configure Ethernet speed
*.*.eth[*].bitrate = 100Mbps

# configure client applications
*.client*.numApps = 1
*.client*.app[*].typename = "UdpSourceApp"
*.client1.app[0].display-name = "best-effort"
*.client2.app[0].display-name = "high-priority"
*.client*.app[*].io.destAddress = "server"
*.client1.app[0].io.destPort = 1000
*.client2.app[0].io.destPort = 1001
*.client1.app[0].io.displayStringTextFormat = "{numSent} best-effort"
*.client2.app[0].io.displayStringTextFormat = "{numSent} high-priority"
*.client1.app[0].source.packetLength = 1500B - 54B # 54B = 8B (UDP) + 20B (IP) + 14B (ETH MAC) + 4B (ETH FCS) + 8B (ETH PHY)
*.client2.app[0].source.packetLength = 64B - 54B # 54B = 8B (UDP) + 20B (IP) + 14B (ETH MAC) + 4B (ETH FCS) + 8B (ETH PHY)
*.client1.app[0].source.productionInterval = exponential(200us) # ~60 Mbps
*.client2.app[0].source.productionInterval = 1ms # ~512 kbps

# configure server applications
*.server.numApps = 2
*.server.app[*].typename = "UdpSinkApp"
*.server.app[0].display-name = "best-effort"
*.server.app[1].display-name = "high-priority"
*.server.app[0].io.localPort = 1000
*.server.app[1].io.localPort = 1001
*.server.app[0].io.displayStringTextFormat = "{numReceived} best-effort"
*.server.app[1].io.displayStringTextFormat = "{numReceived} high-priority"

# display number of packets sent and received on network nodes
```

Form Source

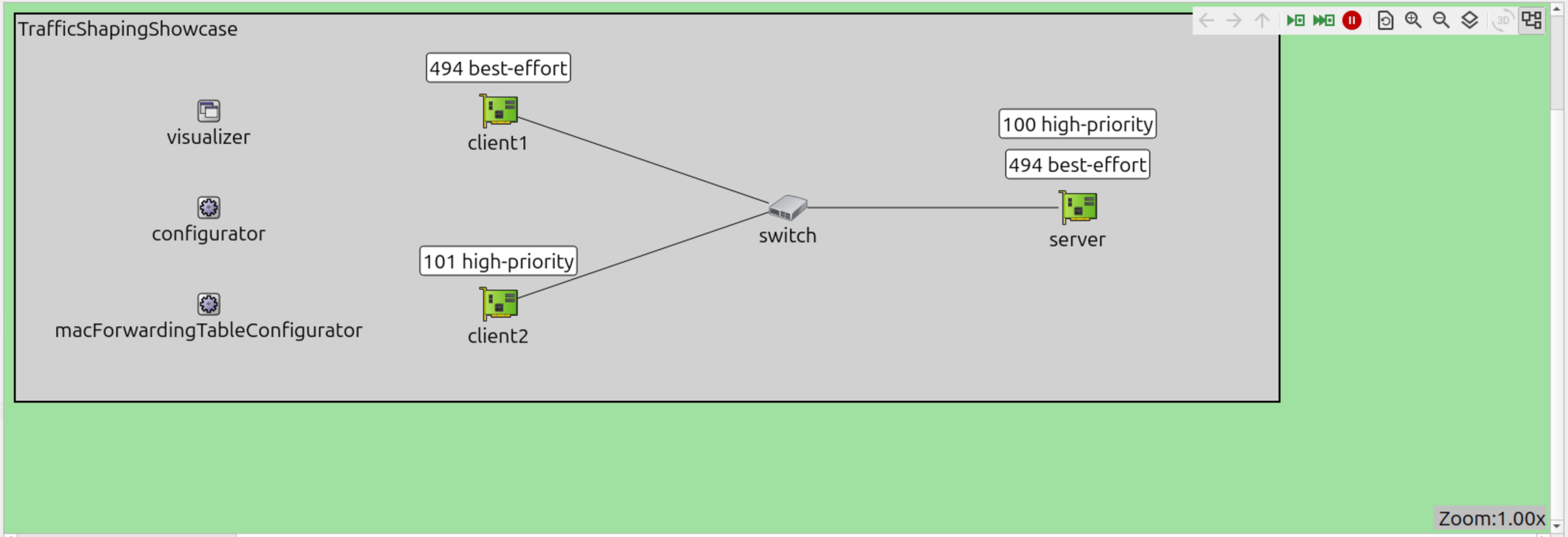
Writable Insert 1 : 1 : 0 Codeium: No comple...erated | Show Chat

OMNeT++/Qtenv (release) - NoTrafficShaping #0 - TrafficShaping.ini - /home/levy/workspace/inet/wfcs2025/step4_traffic_shaping

File Simulate Inspect View Help

next: #11 115 | 0s 100ms 000us 000ns 000ps

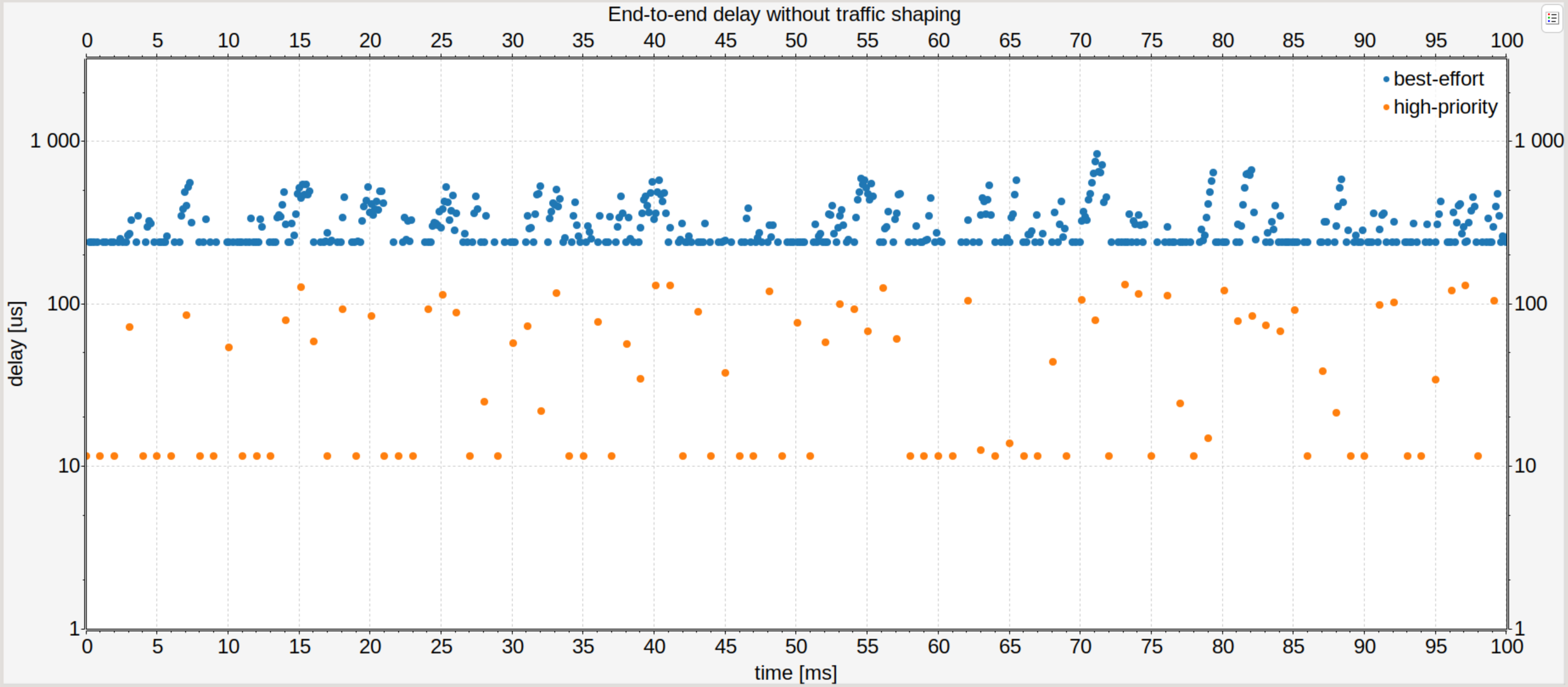
Next: n/a | In: n/a | At: n/a



Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#11050	0.099'485'801'607	client1 --> switch	best-effort-491	10.0.0.1:1025	10.0.0.3:1000	UDP		1500	
#11066	0.099'605'851'607	switch --> server	best-effort-491	10.0.0.1:1025	10.0.0.3:1000	UDP		1500 B	(UNKNOWN)
#11068	0.099'606'761'607	client1 --> switch	best-effort-492	10.0.0.1:1025	10.0.0.3:1000	UDP		1500 B	(UNKNOWN)
#11078	0.099'726'811'607	switch --> server	best-effort-492	10.0.0.1:1025	10.0.0.3:1000	UDP		1500 B	(UNKNOWN)
#11086	0.099'756'780'626	client1 --> switch	best-effort-493	10.0.0.1:1025	10.0.0.3:1000	UDP		1500 B	(UNKNOWN)
#11097	0.099'876'830'626	switch --> server	best-effort-493	10.0.0.1:1025	10.0.0.3:1000	UDP		1500 B	(UNKNOWN)
#11113	0.100	client2 --> switch	high-priority-100	10.0.0.2:1025	10.0.0.3:1001	UDP		72 B	(UNKNOWN)

NoTrafficShaping #0: TrafficShapingShowcase

Msg stats: 4 scheduled / 1305 existing / 10211 created



Time-Aware Shaping

- Suitable for scheduled application traffic
- Periodic gate schedules
- Sets up a “green wave”
- Provides deterministic latency and jitter

TrafficShaping.ini × TrafficShaping.anf

```
55 *.client*.bridging.streamIdentifier.identifier.mapping = [{stream: "best-effort", packetFilter: expr(udp.destPort == 1000)},
56                                                           {stream: "high-priority", packetFilter: expr(udp.destPort == 1001)}]
57
58 # configure client stream encoding
59 *.client*.bridging.streamCoder.encoder.mapping = [{stream: "best-effort", pcp: 0},
60                                                   {stream: "high-priority", pcp: 4}]
61
62 # enable egress traffic shaping
63 *.switch.hasEgressTrafficShaping = true
64
65 # disable forwarding IEEE 802.1Q C-Tag
66 *.switch.bridging.directionReverser.reverser.excludeEncapsulationProtocols = ["ieee8021qctag"]
67
68 # configure time-aware traffic shaping
69 *.switch.eth[*].macLayer.queue.numTrafficClasses = 2
70 *.switch.eth[*].macLayer.queue.*[0].display-name = "best-effort"
71 *.switch.eth[*].macLayer.queue.*[1].display-name = "high-priority"
72 *.switch.eth[*].macLayer.queue.transmissionGate[0].initiallyOpen = false
73 *.switch.eth[*].macLayer.queue.transmissionGate[0].durations = [20us, 980us] # 1ms cycle
74 *.switch.eth[*].macLayer.queue.transmissionGate[1].initiallyOpen = true
75 *.switch.eth[*].macLayer.queue.transmissionGate[1].durations = [20us, 980us] # 1ms cycle
76
77 # configure gate schedule visualization
78 *.visualizer.gateScheduleVisualizer.displayGateSchedules = true
79 *.visualizer.gateScheduleVisualizer.gateFilter = "**.eth[1].**"
80 *.visualizer.gateScheduleVisualizer.width = 200
81 *.visualizer.gateScheduleVisualizer.height = 24
82 *.visualizer.gateScheduleVisualizer.placementHint = "top"
83
```

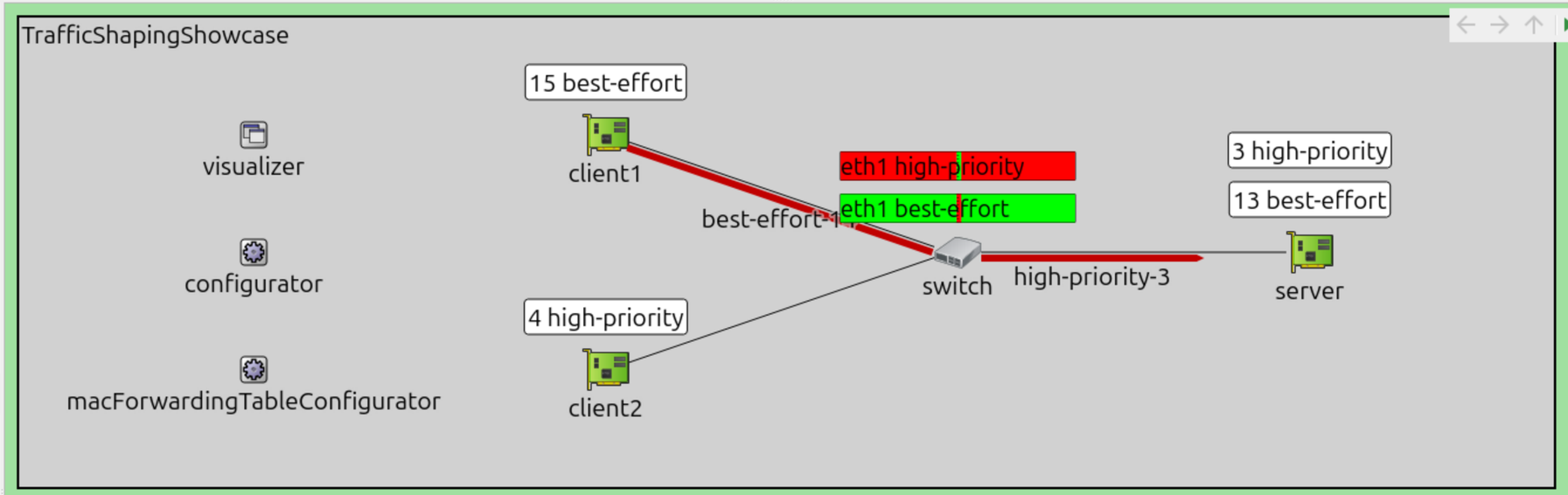
OMNeT++/Qtenv (release) - TimeAwareShaping #0 - TrafficShaping.ini - /home/levy/workspace/inet/wfcs2025/step4_traffic_shaping

File Simulate Inspect View Help

next: #397 | 0s 003ms 005us 846ns 540ps

Next: IfgTimer (inet::ClockEvent, id=28) | In: TrafficShapingShowcase.client2.eth[0].phyLayer.interFrameGapInserter (InterpacketGapInserter, id=243) | At: 0.00300672s (now+0.00000087346s)

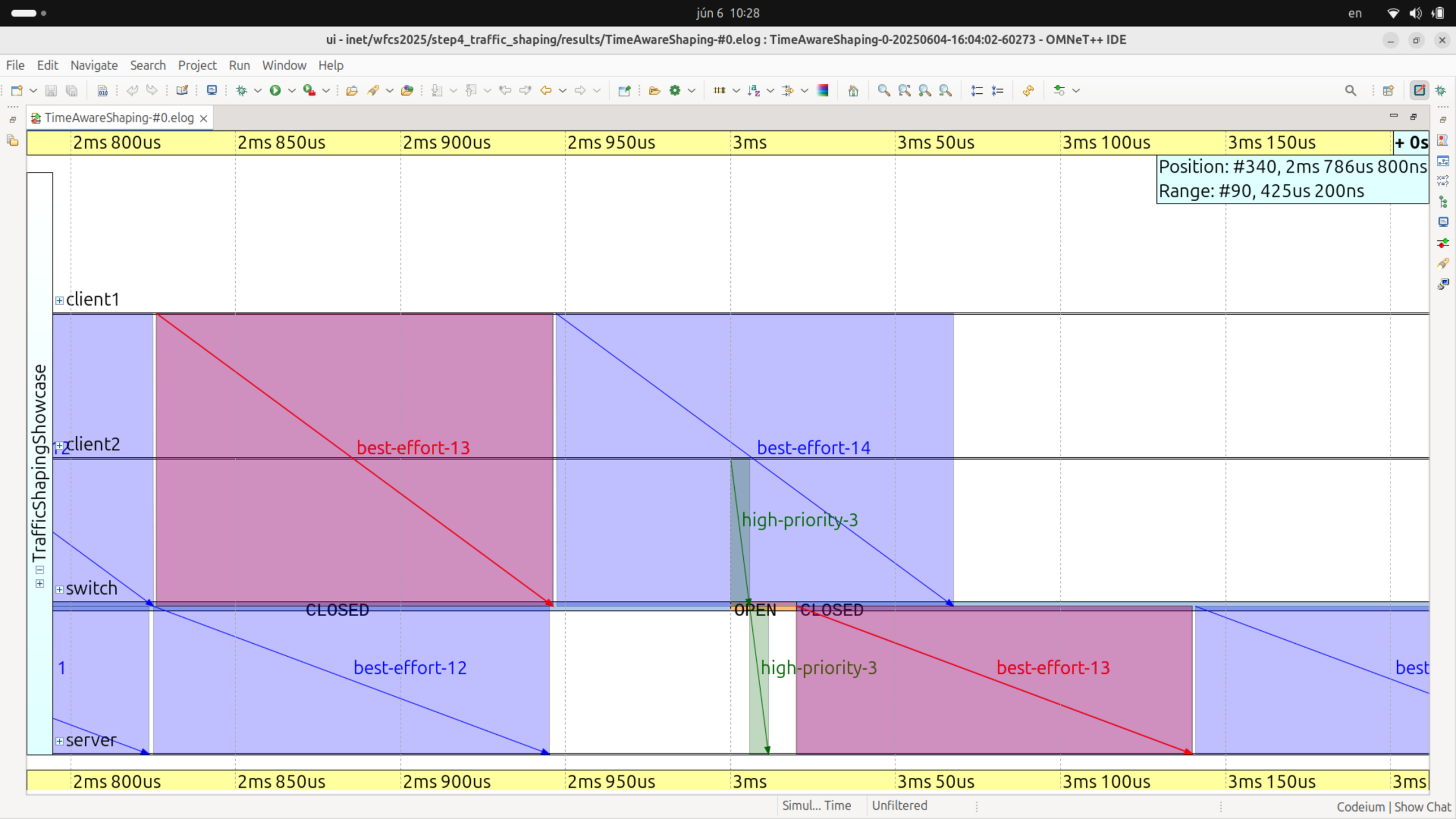
TrafficShapingShowcase (
simulation.scheduled-eve

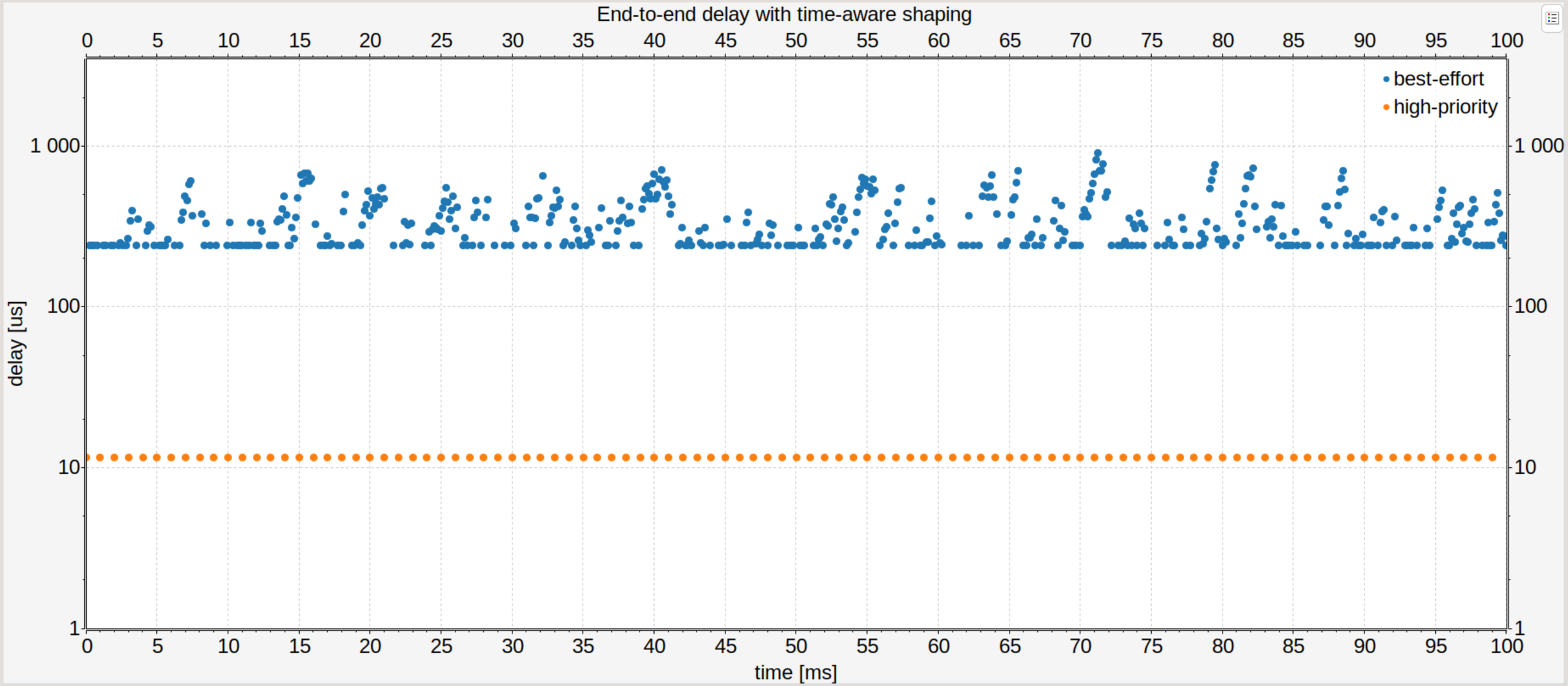


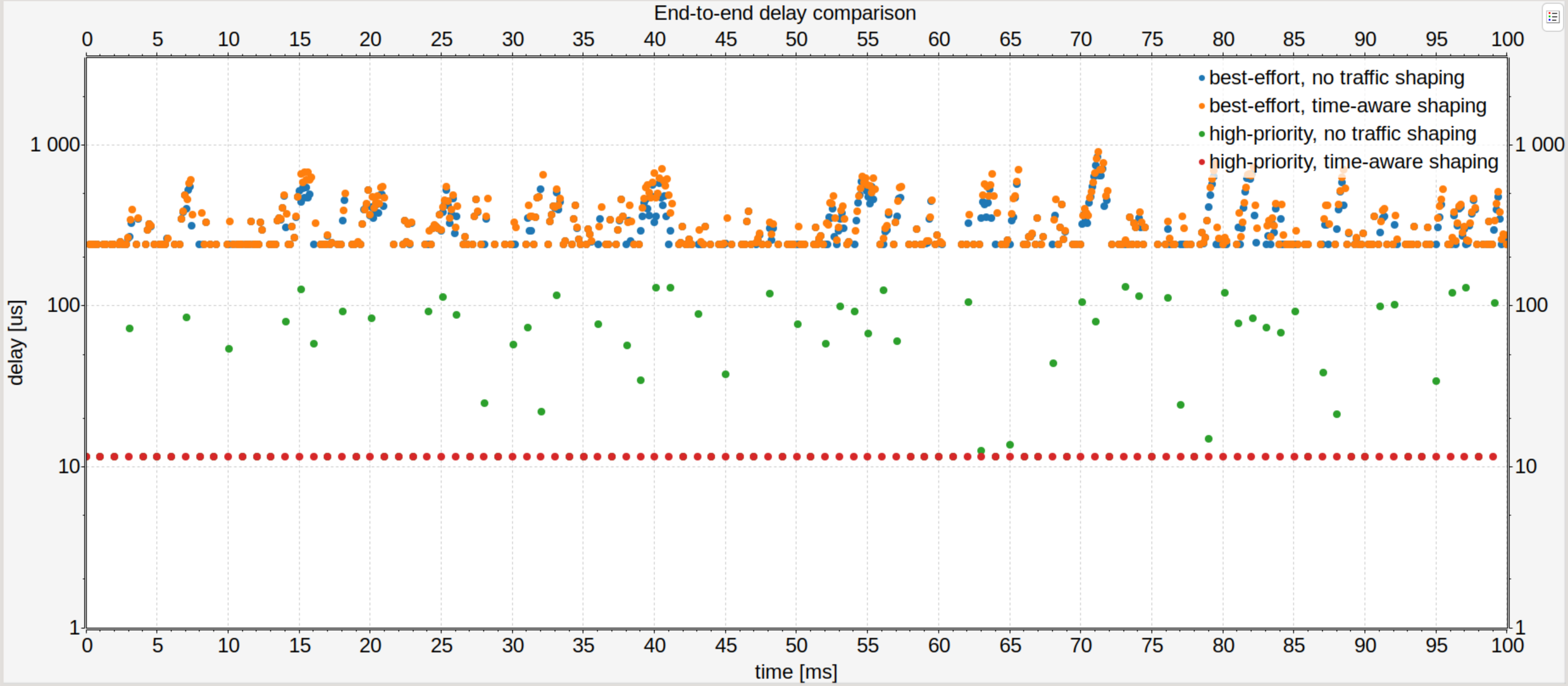
TrafficShapingShowcase
builtinAnimationsAllowe
canvas (cCanvas) canv
className = 'inet::Netw
componentType (cDyr
displayName = '' [...] (str
displayString [...] (omnel
fullName = 'TrafficShapi
fullPath = 'TrafficShapin
gates[0] (omnetpp::cGat
id = 1 (int)
index = <not a vector> (i
info = 'id=1' (string)
isModule = true (bool)
isSimple = false (bool)
isVector = false (bool)
listenedSignals[4] (omne
name = 'TrafficShapingS

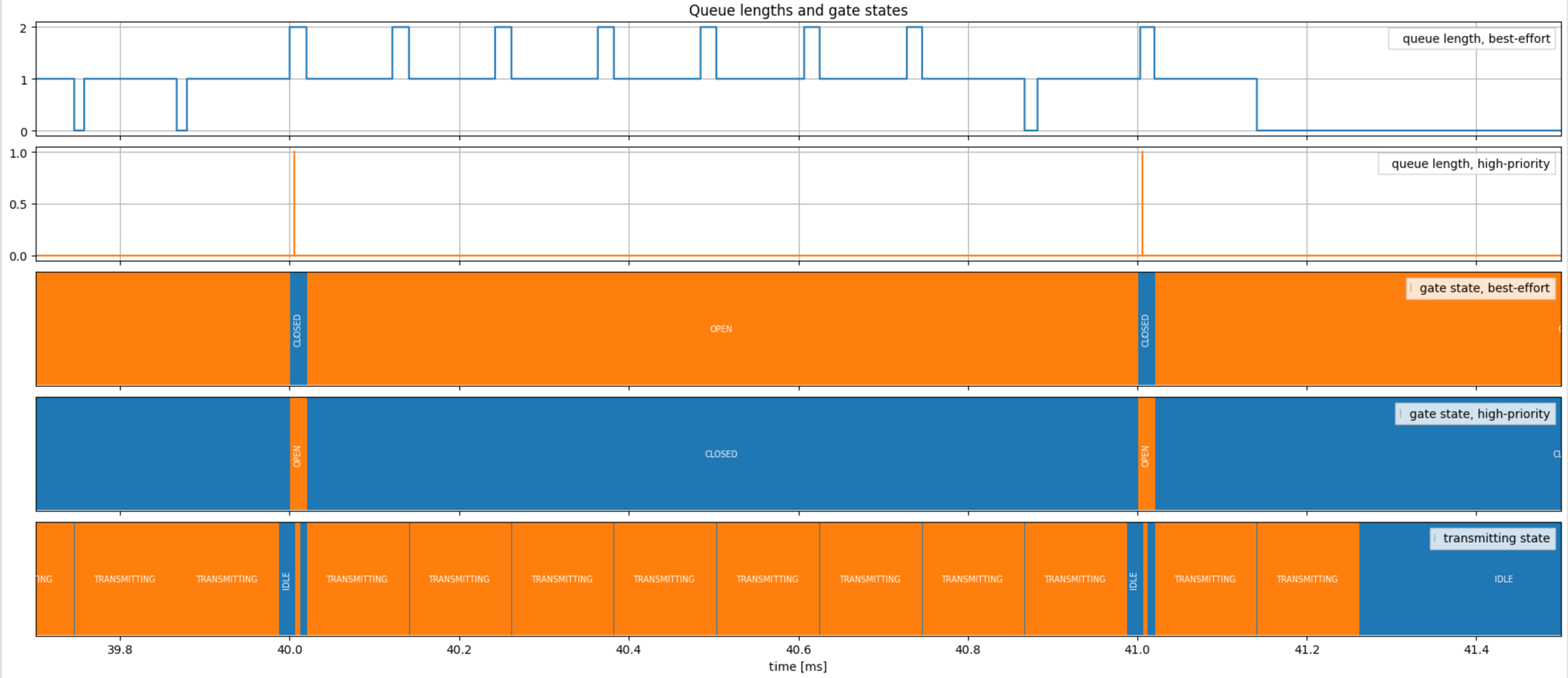
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#357	0.002'825'073'547	switch --> server	best-effort-12	10.0.0.1:1025	10.0.0.3:1000	UDP		1500	
#359	0.002'825'983'547	client1 --> switch	best-effort-13	10.0.0.1:1025	10.0.0.3:1000	UDP		1504 B	(UNKNOWN)
#378	0.002'947'263'547	client1 --> switch	best-effort-14	10.0.0.1:1025	10.0.0.3:1000	UDP		1504 B	(UNKNOWN)
#393	0.003	client2 --> switch	high-priority-3	10.0.0.2:1025	10.0.0.3:1001	UDP		72 B	(UNKNOWN)
#396	0.003'005'810	switch --> server	high-priority-3	10.0.0.2:1025	10.0.0.3:1001	UDP		72 B	(UNKNOWN)

TimeAwareShaping #0: TrafficShapingShowcase | Msg stats: 14 scheduled / 163 existing / 415 created


jún 6 10:28
en
ui - inet/wfcs2025/step4_traffic_shaping/results/TimeAwareShaping-#0.elog : TimeAwareShaping-0-20250604-16:04:02-60273 - OMNeT++ IDE
File Edit Navigate Search Project Run Window Help
TimeAwareShaping-#0.elog
2ms 800us
2ms 850us
2ms 900us
2ms 950us
3ms
3ms 50us
3ms 100us
3ms 150us
+ 0s
Position: #340, 2ms 786us 800ns
Range: #90, 425us 200ns
TrafficShapingShowcase
client1
client2
switch
server
best-effort-13
best-effort-14
high-priority-3
CLOSED
OPEN
CLOSED
best-effort-12
high-priority-3
best-effort-13
best
Simul... Time
Unfiltered
Codeium | Show Chat




End-to-end delay comparison
best-effort, no traffic shaping
best-effort, time-aware shaping
high-priority, no traffic shaping
high-priority, time-aware shaping
delay [us]
1 000
100
10
1
time [ms]
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100



Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

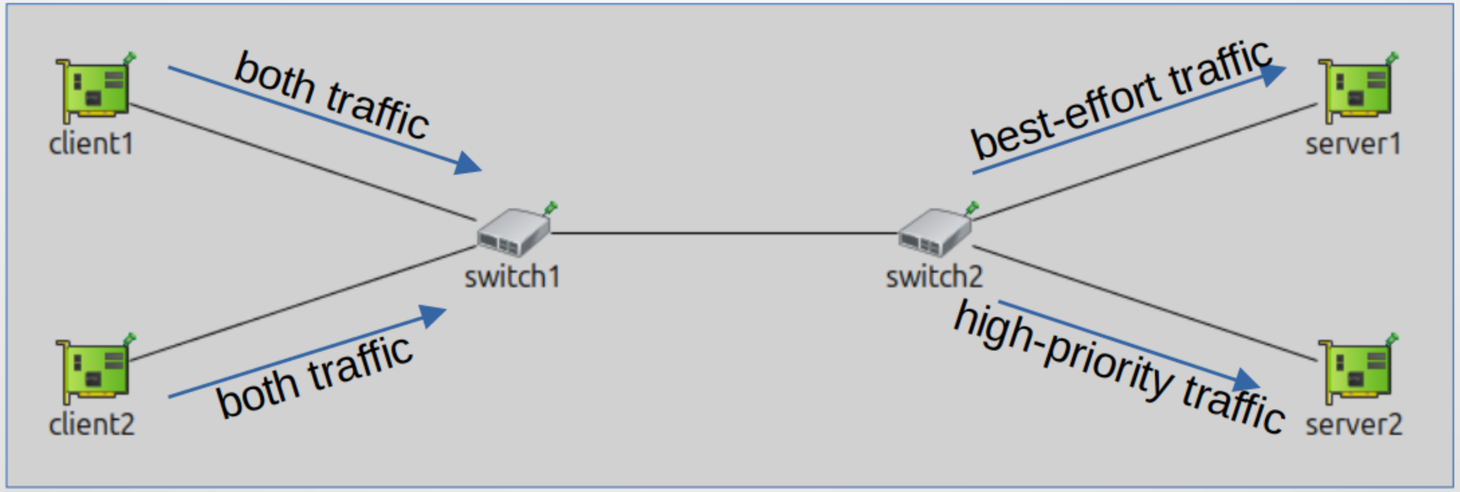
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Manual Gate Schedule Configuration

- Designing an efficient schedule is hard
  - Cyclic dependencies, resource constraints
  - High complexity, scalability issues, error prone
- Poor schedule leads to large delay and jitter
- Difficult to ensure end-to-end guarantees



GateScheduling.ini

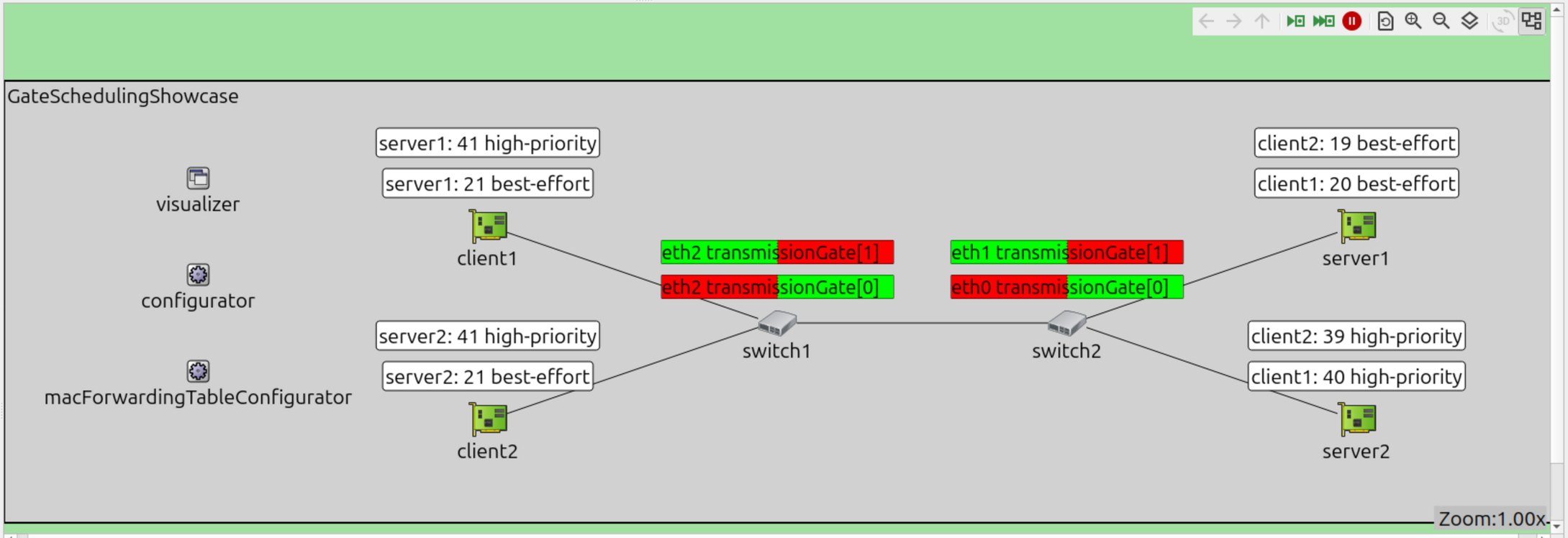
```
83 *.visualizer.infoVisualizer.modules = "*.client*.app[*].io OR *.server1.app[0..1].io OR *.server2.app[2..3].io"
84
85 *.visualizer.networkNodeVisualizer.annotationSpacing = 12
86
87 # configure gate scheduling visualization
88 *.visualizer.gateScheduleVisualizer.displayGateSchedules = true
89 *.visualizer.gateScheduleVisualizer.displayDuration = 200us
90 *.visualizer.gateScheduleVisualizer.gateFilter = "*.switch1.eth[2].** or *.switch2.eth[0].**.transmissionGate[0] or *.switch2.e
91 *.visualizer.gateScheduleVisualizer.height = 24
92 *.visualizer.gateScheduleVisualizer.width = 240
93 *.visualizer.gateScheduleVisualizer.placementHint = "top"
94
95 [ManualGateScheduling]
96 description = "Manual gate schedule configuration leads to larger end-to-end delays due to difficult calculation"
97
98 # configure switch1 manual gate scheduling
99 *.switch1.eth[2].macLayer.queue.transmissionGate[0].initiallyOpen = true
100 *.switch1.eth[2].macLayer.queue.transmissionGate[0].durations = [100us, 100us]
101 *.switch1.eth[2].macLayer.queue.transmissionGate[1].initiallyOpen = false
102 *.switch1.eth[2].macLayer.queue.transmissionGate[1].durations = [100us, 100us]
103
104 # configure switch2 manual gate scheduling
105 *.switch2.eth[0].macLayer.queue.transmissionGate[0].initiallyOpen = true
106 *.switch2.eth[0].macLayer.queue.transmissionGate[0].durations = [100us, 100us]
107 *.switch2.eth[1].macLayer.queue.transmissionGate[1].initiallyOpen = false
108 *.switch2.eth[1].macLayer.queue.transmissionGate[1].durations = [100us, 100us]
109
110 [AutomaticGateScheduling]
111 description = "Automatic gate schedule configuration leads to small (optimal) end-to-end delays"
112
```

OMNeT++/Qtenv (release) - ManualGateScheduling #0 - GateScheduling.ini - /home/levy/workspace/inet/wfcs2025/step5_gate_scheduling

File Simulate Inspect View Help

next: #3 474 | 0s 010ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a



Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#3415	0.009'900	switch1 --> switch2	client1-high-priority-39	10.0.0.1:1026	10.0.0.4:1002	UDP		558 B	
#3417	0.009'900	switch2 --> server2	client2-high-priority-38	10.0.0.2:1026	10.0.0.4:1003	UDP		558 B	(UNKNOWN)
#3429	0.009'945'600	switch1 --> switch2	client2-high-priority-39	10.0.0.2:1026	10.0.0.4:1003	UDP		558 B	(UNKNOWN)
#3430	0.009'945'600	switch2 --> server2	client1-high-priority-39	10.0.0.1:1026	10.0.0.4:1002	UDP		558 B	(UNKNOWN)
#3457	0.010	switch2 --> server1	client2-best-effort-19	10.0.0.2:1025	10.0.0.3:1001	UDP		1058 B	(UNKNOWN)
#3471	0.010	client1 --> switch1	client1-best-effort-20	10.0.0.1:1025	10.0.0.3:1000	UDP		1058 B	(UNKNOWN)
#3472	0.010	client2 --> switch1	client2-best-effort-20	10.0.0.2:1025	10.0.0.3:1001	UDP		1058 B	(UNKNOWN)

ManualGateScheduling #0: GateSchedulingShowcase

Msg stats: 14 scheduled / 580 existing / 3206 created

OMNeT++/Qtenv (release) - ManualGateScheduling #0 - GateScheduling.ini - /home/levy/workspace/inet/wfcs2025/step5_gate_scheduling

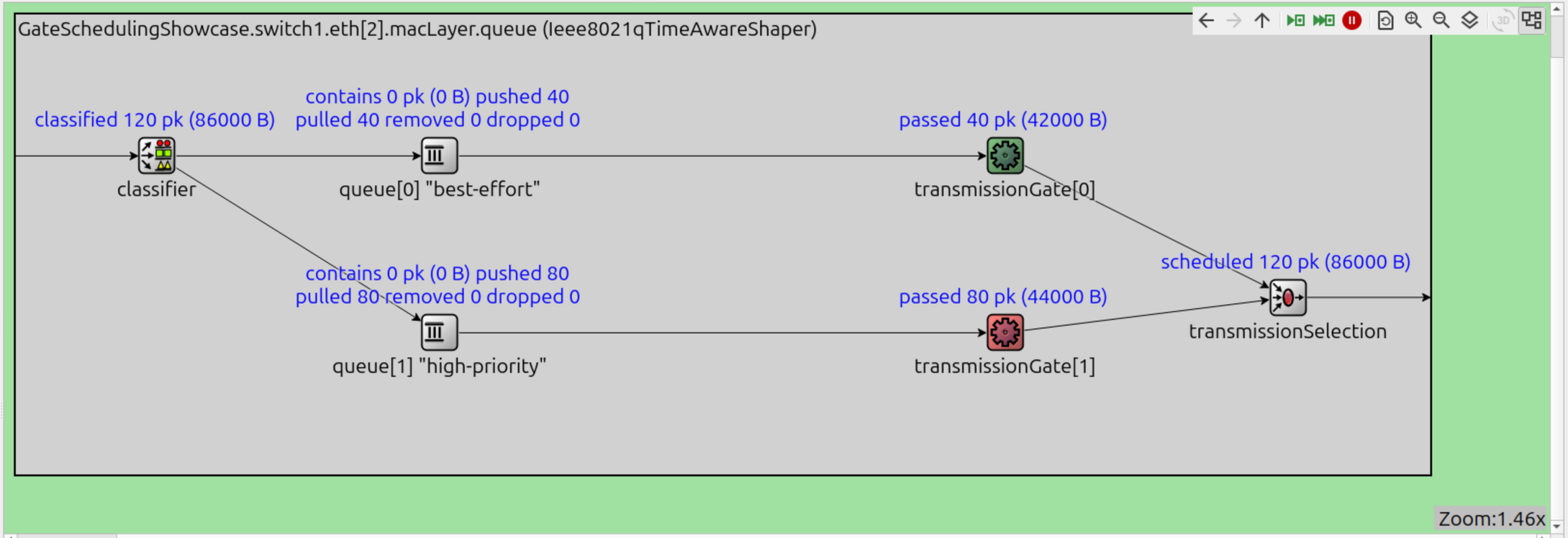
File Simulate Inspect View Help

next: #3 474 | 0s 010ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a

GateSchedulingShowcase
simulation.scheduled-eve

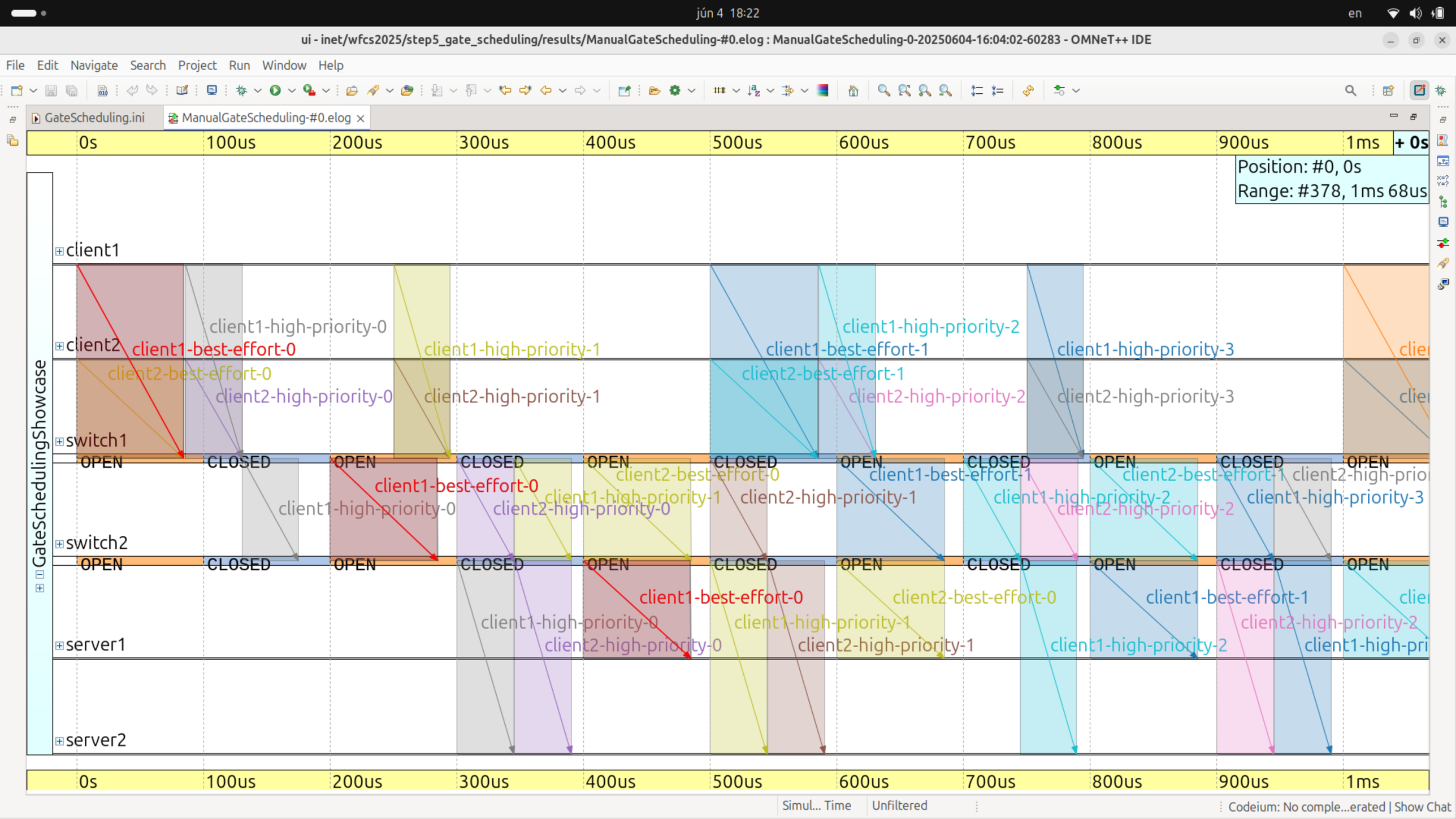
GateSchedulingShowcas
builtinAnimationsAllowe
canvas = nullptr (omnetp
className = 'inet::queue
componentType (cDyn
displayName = '' [...] (str
displayString = t=contair
fullName = 'queue' (strin
fullPath = 'GateScheduli
gates[2] (omnetpp::cGat
id = 459 (int)
index = <not a vector> (i
info = 'id=459' (string)
isModule = true (bool)
isSimple = true (bool)
isTerminated = false (bo
isVector = false (bool)
listenedSignals[6] (omne

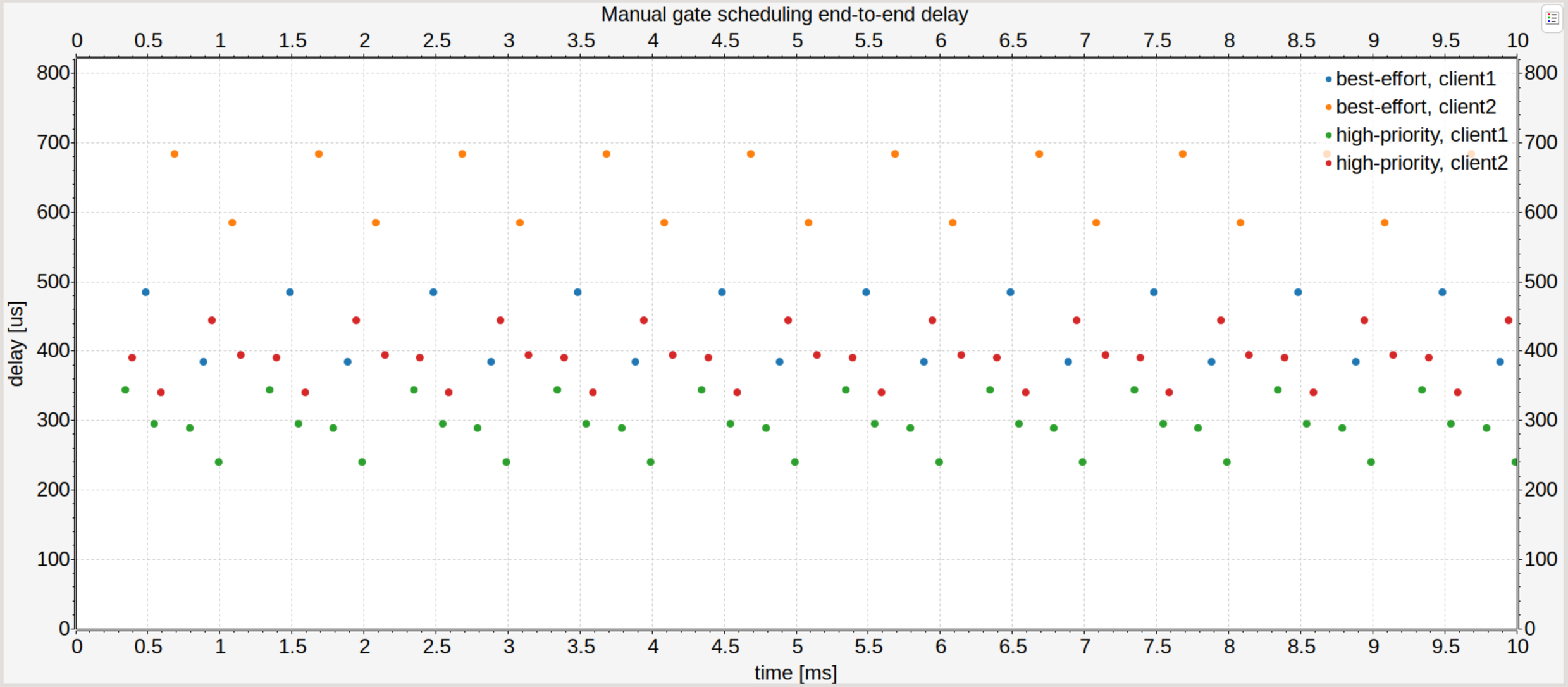


Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#3395	0.009'800	transmissionSelection --> . client2-best-effort-19		10.0.0.2:1025	10.0.0.3:1001	UDP		1050	
#3415	0.009'900	queue[1] --> transmissionGate[1] client1-high-priority-39		10.0.0.1:1026	10.0.0.4:1002	UDP		550 B	(UNKNOWN)
#3415	0.009'900	transmissionGate[1] --> transmissionSelection client1-high-priority-39		10.0.0.1:1026	10.0.0.4:1002	UDP		550 B	(UNKN
#3415	0.009'900	transmissionSelection --> . client1-high-priority-39		10.0.0.1:1026	10.0.0.4:1002	UDP		550 B	(UNKNOWN)
#3429	0.009'945'600	queue[1] --> transmissionGate[1] client2-high-priority-39		10.0.0.2:1026	10.0.0.4:1003	UDP		550 B	(UNKNOWN)
#3429	0.009'945'600	transmissionGate[1] --> transmissionSelection client2-high-priority-39		10.0.0.2:1026	10.0.0.4:1003	UDP		550 B	(U
#3429	0.009'945'600	transmissionSelection --> . client2-high-priority-39		10.0.0.2:1026	10.0.0.4:1003	UDP		550 B	(UNKNOWN)

ManualGateScheduling #0: GateSchedulingShowcase

Msg stats: 14 scheduled / 580 existing / 3206 created


jún 4 18:22
en
ui - inet/wfcs2025/step5_gate_scheduling/results/ManualGateScheduling-#0.elog : ManualGateScheduling-0-20250604-16:04:02-60283 - OMNeT++ IDE
File Edit Navigate Search Project Run Window Help
GateScheduling.ini
ManualGateScheduling-#0.elog
0s 100us 200us 300us 400us 500us 600us 700us 800us 900us 1ms + 0s
Position: #0, 0s
Range: #378, 1ms 68us
GateSchedulingShowcase
client1
client2
switch1
switch2
server1
server2
OPEN
CLOSED
client1-high-priority-0
client1-best-effort-0
client1-high-priority-1
client1-high-priority-2
client1-best-effort-1
client1-high-priority-3
client2-best-effort-0
client2-high-priority-0
client2-high-priority-1
client2-best-effort-1
client2-high-priority-2
client2-high-priority-3
client1-high-priority-0
client1-best-effort-0
client2-best-effort-0
client1-high-priority-1
client2-high-priority-0
client1-best-effort-1
client2-high-priority-1
client1-high-priority-2
client2-best-effort-1
client2-high-priority-2
client1-high-priority-3
client1-best-effort-0
client1-high-priority-0
client1-high-priority-1
client2-high-priority-0
client2-best-effort-0
client1-best-effort-1
client2-high-priority-1
client1-high-priority-2
client2-best-effort-1
client2-high-priority-2
client1-high-priority-3
0s 100us 200us 300us 400us 500us 600us 700us 800us 900us 1ms
Simul... Time
Unfiltered
Codeium: No comple...erated | Show Chat



Automatic Gate Schedule Configuration

- Takes into account
  - Network topology
  - Traffic flows
  - Timing constraints
  - Optimization criteria
- Calculates gate schedule using a SAT solver
- Ensures bounded end-to-end delay and jitter

ui - inet/wfcs2025/step5_gate_scheduling/GateScheduling.ini - OMNeT++ IDE

File Edit Source Navigate Search Project Run Window Help

GateScheduling.ini | ManualGateScheduling-#0.elog | GateScheduling.anf

```
93 *.visualizer.gateScheduleVisualizer.placementHint = "top"
94
95 [ManualGateScheduling]
96 description = "Manual gate schedule configuration leads to larger end-to-end delays due to difficult calculation"
97
98 # configure switch1 manual gate scheduling
99 *.switch1.eth[2].macLayer.queue.transmissionGate[0].initiallyOpen = true
100 *.switch1.eth[2].macLayer.queue.transmissionGate[0].durations = [100us, 100us]
101 *.switch1.eth[2].macLayer.queue.transmissionGate[1].initiallyOpen = false
102 *.switch1.eth[2].macLayer.queue.transmissionGate[1].durations = [100us, 100us]
103
104 # configure switch2 manual gate scheduling
105 *.switch2.eth[0].macLayer.queue.transmissionGate[0].initiallyOpen = true
106 *.switch2.eth[0].macLayer.queue.transmissionGate[0].durations = [100us, 100us]
107 *.switch2.eth[1].macLayer.queue.transmissionGate[1].initiallyOpen = false
108 *.switch2.eth[1].macLayer.queue.transmissionGate[1].durations = [100us, 100us]
109
110 [AutomaticGateScheduling]
111 description = "Automatic gate schedule configuration leads to small (optimal) end-to-end delays"
112
113 *.gateScheduleConfigurator.typename = "Z3GateScheduleConfigurator"
114 # configure automatic gate scheduling
115 *.gateScheduleConfigurator.gateCycleDuration = 1ms
116 *.gateScheduleConfigurator.configuration =
117     [{pcp: 0, gateIndex: 0, application: "app[0]", source: "client1", destination: "server1", packetLength: 1000B + 58B, packet
118      {pcp: 4, gateIndex: 1, application: "app[1]", source: "client1", destination: "server2", packetLength: 500B + 58B, packetI
119      {pcp: 0, gateIndex: 0, application: "app[0]", source: "client2", destination: "server1", packetLength: 1000B + 58B, packet
120      {pcp: 4, gateIndex: 1, application: "app[1]", source: "client2", destination: "server2", packetLength: 500B + 58B, packetI
121
```

Form Source

Writable Insert 112 : 1 : 5276 Codeium: No comple...erated | Show Chat

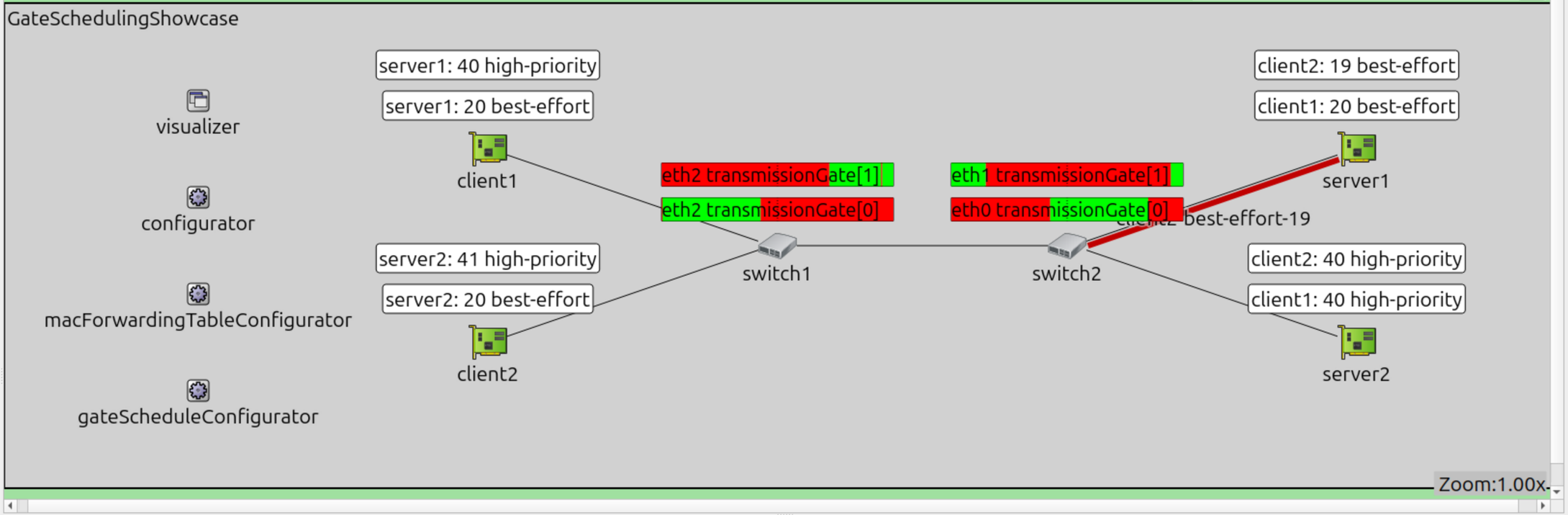
OMNeT++/Qtenv (release) - AutomaticGateScheduling #0 - GateScheduling.ini - /home/levy/workspace/inet/wfcs2025/step5_gate_scheduling

File Simulate Inspect View Help

next: #3 550 | 0s 010ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a

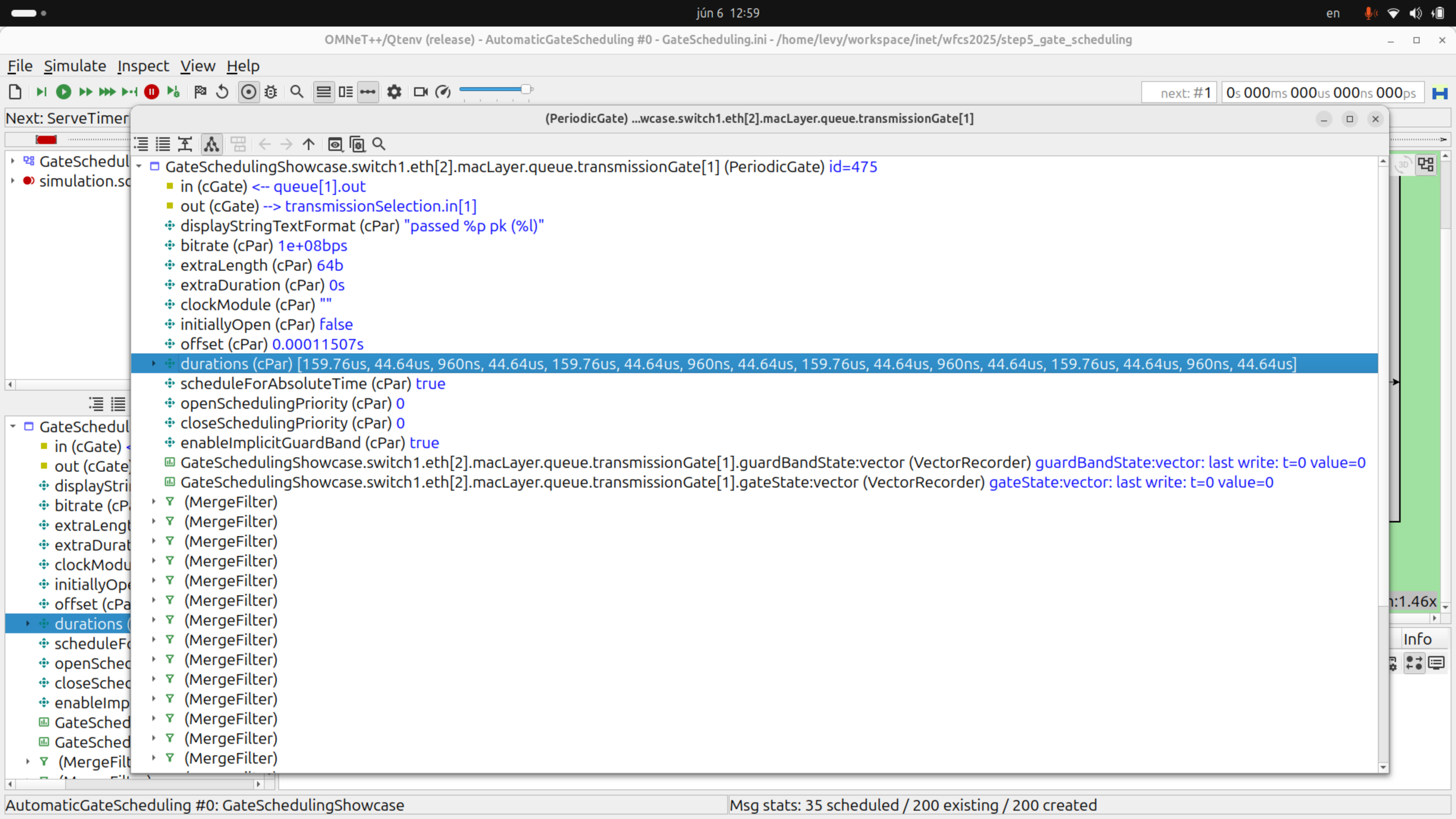
GateSchedulingShowcase
simulation.scheduled-eve

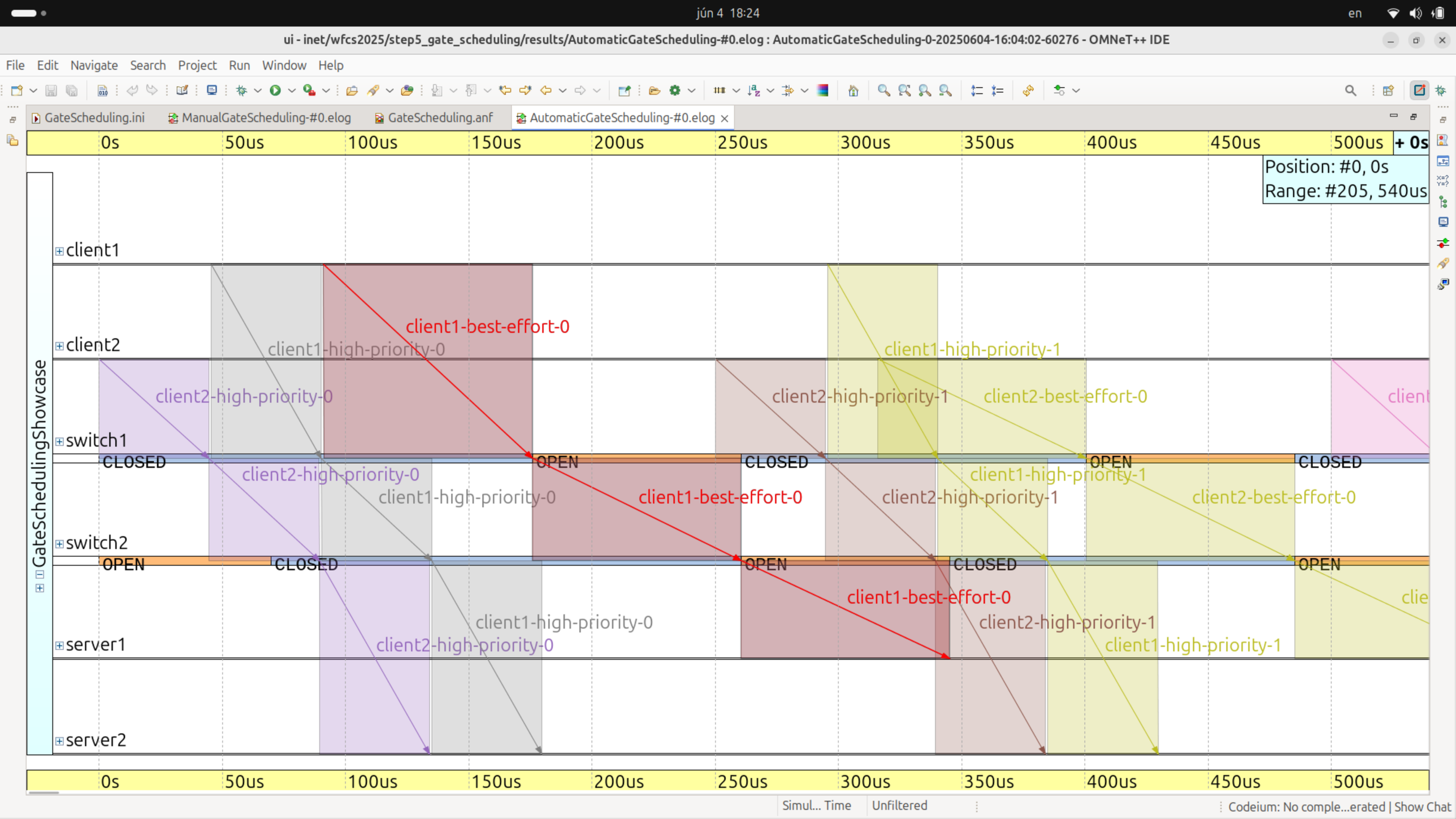


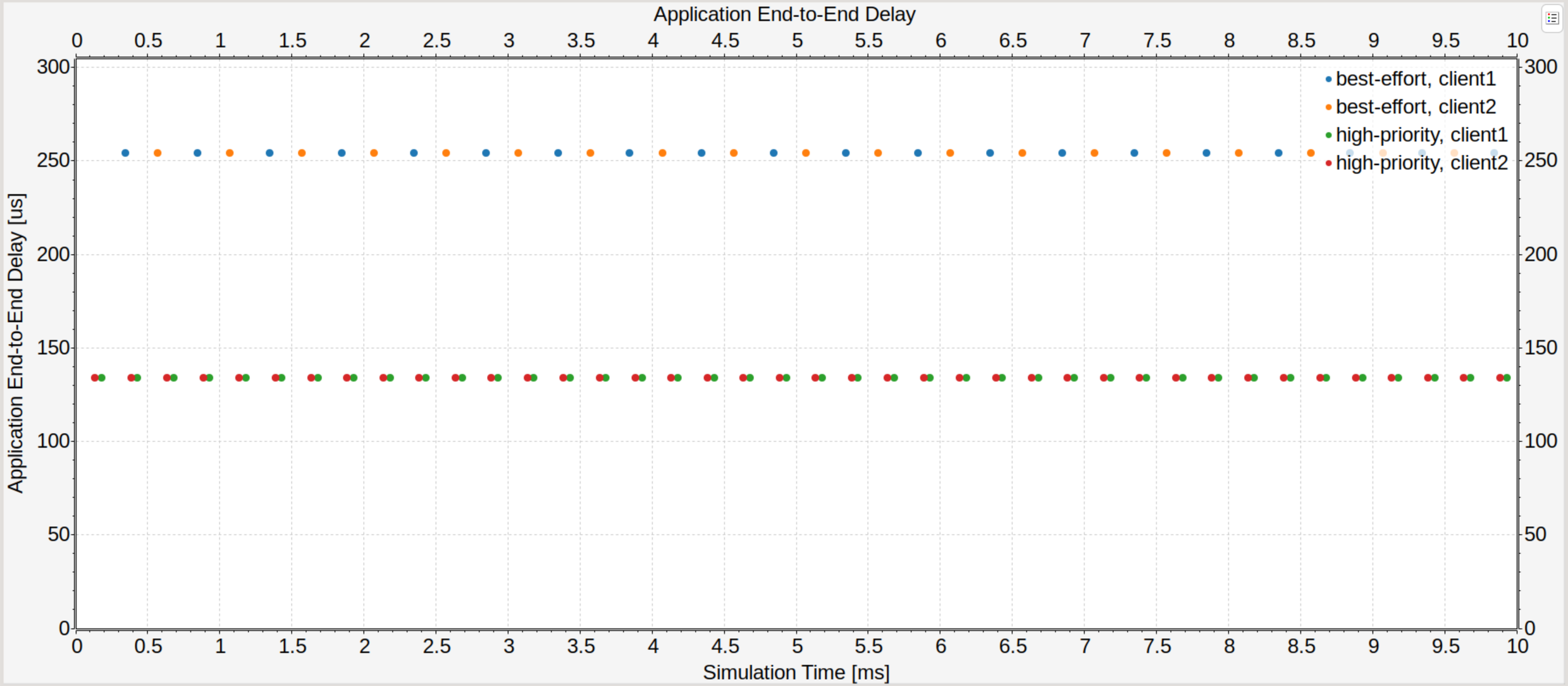
GateSchedulingShowcas
builtinAnimationsAllowe
canvas (cCanvas) canv
className = 'inet::Netw
componentType (cDyr
displayName = '' [...] (str
displayString [...] (omnet
fullName = 'GateSchedu
fullPath = 'GateScheduli
gates[0] (omnetpp::cGat
id = 1 (int)
index = <not a vector> (i
info = 'id=1' (string)
isModule = true (bool)
isSimple = false (bool)
isVector = false (bool)
listenedSignals[4] (omne
name = 'GateScheduling

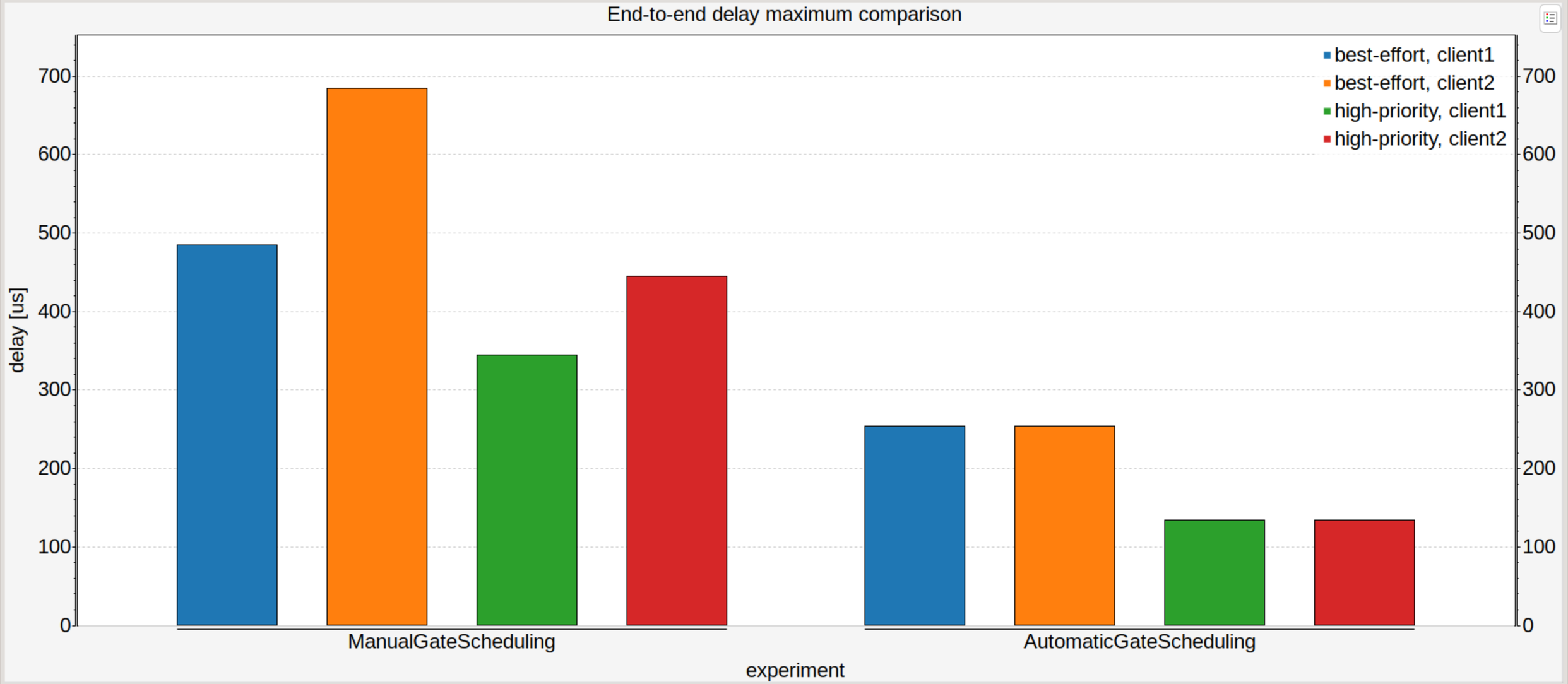
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#3472	0.009 793 600	client1 --> switch1	client1-high-priority-39	10.0.0.1:1026	10.0.0.4:1002	UDP		558 B	
#3478	0.009 815 910	client2 --> switch1	client2-best-effort-19	10.0.0.2:1025	10.0.0.3:1001	UDP		1058 B	
#3484	0.009 839 380	switch2 --> server2	client2-high-priority-39	10.0.0.2:1026	10.0.0.4:1003	UDP		558 B	(UNKNOWN)
#3489	0.009 840 290	switch1 --> switch2	client1-high-priority-39	10.0.0.1:1026	10.0.0.4:1002	UDP		558 B	(UNKNOWN)
#3516	0.009 884 980	switch2 --> server2	client1-high-priority-39	10.0.0.1:1026	10.0.0.4:1002	UDP		558 B	(UNKNOWN)
#3522	0.009 900 600	switch1 --> switch2	client2-best-effort-19	10.0.0.2:1025	10.0.0.3:1001	UDP		1058 B	(UNKNOWN)
#3540	0.009 985 290	switch2 --> server1	client2-best-effort-19	10.0.0.2:1025	10.0.0.3:1001	UDP		1058 B	(UNKNOWN)
#3548	0.010	client2 --> switch1	client2-high-priority-40	10.0.0.2:1026	10.0.0.4:1003	UDP		558 B	(UNKNOWN)

AutomaticGateScheduling #0: GateSchedulingShowcase | Msg stats: 12 scheduled / 573 existing / 3205 created


jún 6 12:59
en
OMNeT++/Qtenv (release) - AutomaticGateScheduling #0 - GateScheduling.ini - /home/levy/workspace/inet/wfcs2025/step5_gate_scheduling
File Simulate Inspect View Help
next: #1
0s 000ms 000us 000ns 000ps
Next: ServeTimer
(PeriodicGate) ...wcase.switch1.eth[2].macLayer.queue.transmissionGate[1]
GateSchedulingShowcase.switch1.eth[2].macLayer.queue.transmissionGate[1] (PeriodicGate) id=475
in (cGate) <-- queue[1].out
out (cGate) --> transmissionSelection.in[1]
displayStringTextFormat (cPar) "passed %p pk (%l)"
bitrate (cPar) 1e+08bps
extraLength (cPar) 64b
extraDuration (cPar) 0s
clockModule (cPar) ""
initiallyOpen (cPar) false
offset (cPar) 0.00011507s
durations (cPar) [159.76us, 44.64us, 960ns, 44.64us, 159.76us, 44.64us, 960ns, 44.64us, 159.76us, 44.64us, 960ns, 44.64us, 159.76us, 44.64us, 960ns, 44.64us]
scheduleForAbsoluteTime (cPar) true
openSchedulingPriority (cPar) 0
closeSchedulingPriority (cPar) 0
enableImplicitGuardBand (cPar) true
GateSchedulingShowcase.switch1.eth[2].macLayer.queue.transmissionGate[1].guardBandState:vector (VectorRecorder) guardBandState:vector: last write: t=0 value=0
GateSchedulingShowcase.switch1.eth[2].macLayer.queue.transmissionGate[1].gateState:vector (VectorRecorder) gateState:vector: last write: t=0 value=0
(MergeFilter)
Info
AutomaticGateScheduling #0: GateSchedulingShowcase
Msg stats: 35 scheduled / 200 existing / 200 created


jún 4 18:24
en
ui - inet/wfcs2025/step5_gate_scheduling/results/AutomaticGateScheduling-#0.elog : AutomaticGateScheduling-0-20250604-16:04:02-60276 - OMNeT++ IDE
File Edit Navigate Search Project Run Window Help
GateScheduling.ini
ManualGateScheduling-#0.elog
GateScheduling.anf
AutomaticGateScheduling-#0.elog
0s 50us 100us 150us 200us 250us 300us 350us 400us 450us 500us + 0s
Position: #0, 0s
Range: #205, 540us
GateSchedulingShowcase
client1
client2
switch1
switch2
server1
server2
client1-best-effort-0
client1-high-priority-0
client1-high-priority-1
client2-high-priority-0
client2-high-priority-1
client2-best-effort-0
CLOSED
OPEN
Simul... Time
Unfiltered
Codeium: No comple...erated | Show Chat





Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

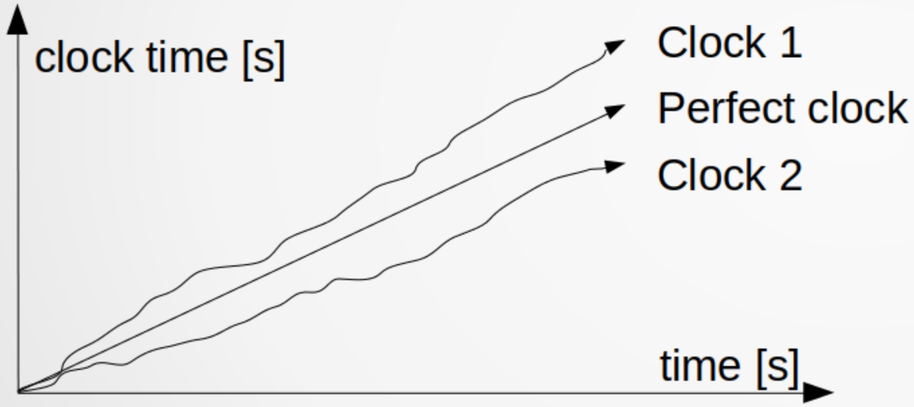
Automatic gate schedule configuration

Time synchronization

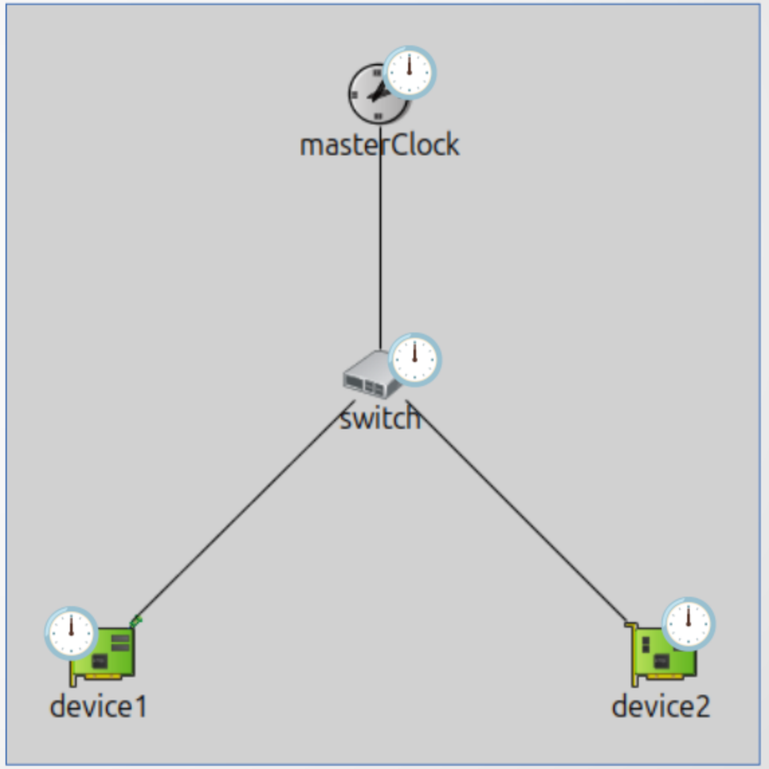
Frame replication and elimination for reliability

Imperfect Clocks

- Application traffic and gate schedules follow clocks
- Clocks diverge



- Disrupts time-aware shaping



OMNeT++/Qtenv (release) - NoTimeSynchronization #0 - TimeSynchronization.ini - /home/levy/workspace/inet/wfcs2025/step6_time_synchronization

File Simulate Inspect View Help

next: #3 208 | 10s 000ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a

TimeSynchronizationShov
simulation.scheduled-eve

TimeSynchronizationShowcase

time: 10.000012593088s

visualizer

masterClock

configurator

diff: -100.611182us

macForwardingTableConfigurator

switch

diff: -64.127422us

diff: 193.981201us

device1

device2

Zoom:1.00x

TimeSynchronizationSho
builtinAnimationsAllowe
canvas (cCanvas) canv
className = 'inet::Netw
componentType (cDyr
displayName = '' [...] (str
displayString [...] (omnel
fullName = 'TimeSynchro
fullPath = 'TimeSynchror
gates[0] (omnetpp::cGat
id = 1 (int)
index = <not a vector> (i
info = 'id=1' (string)
isModule = true (bool)
isSimple = false (bool)
isVector = false (bool)
listenedSignals[4] (omne
name = 'TimeSynchroniz

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info

NoTimeSynchronization #0: TimeSynchronizationShowcase | Msg stats: 4 scheduled / 92 existing / 92 created

OMNeT++/Qtenv (release) - NoTimeSynchronization #0 - TimeSynchronization.ini - /home/levy/workspace/inet/wfcs2025/step6_time_synchronization

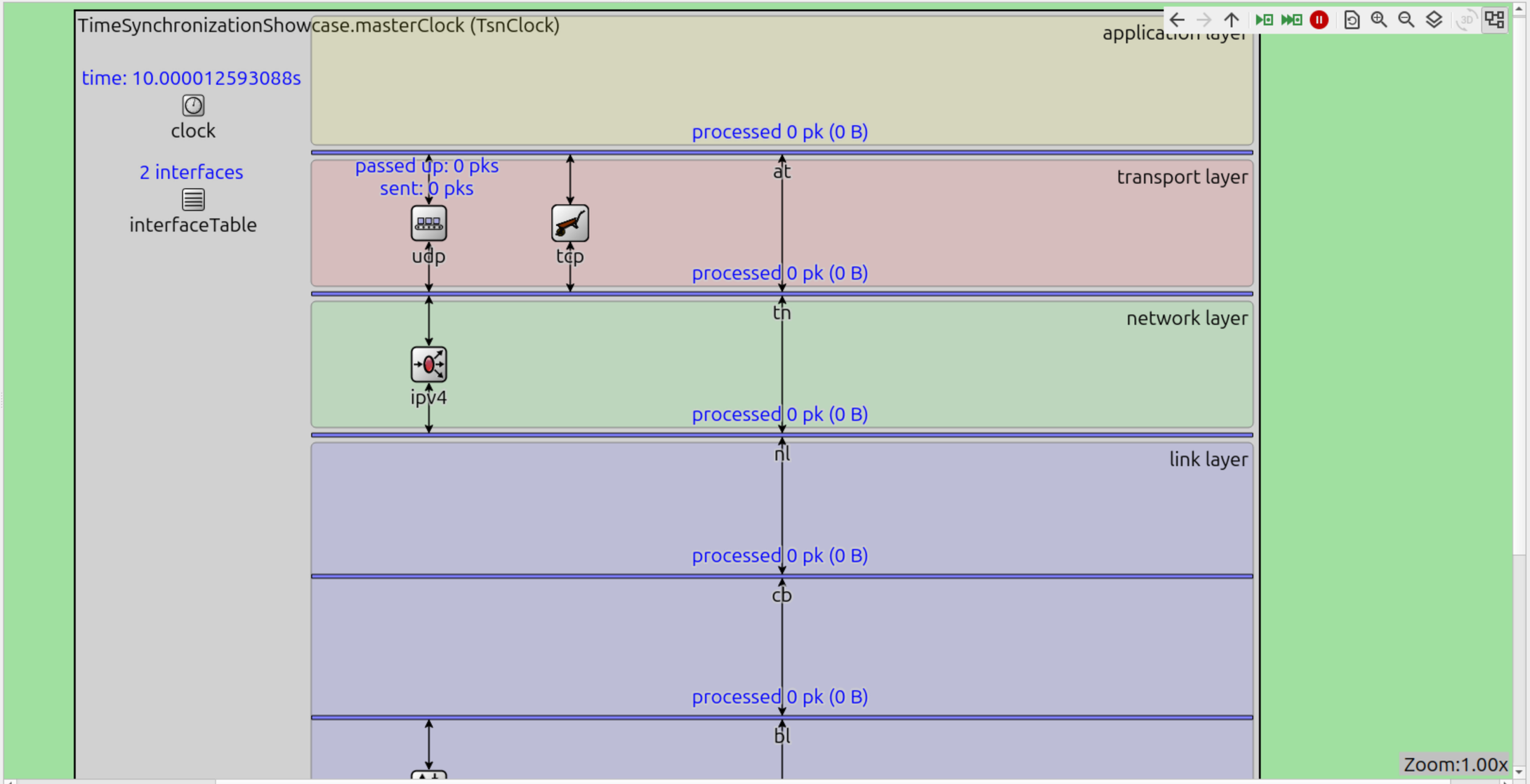
File Simulate Inspect View Help

next: #3 208 | 10s 000ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a

TimeSynchronizationShov
simulation.scheduled-eve

TimeSynchronizationSho
builtinAnimationsAllowe
canvas = nullptr (omnetp
className = 'inet::Oscill
componentType (cDyr
displayName = '' [...] (str
displayString = t=time: 1
fullName = 'clock' (string
fullPath = 'TimeSynchror
gates[0] (omnetpp::cGat
id = 42 (int)
index = <not a vector> (i
info = 'id=42' (string)
isModule = true (bool)
isSimple = true (bool)
isTerminated = false (boo
isVector = false (bool)
listenedSignals[1] (omne



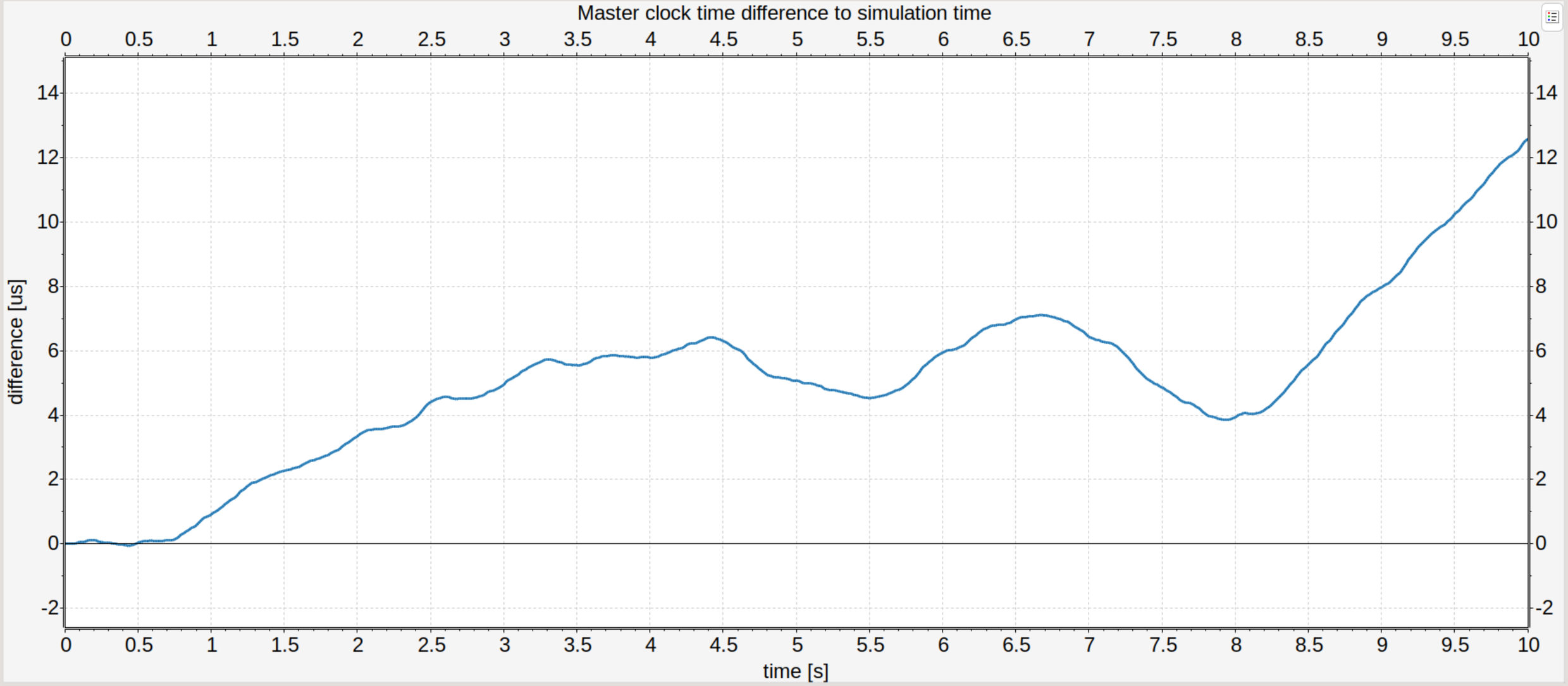
NoTimeSynchronization #0: TimeSynchronizationShowcase | Msg stats: 4 scheduled / 92 existing / 92 created

ui - inet/wfcs2025/step6_time_synchronization/TimeSynchronization.anf - OMNeT++ IDE

File Edit Navigate Search Project Run Window Help

TimeSynchronization.anf

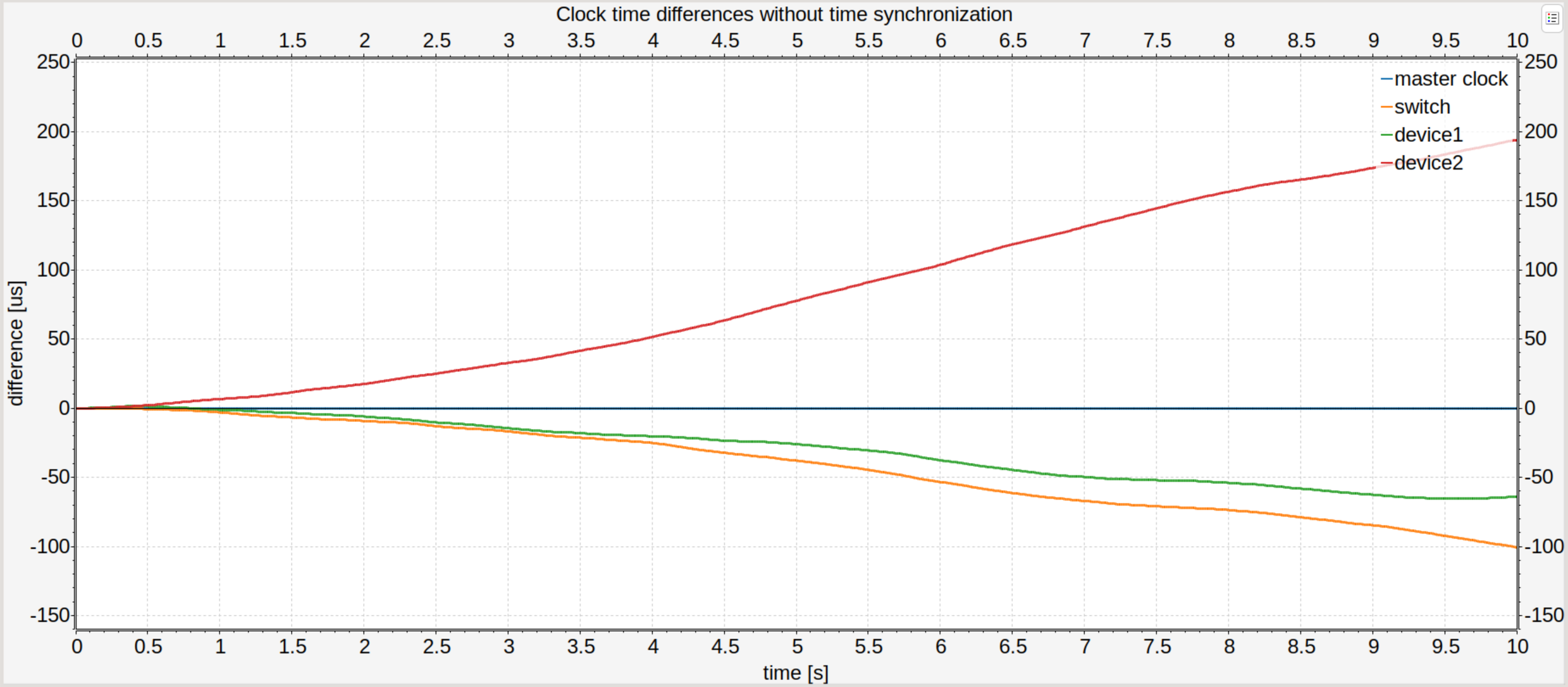
Master clock time difference to simulation time



Inputs | Browse Data | Charts | Master clock time difference to simulation time

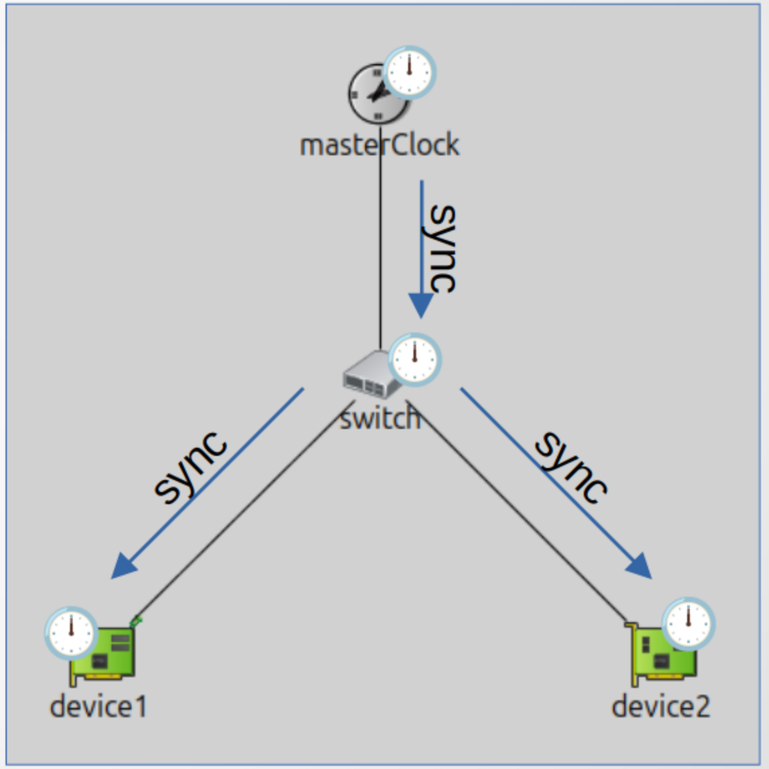
Selected: Chart 'Master clock time difference to simulation time'

Codeium: No comple...erated | Show Chat



Time Synchronization (gPTP)

- Shared time base
- Master-slave hierarchy
- Time dissemination
- Link delay measurement
- Continuous clock correction
- Stability and convergence



TimeSynchronization.anf | TimeSynchronization.ini

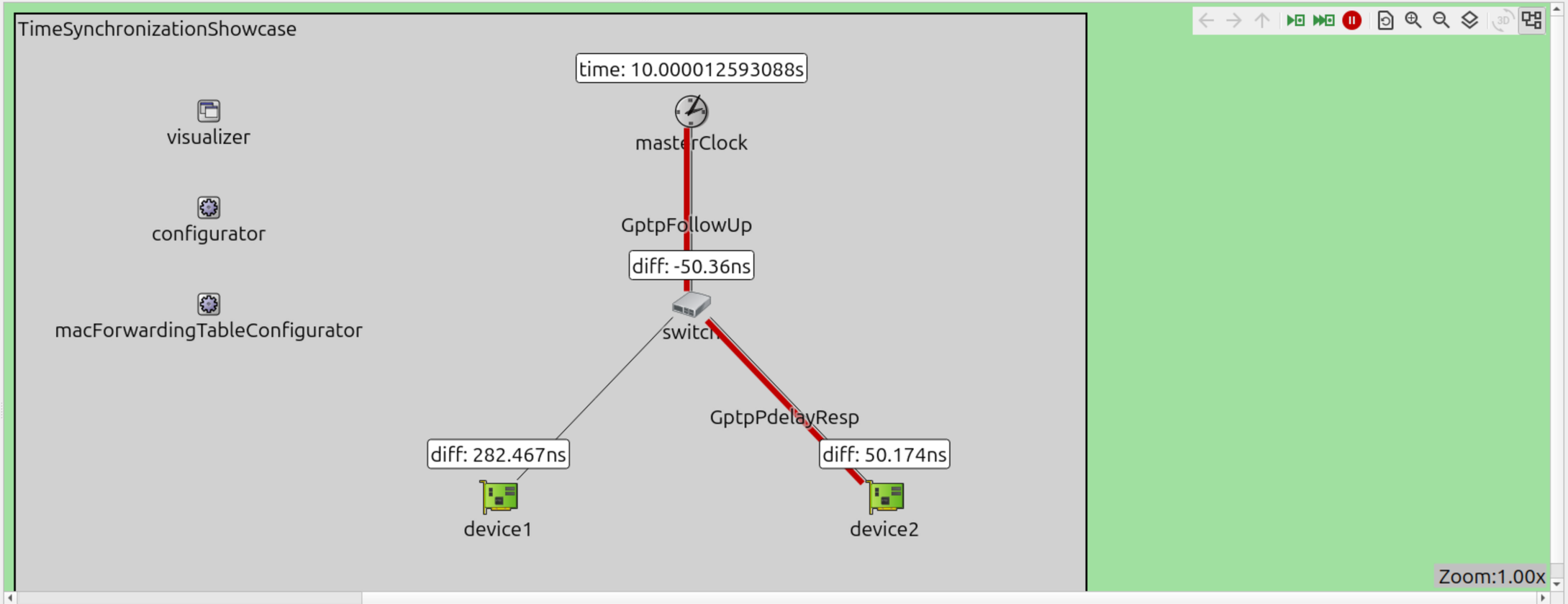
```
28 *.visualizer.infoVisualizer.displayInfos = true
29 *.visualizer.infoVisualizer.placementHint = "top"
30 *.visualizer.infoVisualizer.modules = "*.*.clock"
31
32 *.visualizer.networkNodeVisualizer.annotationSpacing = 12
33
34 [NoTimeSynchronization]
35 description = "Clock drift without time synchronization increases clock time differences indefinitely"
36
37 # select clock type
38 *.*.clock.typename = "OscillatorBasedClock"
39
40 # disable time synchronization in all network nodes
41 *.*.hasGptp = false
42 *.*.hasTimeSynchronization = false
43
44 [GptpTimeSynchronization]
45 description = "Clock drift with gPTP time synchronization keeps clock time differences within limits"
46
47 # enable time synchronization in all network nodes
48 *.*.hasGptp = true
49 *.*.hasTimeSynchronization = true
50
51 # configure TSN clock gPTP master ports
52 *.masterClock.gptp.masterPorts = ["eth0"]
53
54 # configure TSN switch gPTP bridge master ports
55 *.switch.gptp.masterPorts = ["eth1", "eth2"]
56
```

OMNeT++/Qtenv (release) - GptpTimeSynchronization #0 - TimeSynchronization.ini - /home/levy/workspace/inet/wfcs2025/step6_time_synchronization

File Simulate Inspect View Help

next: #7 332 | 10s 000ms 000us 000ns 000ps

Next: n/a | In: n/a | At: n/a



Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#7295	9.999 986 755 697	device1 --> switch	GptpPdelayReq	0A-AA-00-00-00-05	01-80-C2-00-00-0E	gPTP		80 B	
#7298	9.999 987 406 974	masterClock --> switch	GptpSync	0A-AA-00-00-00-01	01-80-C2-00-00-0E	gPTP		72 B	(UNIMPLEME
#7301	9.999 989 482 017	switch --> masterClock	GptpPdelayReq	0A-AA-00-00-00-02	01-80-C2-00-00-0E	gPTP		80 B	(UNIMPLEME
#7318	9.999 994 126 974	masterClock --> switch	GptpFollowUp	0A-AA-00-00-00-01	01-80-C2-00-00-0E	gPTP		102 B	(UNIMPLEME
#7326	9.999 999 277 198	switch --> device2	GptpPdelayResp	0A-AA-00-00-00-04	01-80-C2-00-00-0E	gPTP		80 B	(UNIMPLEME

GptpTimeSynchronization #0: TimeSynchronizationShowcase

Msg stats: 14 scheduled / 703 existing / 5417 created

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

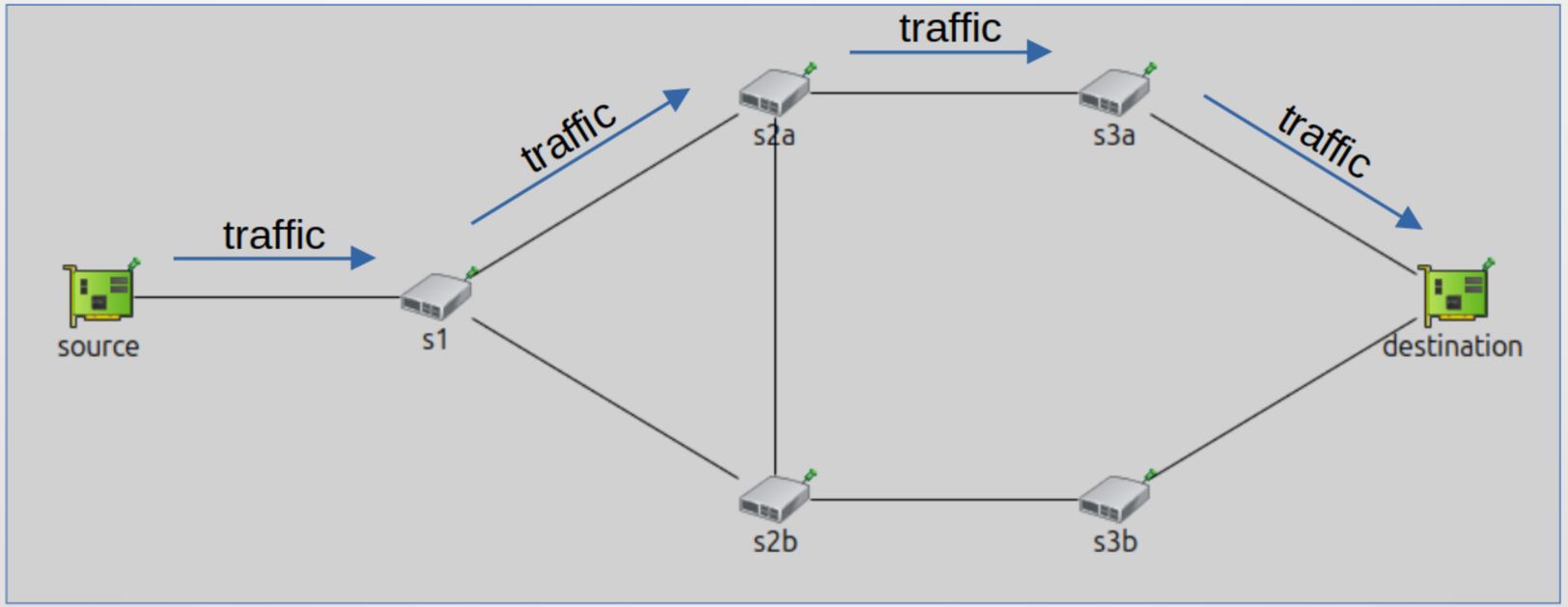
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Node Failure

- Node failure causes packet loss
- Critical traffic is not allowed to lose packets
- Networks are unprotected against failures by default



ui - inet/wfcs2025/step7_frame_replication/FrameReplication.ini - OMNeT++ IDE

File Edit Source Navigate Search Project Run Window Help

FrameReplication.ini × FramePreemption.anf

```
4  sim-time-limit = 100ms
5  result-dir = "results/wip"
6
7  # enable network node status
8  *.*.hasStatus = true
9
10 # configure Ethernet speed
11 *.*.eth[*].bitrate = 100Mbps
12
13 # configure source application
14 *.source.numApps = 1
15 *.source.app[0].typename = "UdpSourceApp"
16 *.source.app[0].io.destAddress = "destination"
17 *.source.app[0].io.destPort = 1000
18 *.source.app[0].source.displayStringTextFormat = "sent %p pk (%l)"
19 *.source.app[0].source.packetLength = 1200B
20 *.source.app[0].source.productionInterval = 1ms
21
22 # configure destination application
23 *.destination.numApps = 1
24 *.destination.app[0].typename = "UdpSinkApp"
25 *.destination.app[0].io.localPort = 1000
26
27 # configure node shutdown/startup
28 *.scenarioManager.script = xml("<script>\
29                                 <at t='20ms'><crash module='s2a'/></at> \
30                                 <at t='80ms'><startup module='s2a'/></at> \
31                                 </script>")
32
```

Form Source

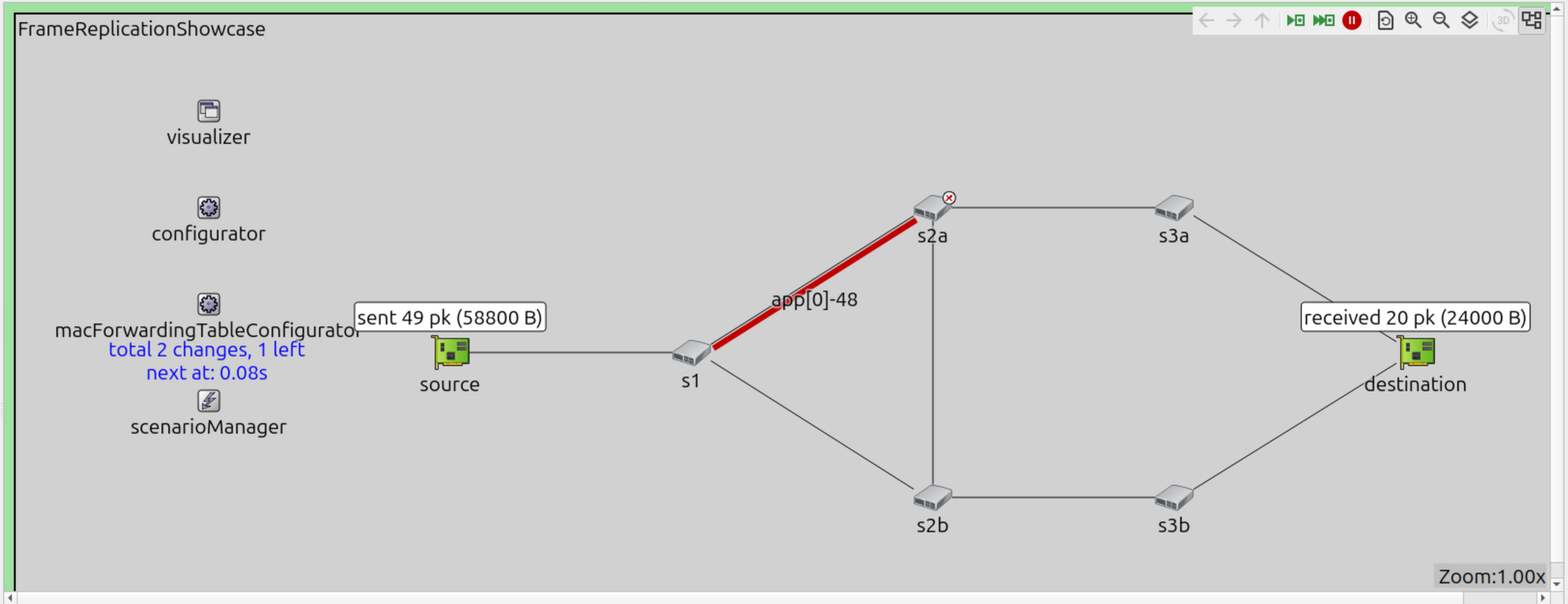
Writable Insert 26 : 1 : 704 Codeium | Show Chat

OMNeT++/Qtenv (release) - NoFrameReplication #0 - FrameReplication.ini - /home/levy/workspace/inet/wfcs2025/step7_frame_replication

File Simulate Inspect View Help

next: #1 032 | 0s 048ms 117us 992ns 820ps

Next: TxEndTimer (inet::ClockEvent, id=34) | In: FrameReplicationShowcase.s1.eth[0].phyLayer.transmitter (PacketTransmitter, id=227) | At: 0.04820069s (now+0.00008269718s)



Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#999	0.046'100'370	s1 --> s2a	app[0]-46	10.0.0.1:1025	10.0.0.2:1000	UDP		1254	
#1011	0.047	source --> s1	app[0]-47	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN)
#1014	0.047'100'370	s1 --> s2a	app[0]-47	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN)
#1026	0.048	source --> s1	app[0]-48	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN)
#1029	0.048'100'370	s1 --> s2a	app[0]-48	10.0.0.1:1025	10.0.0.2:1000	UDP		1254 B	(UNKNOWN)

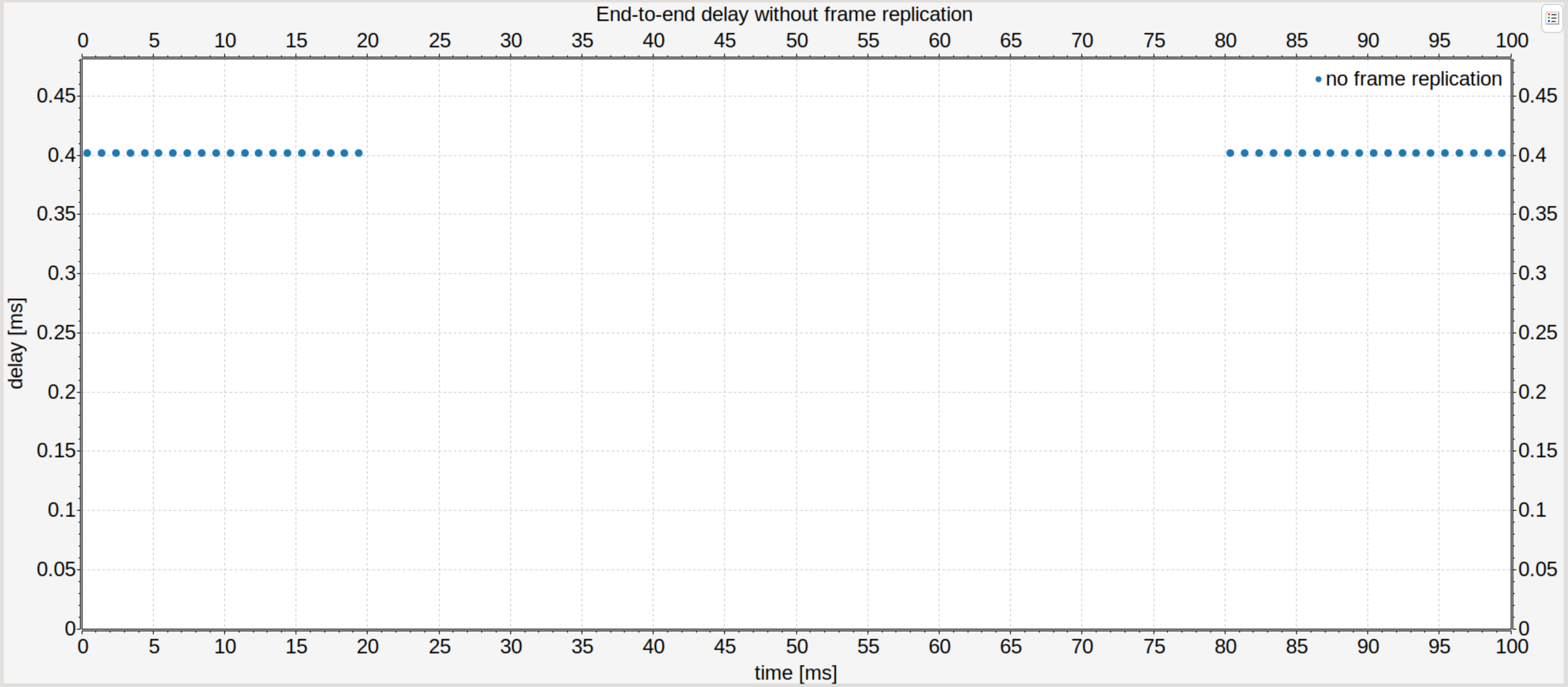
NoFrameReplication #0: FrameReplicationShowcase | Msg stats: 5 scheduled / 337 existing / 1278 created

ui - inet/wfcs2025/step7_frame_replication/FrameReplication.anf - OMNeT++ IDE

File Edit Navigate Search Project Run Window Help

FrameReplication.anf

End-to-end delay without frame replication



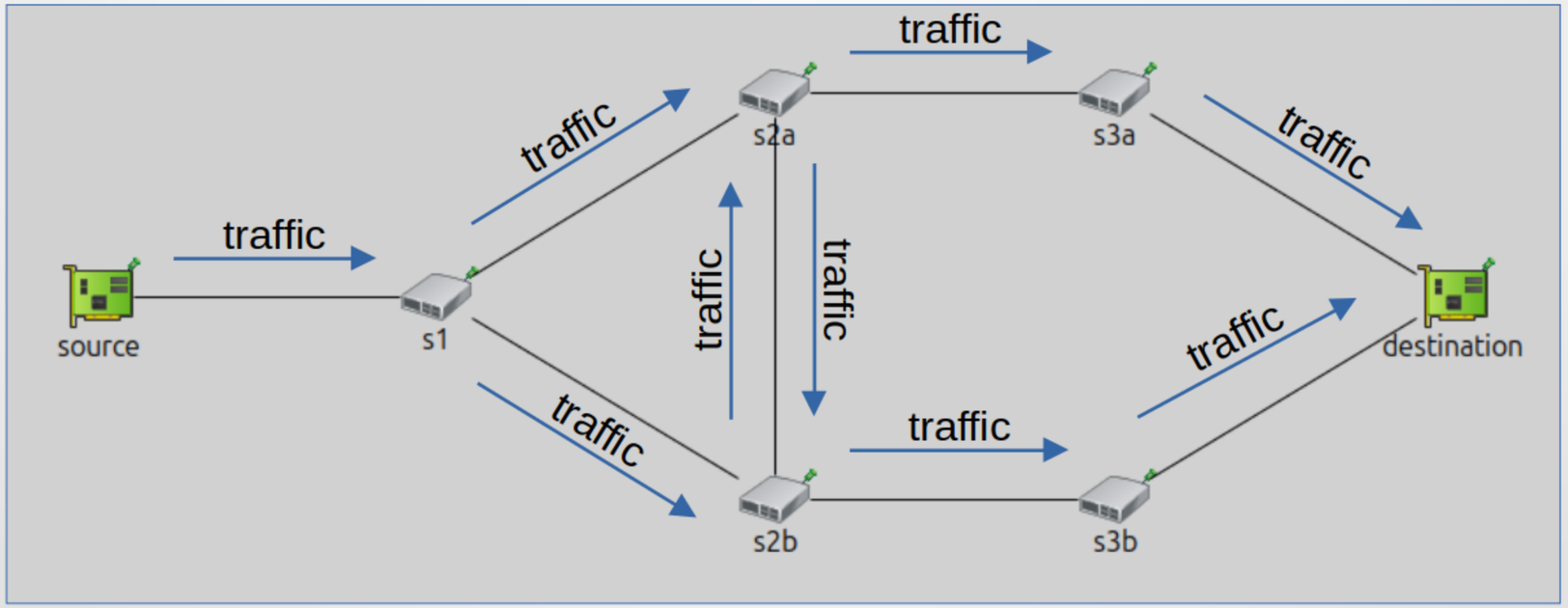
Inputs | Browse Data | Charts | End-to-end delay without frame replication

Selected: Chart 'End-to-end delay without frame replication'

Codeium: No comple...erated | Show Chat

Frame Replication and Elimination

- Replicate frames over multiple paths
- Identify stream split and merge points, eliminate duplicates
- Auto-configuration for specified node failure protection



FrameReplication.anf | FrameReplication.ini ×

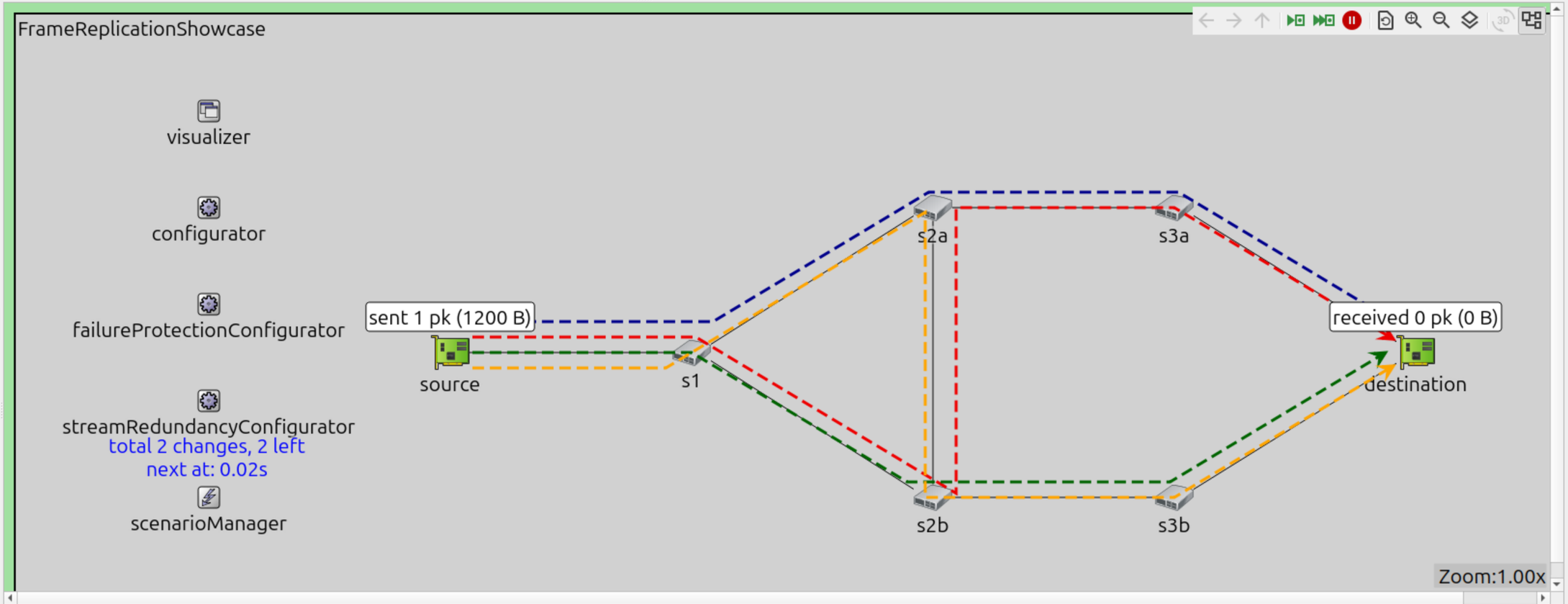
```
46 *.destination.eth[*].address = "0A-AA-12-34-56-78"
47
48 # enable frame replication and elimination
49 *.*.hasStreamRedundancy = true
50
51 # enable all automatic configurators
52 *.streamRedundancyConfigurator.typename = "StreamRedundancyConfigurator"
53 *.failureProtectionConfigurator.typename = "FailureProtectionConfigurator"
54
55 # configure TSN failure protection configurator
56 *.failureProtectionConfigurator.gateScheduleConfiguratorModule = ""
57 # 64B = 8B (UDP) + 20B (IP) + 4B (802.1R) + 6B (802.1Q) + 14B + 4B (ETH MAC) + 8B (ETH PHY)
58 *.failureProtectionConfigurator.configuration = [{name: "S1", application: "app[0]", source: "source", destination: "destinatior
59                                                  pcp: 0, packetFilter: "*",
60                                                  packetLength: 100B + 64B, packetInterval: 1ms, maxLatency: 100us,
61                                                  nodeFailureProtection: [{any: 1, of: "s2a or s2b or s3a or s3b"}],
62                                                  # this link failure protection is somewhat redundant for demonstration purpose
63                                                  linkFailureProtection: [{any: 1, of: "*->* and not source->s1"},
64                                                                          {any: 2, of: "s1->s2a or s2a->s2b or s2b->s3b"},
65                                                                          {any: 2, of: "s1->s2b or s2b->s2a or s2a->s3a"}]}]
66
67 # configure failure protection visualizer
68 *.visualizer.failureProtectionConfigurationVisualizer.displayTrees = true
69 *.visualizer.failureProtectionConfigurationVisualizer.lineStyle = "dashed"
70
71 # configure stream redundancy visualizer
72 *.visualizer.streamRedundancyConfigurationVisualizer.displayTrees = true
73 *.visualizer.streamRedundancyConfigurationVisualizer.lineColor = "black"
74
```

OMNeT++/Qtenv (release) - FrameReplication #0 - FrameReplication.ini - /home/levy/workspace/inet/wfcs2025/step7_frame_replication

File Simulate Inspect View Help

next: #1 | 0s 000ms 000us 000ns 000ps

Next: ServeTimer (omnetpp::cMessage, id=6) | In: FrameReplicationShowcase.source.eth[0].macLayer.server (InstantServer, id=147) | At: 0s (now+0s)



FrameReplicationShowcas
simulation.scheduled-eve

FrameReplicationShowc
builtinAnimationsAllowe
canvas (cCanvas) canv
className = 'inet::Netw
componentType (cDyr
displayName = '' [...] (str
displayString [...] (omnel
fullName = 'FrameReplic
fullPath = 'FrameReplica
gates[0] (omnetpp::cGat
id = 1 (int)
index = <not a vector> (i
info = 'id=1' (string)
isModule = true (bool)
isSimple = false (bool)
isVector = false (bool)
listenedSignals[3] (omne
name = 'FrameReplicatic

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info

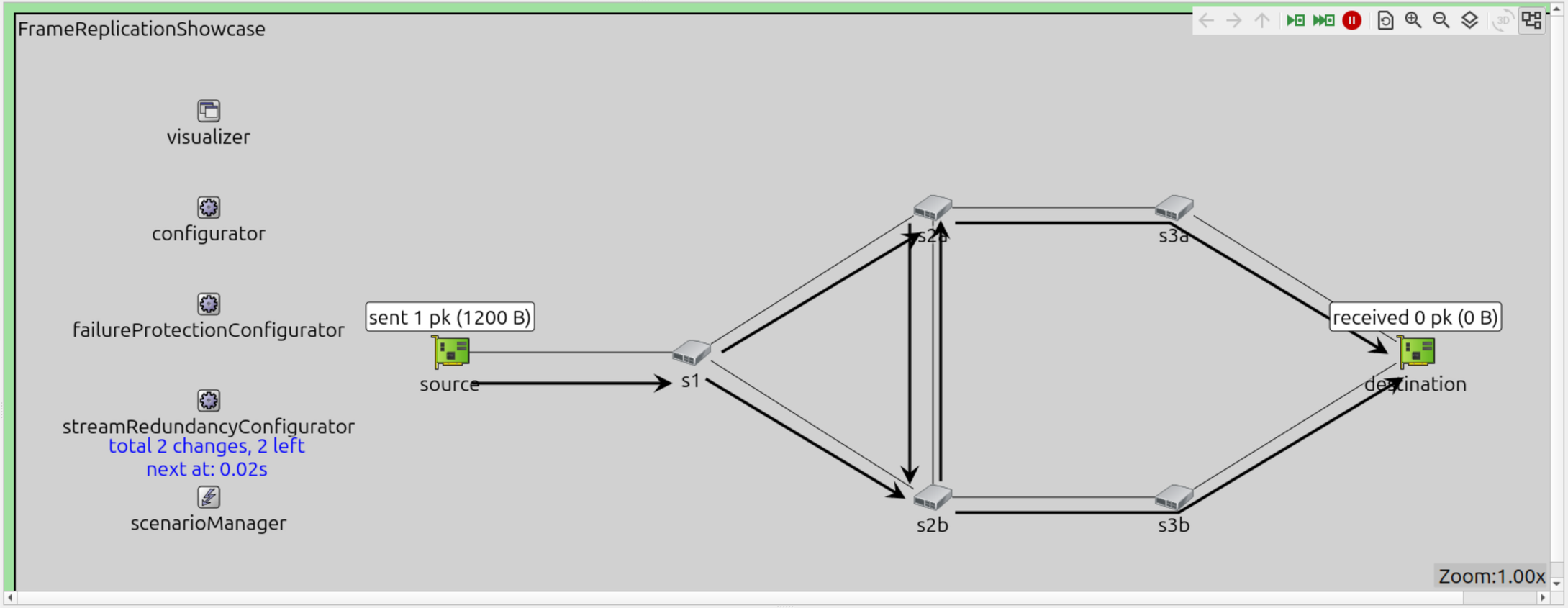
FrameReplication #0: FrameReplicationShowcase | Msg stats: 24 scheduled / 184 existing / 184 created

OMNeT++/Qtenv (release) - FrameReplication #0 - FrameReplication.ini - /home/levy/workspace/inet/wfcs2025/step7_frame_replication

File Simulate Inspect View Help

next: #1 | 0s 000ms 000us 000ns 000ps

Next: ServeTimer (omnetpp::cMessage, id=6) | In: FrameReplicationShowcase.source.eth[0].macLayer.server (InstantServer, id=147) | At: 0s (now+0s)



FrameReplicationShowcase
simulation.scheduled-eve

FrameReplicationShowc
builtinAnimationsAllowe
canvas (cCanvas) canv
className = 'inet::Netw
componentType (cDyr
displayName = '' [...] (str
displayString [...] (omnel
fullName = 'FrameReplic
fullPath = 'FrameReplica
gates[0] (omnetpp::cGat
id = 1 (int)
index = <not a vector> (i
info = 'id=1' (string)
isModule = true (bool)
isSimple = false (bool)
isVector = false (bool)
listenedSignals[3] (omne
name = 'FrameReplicatic

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info

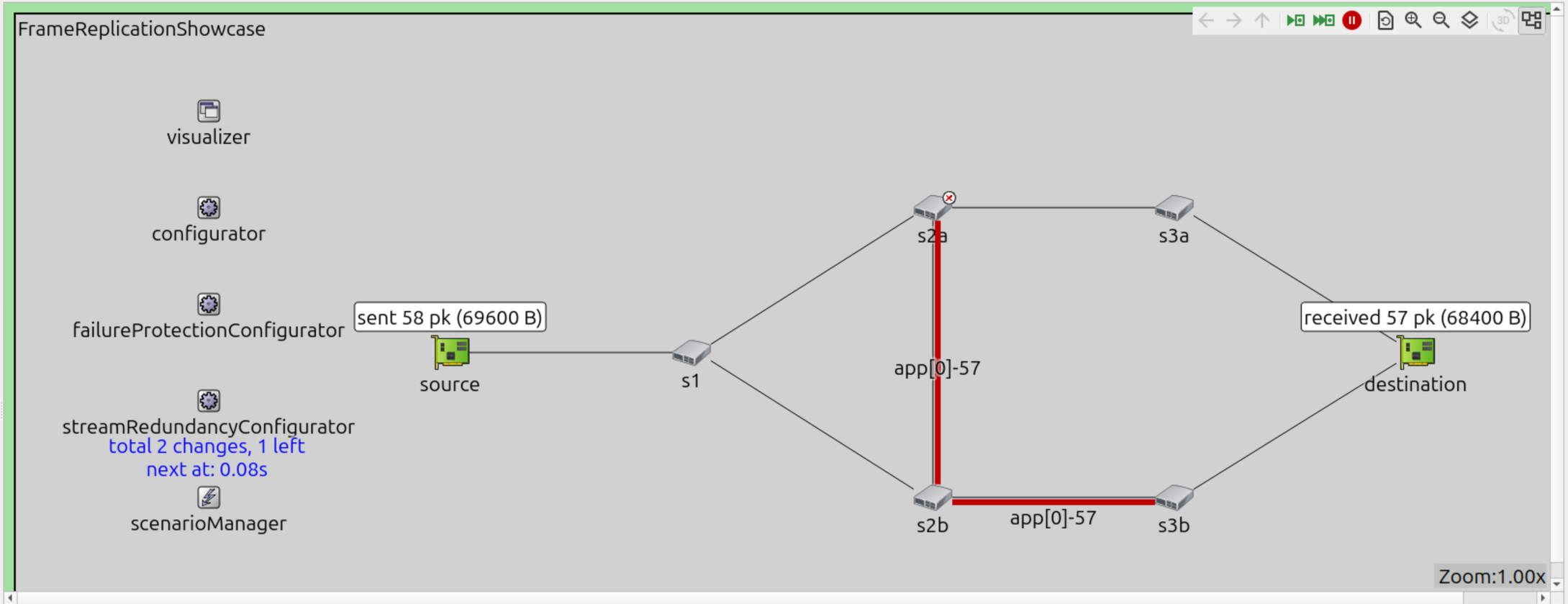
FrameReplication #0: FrameReplicationShowcase | Msg stats: 24 scheduled / 184 existing / 184 created

OMNeT++/Qtenv (release) - FrameReplication #0 - FrameReplication.ini - /home/levy/workspace/inet/wfcs2025/step7_frame_replication

File Simulate Inspect View Help

last: #2 561 | 0s 057ms 202us 659ns 978ps

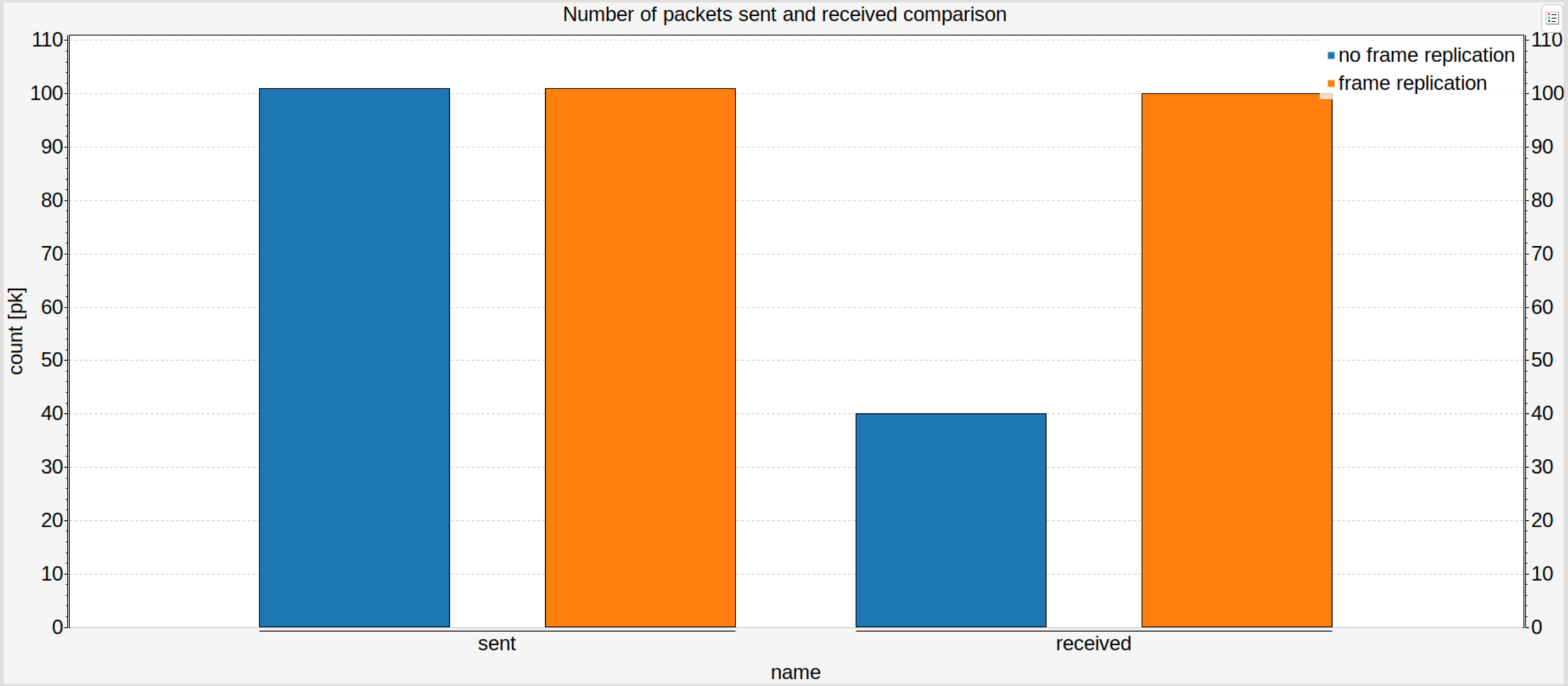
Ev/sec: 381.911 | Simsec/sec: 0.00979259 | Ev/simsec: 39000

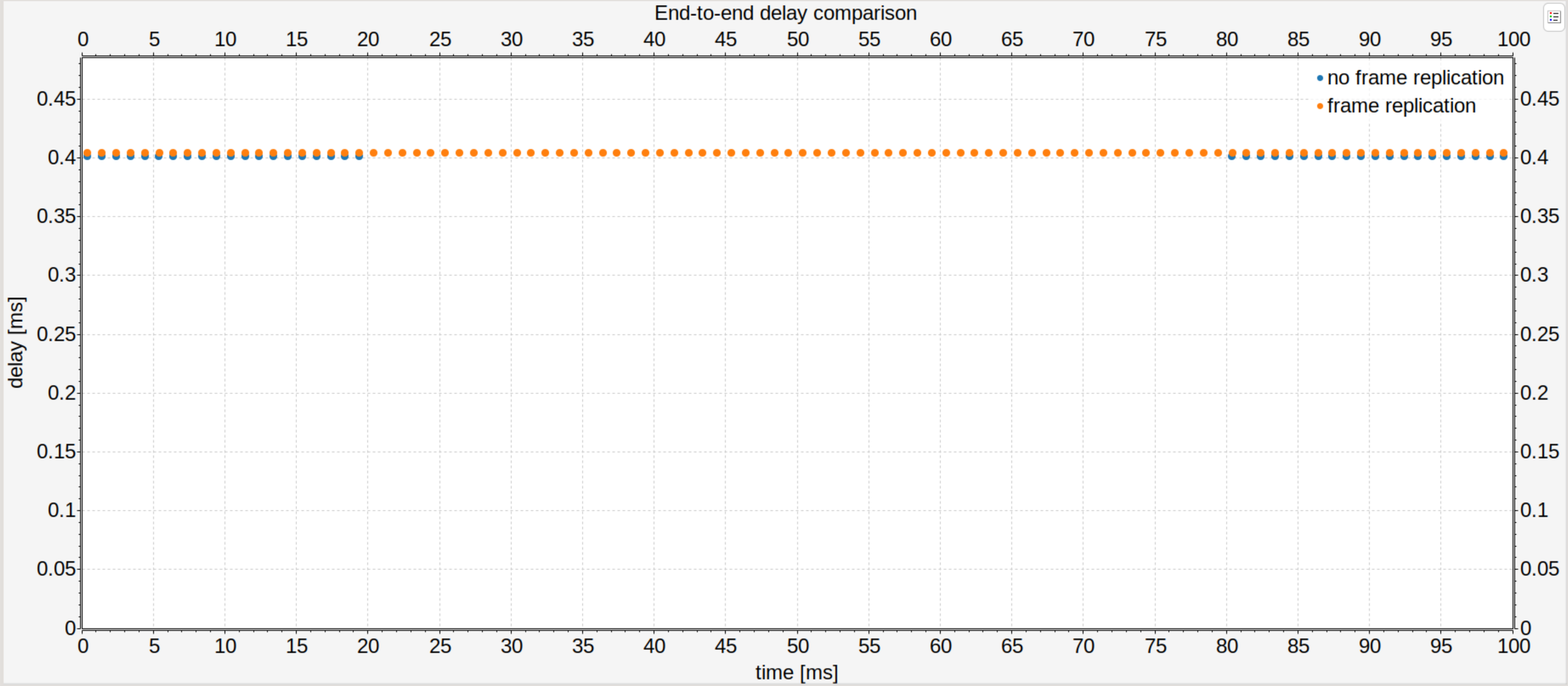


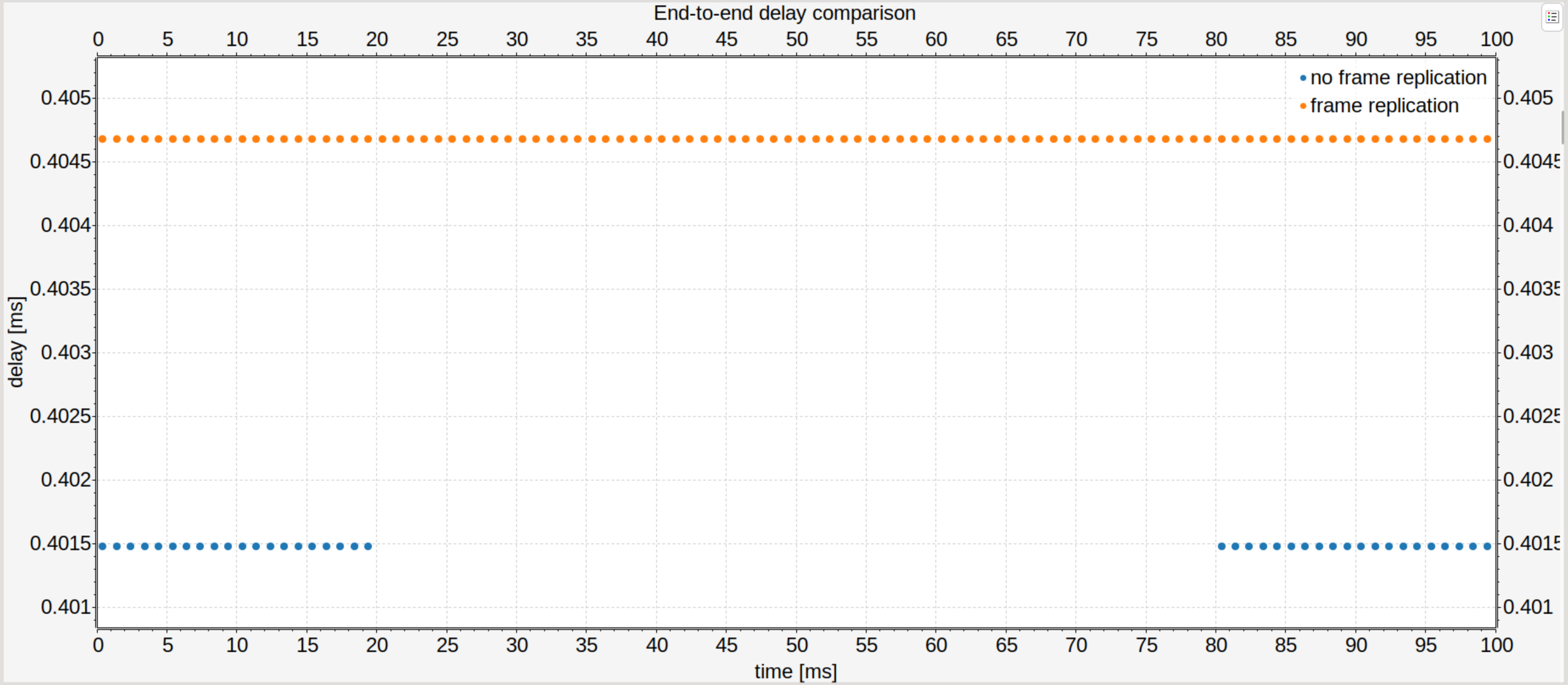
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protoc	Type	Length	Info
#2549	0.057	source --> s1	app[0]-57	10.0.0.1:1025	10.0.0.2:1000	UDP		1264	
#2552	0.057'101'170	s1 --> s2a	app[0]-57	10.0.0.1:1025	10.0.0.2:1000	UDP		1264 B	(UNKNOWN)
#2553	0.057'101'170	s1 --> s2b	app[0]-57	10.0.0.1:1025	10.0.0.2:1000	UDP		1264 B	(UNKNOWN)
#2560	0.057'202'340	s2b --> s2a	app[0]-57	10.0.0.1:1025	10.0.0.2:1000	UDP		1264 B	(UNKNOWN)
#2561	0.057'202'340	s2b --> s3b	app[0]-57	10.0.0.1:1025	10.0.0.2:1000	UDP		1264 B	(UNKNOWN)

FrameReplication #0: FrameReplicationShowcase

Msg stats: 9 scheduled / 628 existing / 3613 created







Costs and Benefits

- Benefits
  - No packet loss or recovery delay on failure
- Costs
  - Negligible end-to-end delay increase
  - Increased configuration complexity
  - May need additional switches and links
  - May increase end-to-end delay for other streams

Try it Yourself

```
$ pip install --upgrade pip
$ pip install opp_env
$ opp_env init -w inet-workspace
$ cd inet-workspace
$ opp_env install inet-git@topic/wfcs2025
$ opp_env shell
$ omnetpp
```

Questions and Answers

Thank you for your attention!