

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

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

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

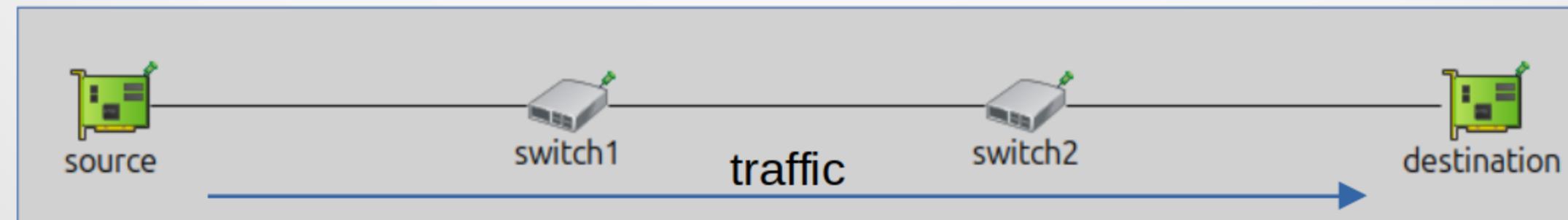
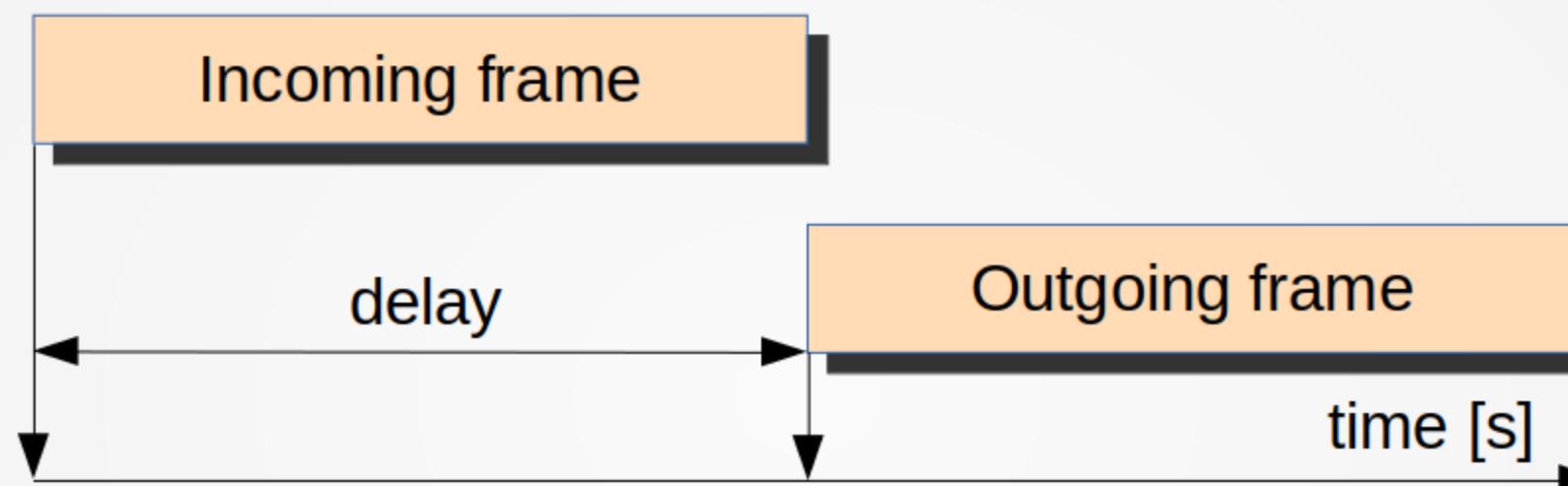
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Store-and-forward Switching

- Receive whole frame before forwarding



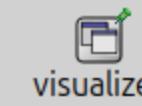
File Edit Source View Navigate Search Project Run Window Help



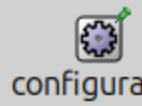
CutthroughSwitching.ned x

package step1_cutthrough_switching

CutthroughSwitchingShowcase



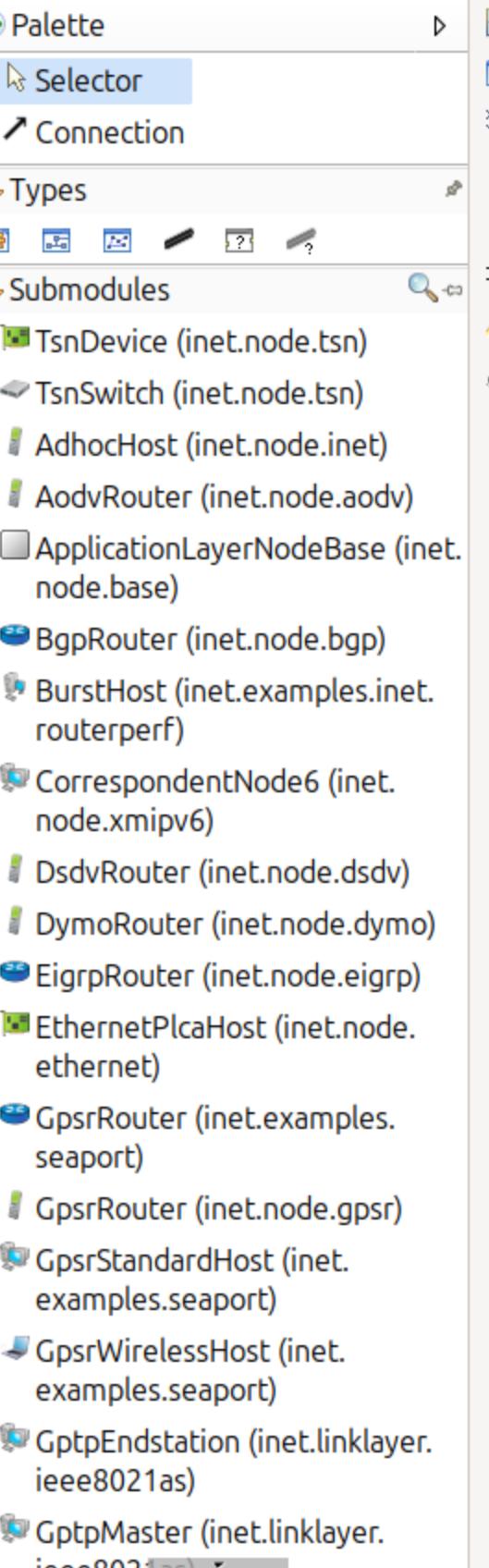
visualizer



configurator



macForwardingTableConfigurator



Design Source

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CutthroughSwitching.ned x

```
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 }
```

Design Source

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CutthroughSwitching.ned CutthroughSwitching.ini x

```
1 [General]
2 abstract = true
3 network = CutthroughSwitchingShowcase
4 sim-time-limit = 10ms
5 record-eventlog = true
6 result-dir = "results/wip"
7
8 # configure Ethernet speed
9 *.*.eth[*].bitrate = 1Gbps
10
11 # configure source applications
12 *.source.numApps = 1
13 *.source.app[0].typename = "UdpSourceApp"
14 *.source.app[0].io.destAddress = "destination"
15 *.source.app[0].io.destPort = 1000
16 *.source.app[0].source.packetLength = 1200B # ~10us transmission duration
17 *.source.app[0].source.productionInterval = truncnormal(200us, 50us) # 3 hops without cut-through would fill up the queues
18
19 # configure destination applications
20 *.destination.numApps = 1
21 *.destination.app[0].typename = "UdpSinkApp"
22 *.destination.app[0].io.localPort = 1000
23
24 [StoreAndForward]
25 description = "Ethernet switches completely receive incoming frames before forwarding them"
26
27 # no configuration required
28
29 [CutthroughSwitching]
```

Form Source

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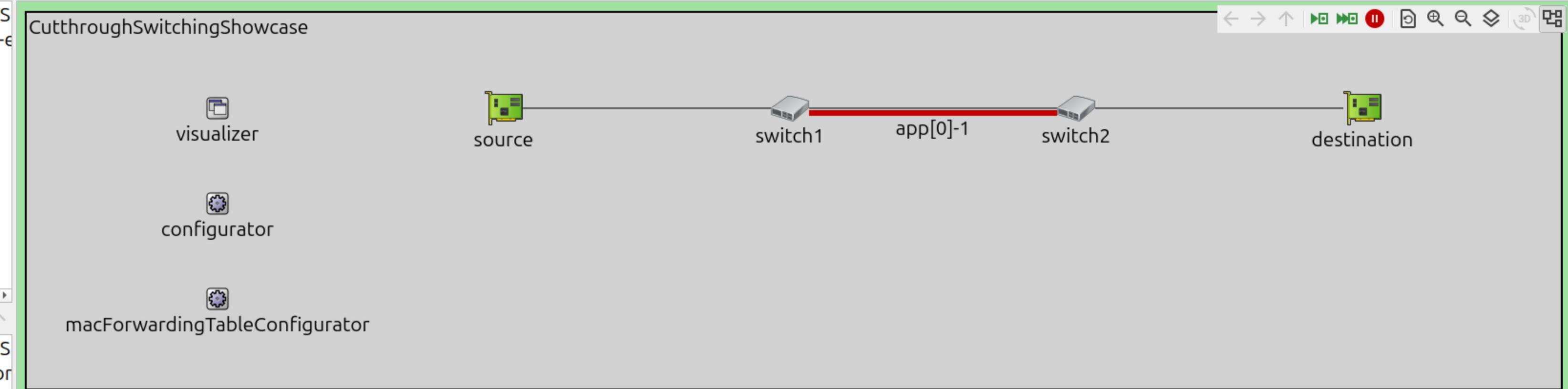
next: #45 | 0s 000ms 165us 025ns 796ps

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 (Integrated)
 □ configurator (Ipv4Ne
 □ macForwardingTable
 ▶ source (TsnDevice) i
 ▶ switch1 (TsnSwitch) i
 ▶ switch2 (TsnSwitch) i
 ▶ destination (TsnDev
 ▣ canvas (cCanvas) 25 t

Zoom:1.00x

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

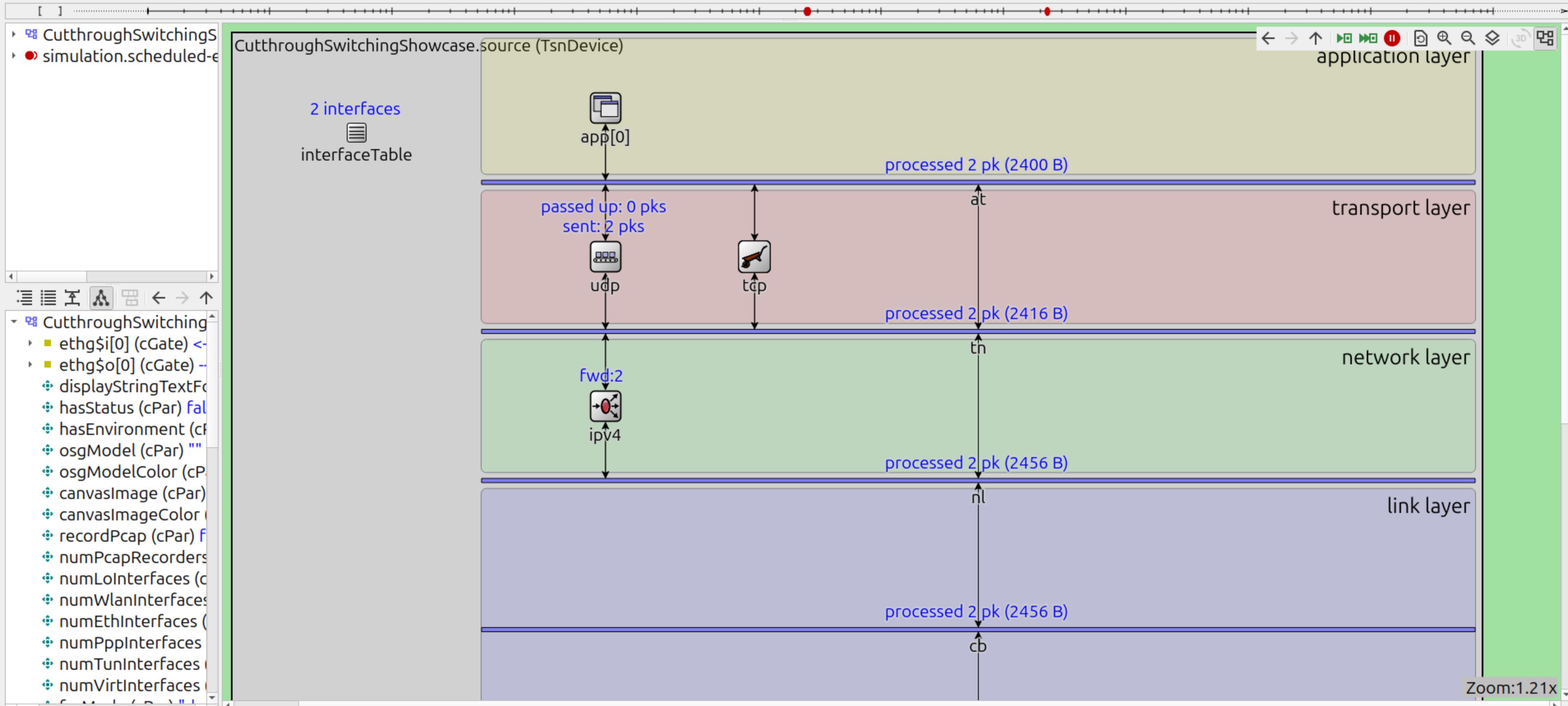
File Simulate Inspect View Help



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)

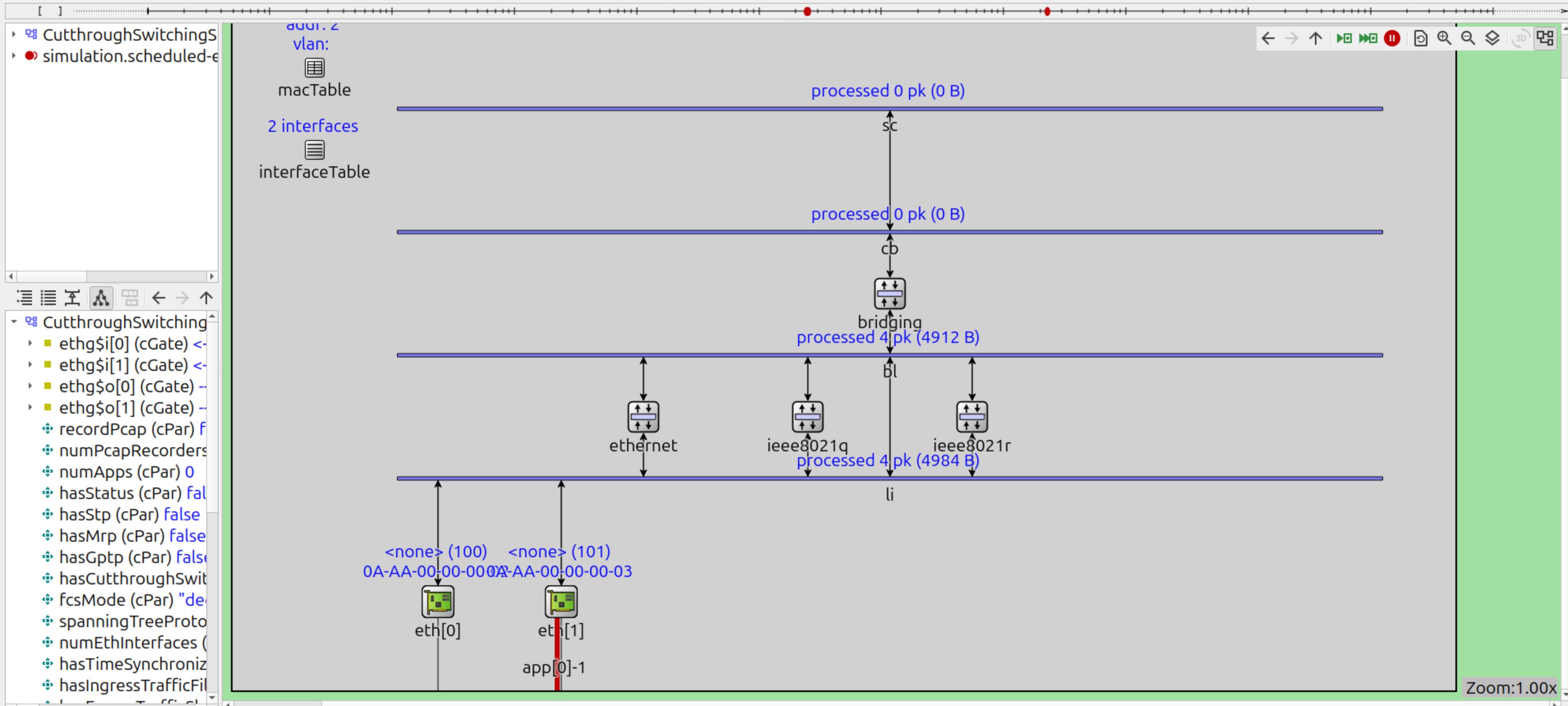


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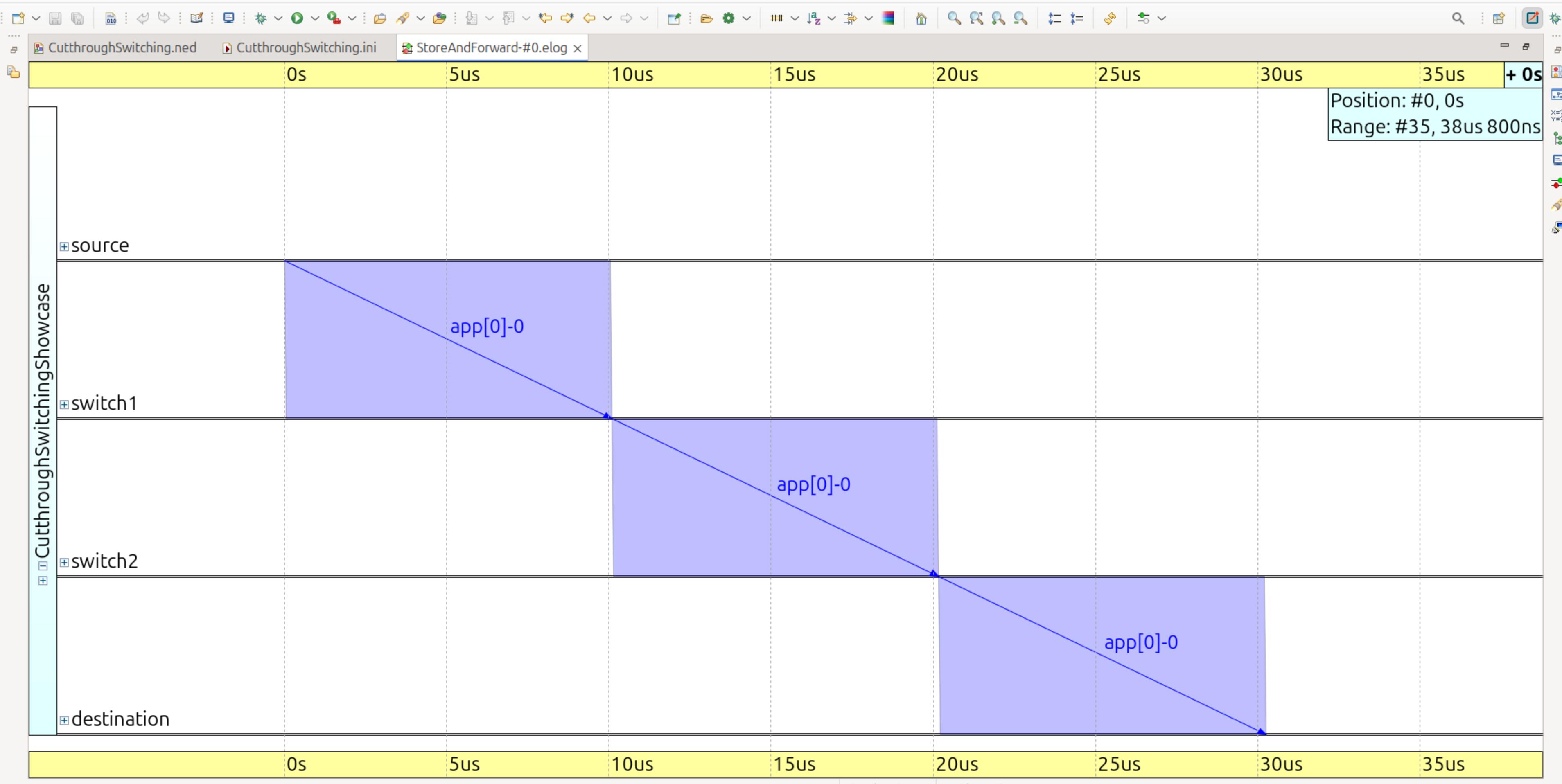


next: #45 | 0s 000ms 165us 025ns 796ps

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



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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

SO

CutthroughSwitchingShowcase

switch2

de



OS

SUS

TOSUS

TSUS

ZOUS

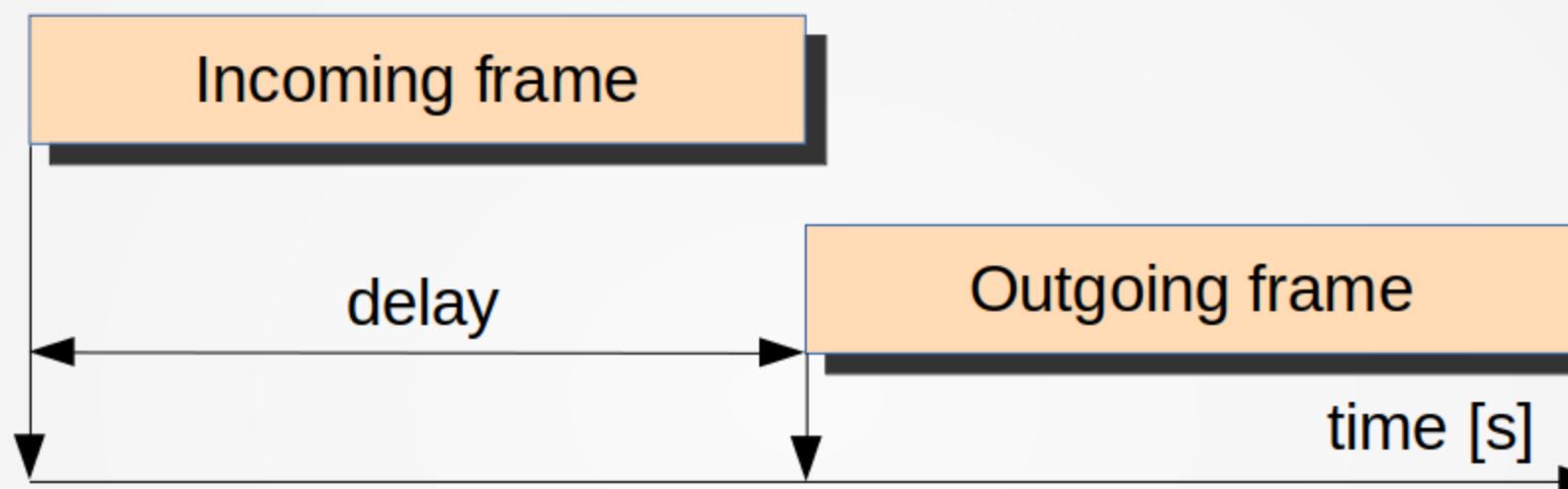
ZSUS

SUS

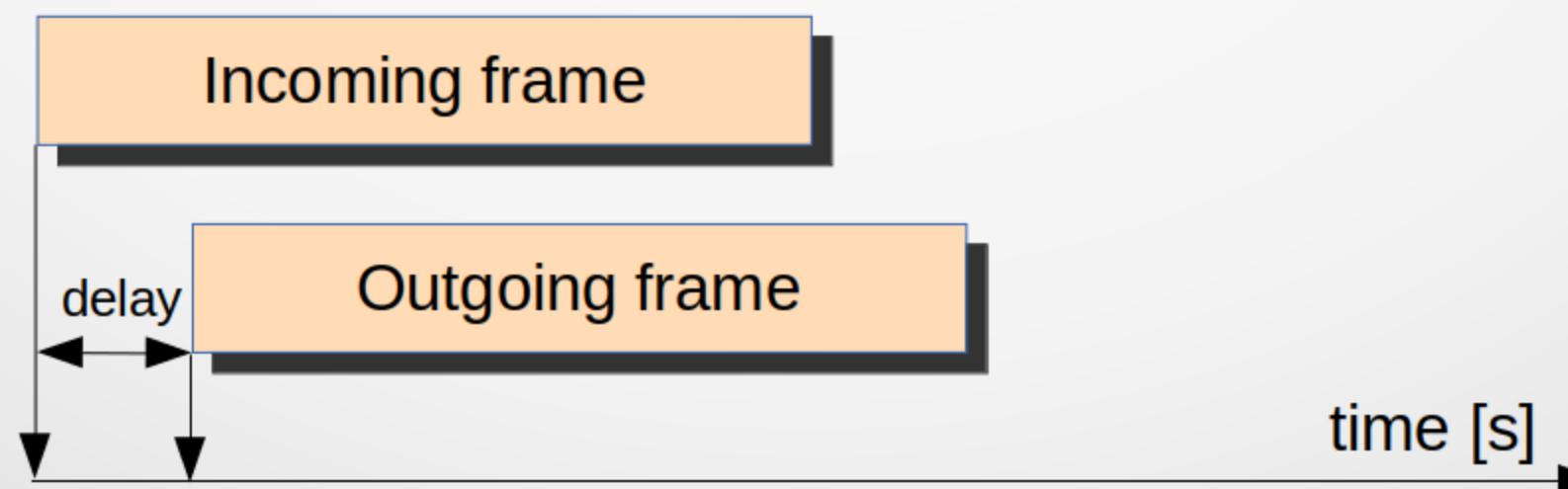
TSUS

Cut-through Switching

- Receive whole frame before forwarding



- Start forwarding as soon as MAC header is received



File Edit Source Navigate Search Project Run Window Help



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

```
6 result-dir = "results/wip"
7
8 # configure Ethernet speed
9 *.eth[*].bitrate = 1Gbps
10
11 # configure source applications
12 *.source.numApps = 1
13 *.source.app[0].typename = "UdpSourceApp"
14 *.source.app[0].io.destAddress = "destination"
15 *.source.app[0].io.destPort = 1000
16 *.source.app[0].source.packetLength = 1200B # ~10us transmission duration
17 *.source.app[0].source.productionInterval = truncnormal(200us, 50us) # 3 hops without cut-through would fill up the queues
18
19 # configure destination applications
20 *.destination.numApps = 1
21 *.destination.app[0].typename = "UdpSinkApp"
22 *.destination.app[0].io.localPort = 1000
23
24 [StoreAndForward]
25 description = "Ethernet switches completely receive incoming frames before forwarding them"
26
27 # no configuration required
28
29 [CutthroughSwitching]
30 description = "Ethernet switches start forwarding incoming frames after the Ethernet MAC header has been received"
31
32 # enable cut-through in all network nodes
33 *.*.hasCutthroughSwitching = true
34
```

Form Source

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9 : 9 : 172

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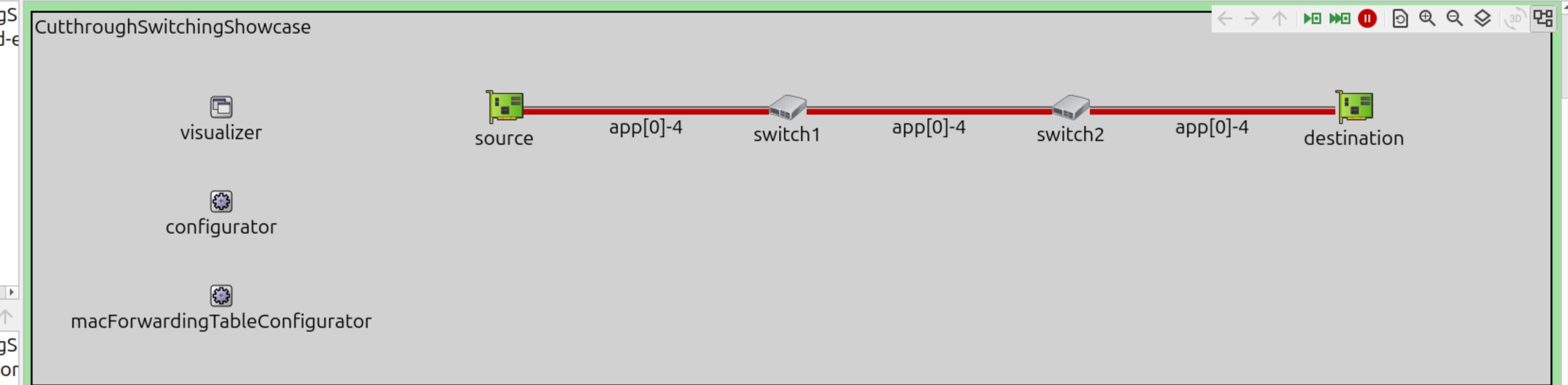


next: #139 | 0s 000ms 872us 134ns 659ps

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

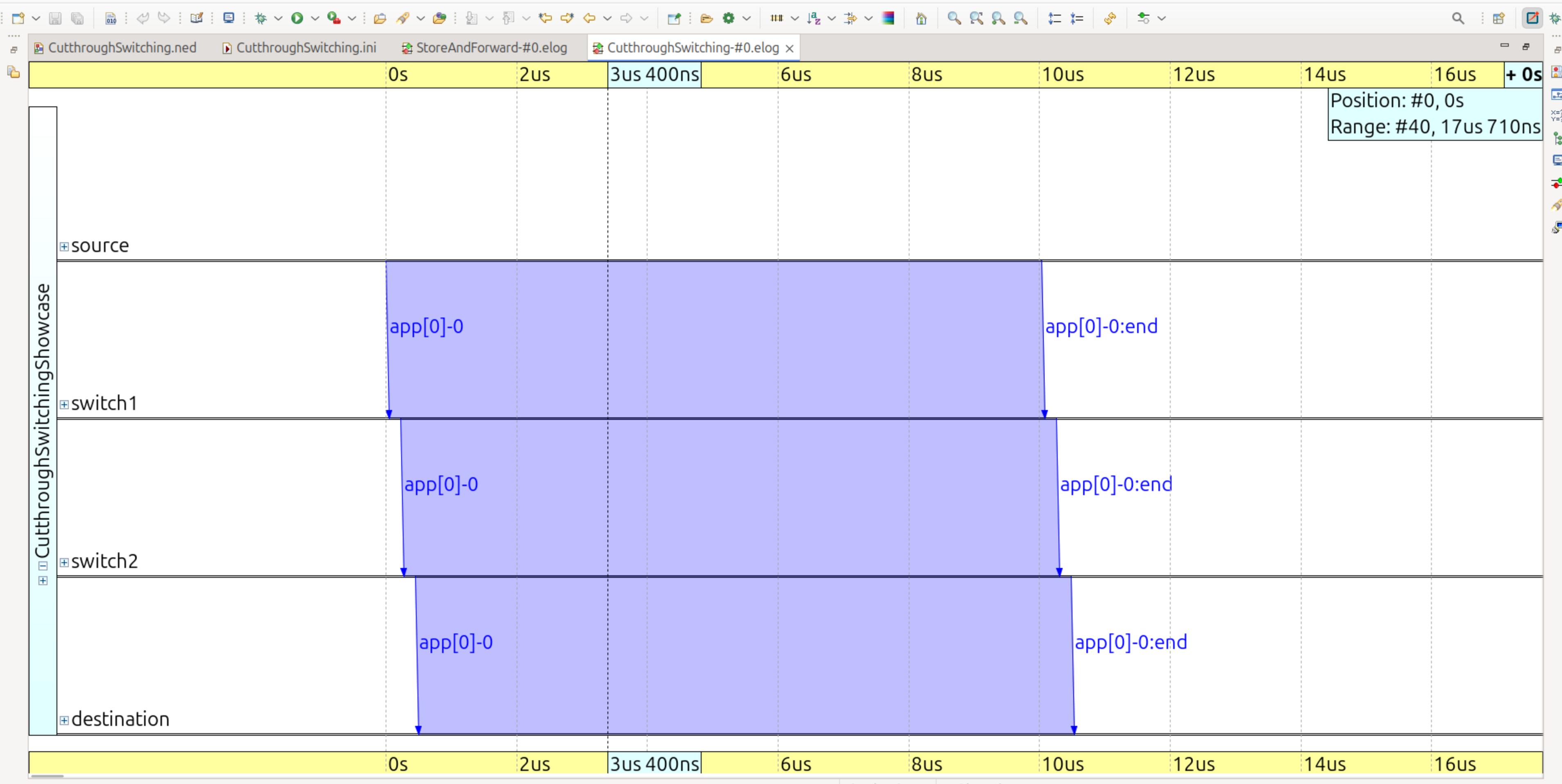


▼ CutthroughSwitchingS
 ❖ displayStringTextFor
 ❖ hasGlobalArp (cPar)
▶ visualizer (Integrated)
▶ configurator (Ipv4Ne
▶ macForwardingTable
▶ source (TsnDevice) i
▶ switch1 (TsnSwitch) i
▶ switch2 (TsnSwitch) i
▶ destination (TsnDev
▶ canvas (cCanvas) 25 t

Zoom:1.00x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protocol	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) 120
#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) 120
#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) 120
#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) 120
#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) 120
#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	

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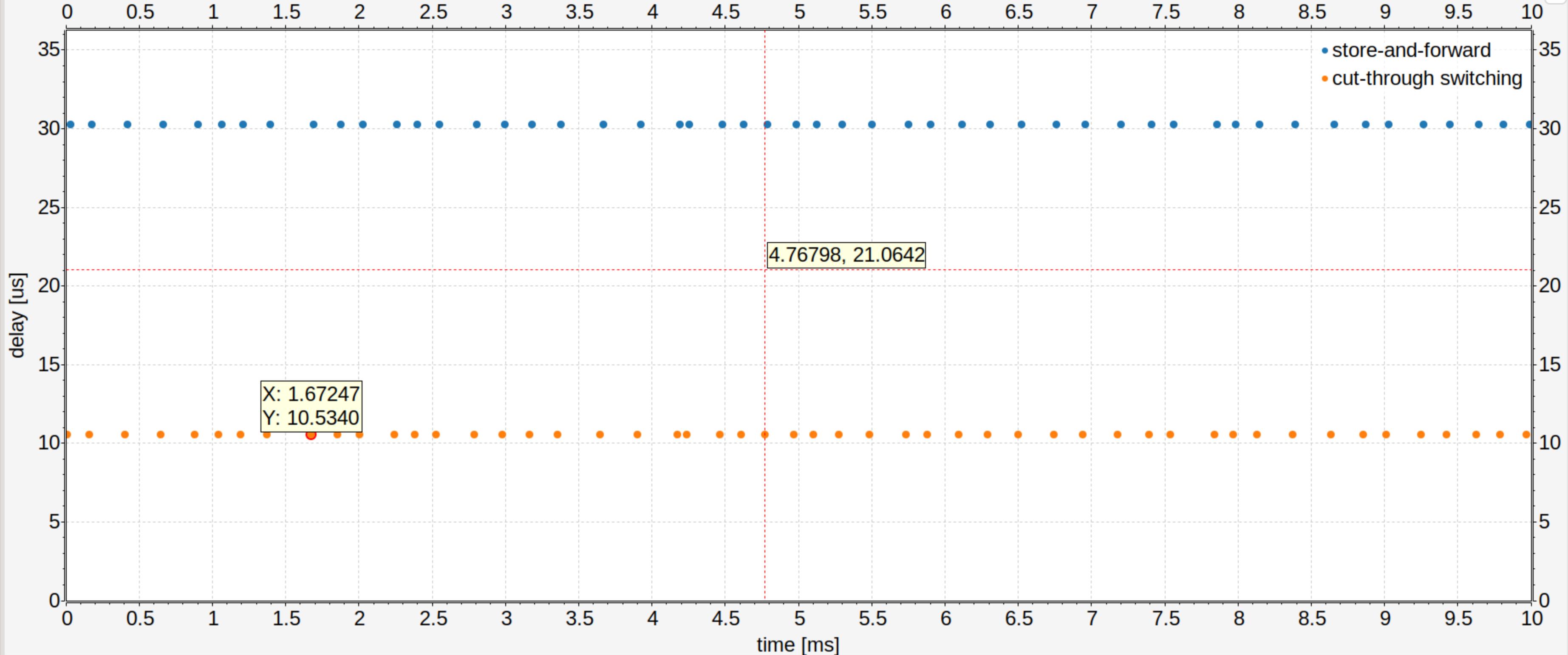
File Edit Navigate Search Project Run Window Help



CutthroughSwitching.ned CutthroughSwitching.ini StoreAndForward-#0.elog CutthroughSwitching-#0.elog CutthroughSwitching.anf x

End-to-end delay comparison

End-to-end delay comparison



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

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

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End-to-end Delay Validation

- Propagation time = 50ns
- Transmission time = $1254B * 8 / 1\text{Gbps} = 10.032\mu\text{s}$
- Cut-through delay = $22B * 8 / 1\text{Gbps} = 176\text{ns}$
- Store-and-forward end-to-end delay =
 $3 * (\text{Transmission time} + \text{Propagation time}) = 30.246\mu\text{s}$
- Cut-through switching end-to-end delay =
 $1 * \text{Transmission time} + 3 * \text{Propagation time} + 2 * \text{Cut-through delay} = 10.534\mu\text{s}$

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

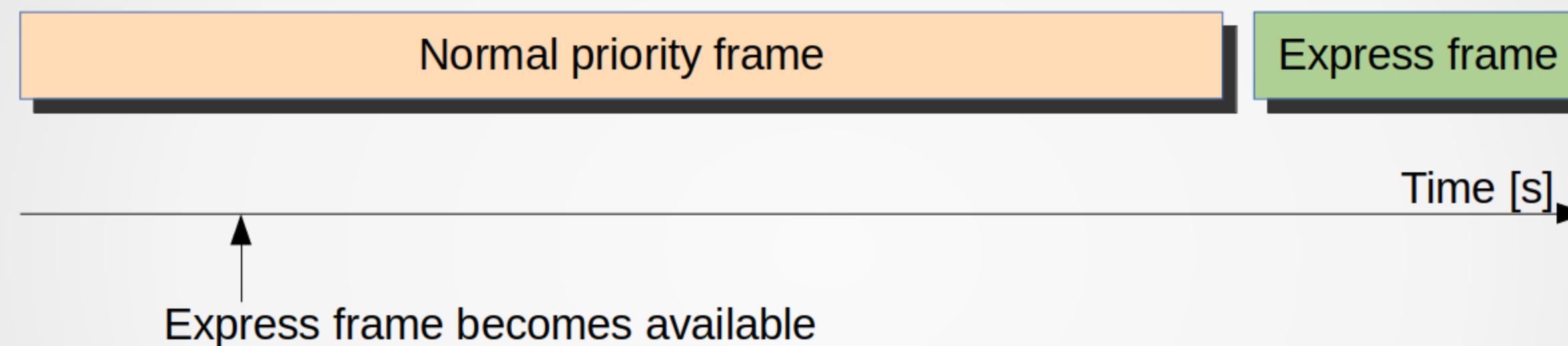
Automatic gate schedule configuration

Time synchronization

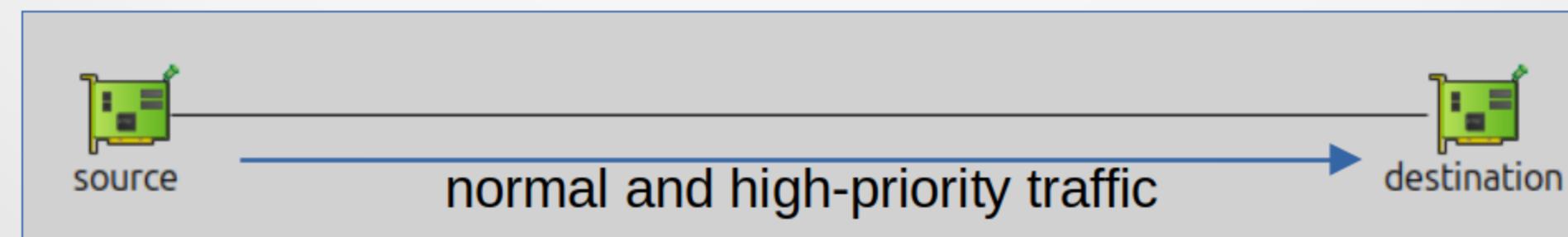
Frame replication and elimination for reliability

Long Frame Problem

- Long frame delays high priority frame



- Express frame waits in the queue



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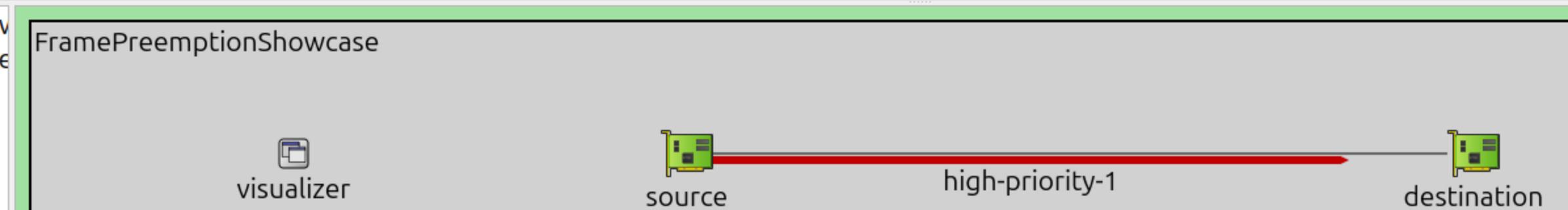


next: #92 | 0s 000ms 529us 185ns 209ps

Next: TxEndTimer (inet::ClockEvent, id=9)

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

FramePreemptionShowcase
simulation.scheduled-events



macForwardingTableConfigurator

FramePreemptionShowcase
displayStringTextFor
hasGlobalArp (cPar)
visualizer (Integrated)
configurator (Ipv4Neigh)
macForwardingTable
source (TsnDevice) id
destination (TsnDevice)
canvas (cCanvas) 19 t

Zoom:1.00x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des	Info / Protocol	Type	Length	Info
#13	0.000	source --> destination	high-priority-0	10.0.0.1:1026	10.0.0.2:1001	UDP		174 B	(UNKNOWN) 1200
#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) 1200

File Simulate Inspect View Help

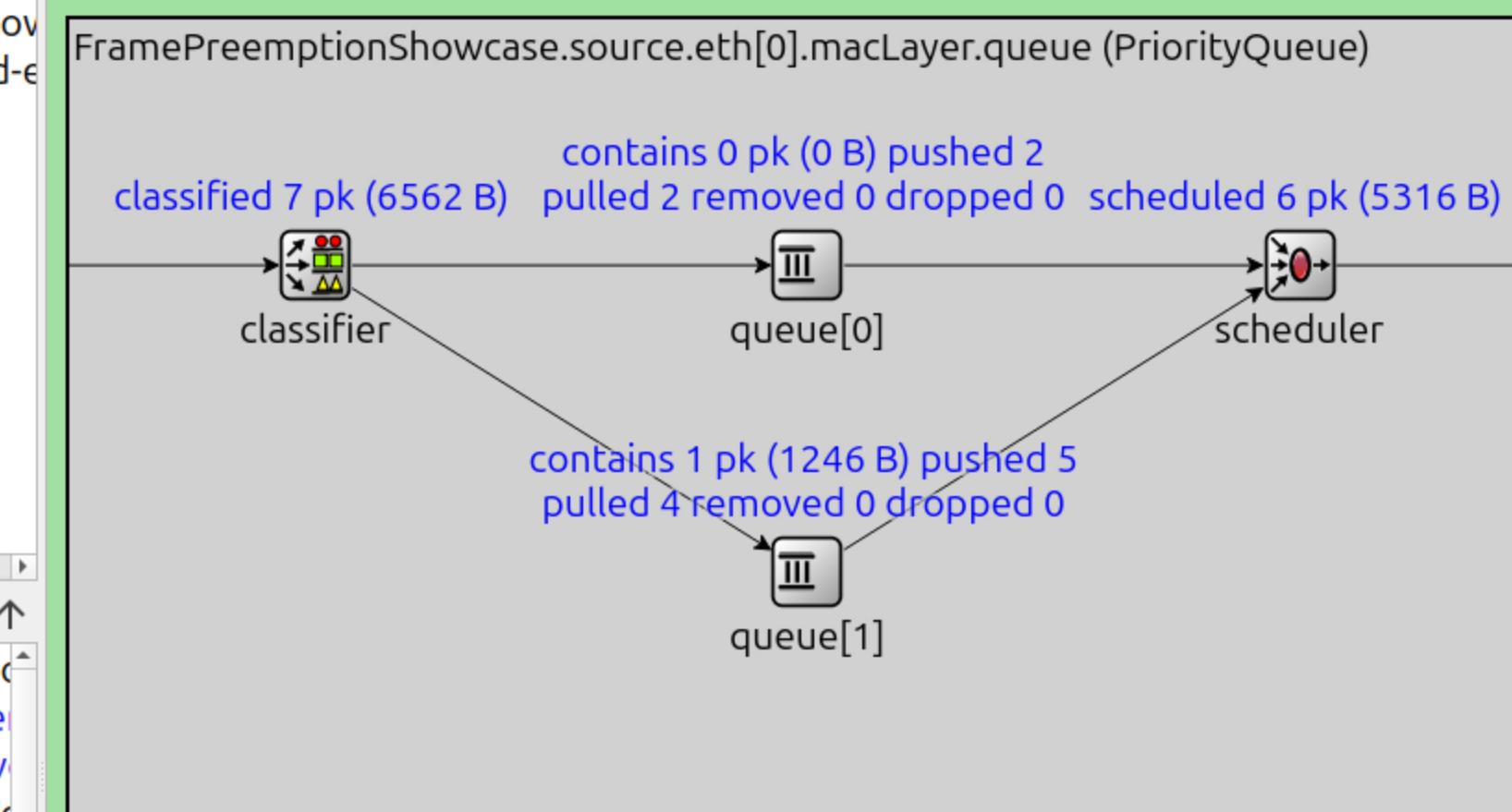


next: #92 | 0s 000ms 529us 185ns 209ps |

Next: TxEndTimer (inet::ClockEvent, id=9)

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

FramePreemptionShowcase
simulation.scheduled-events



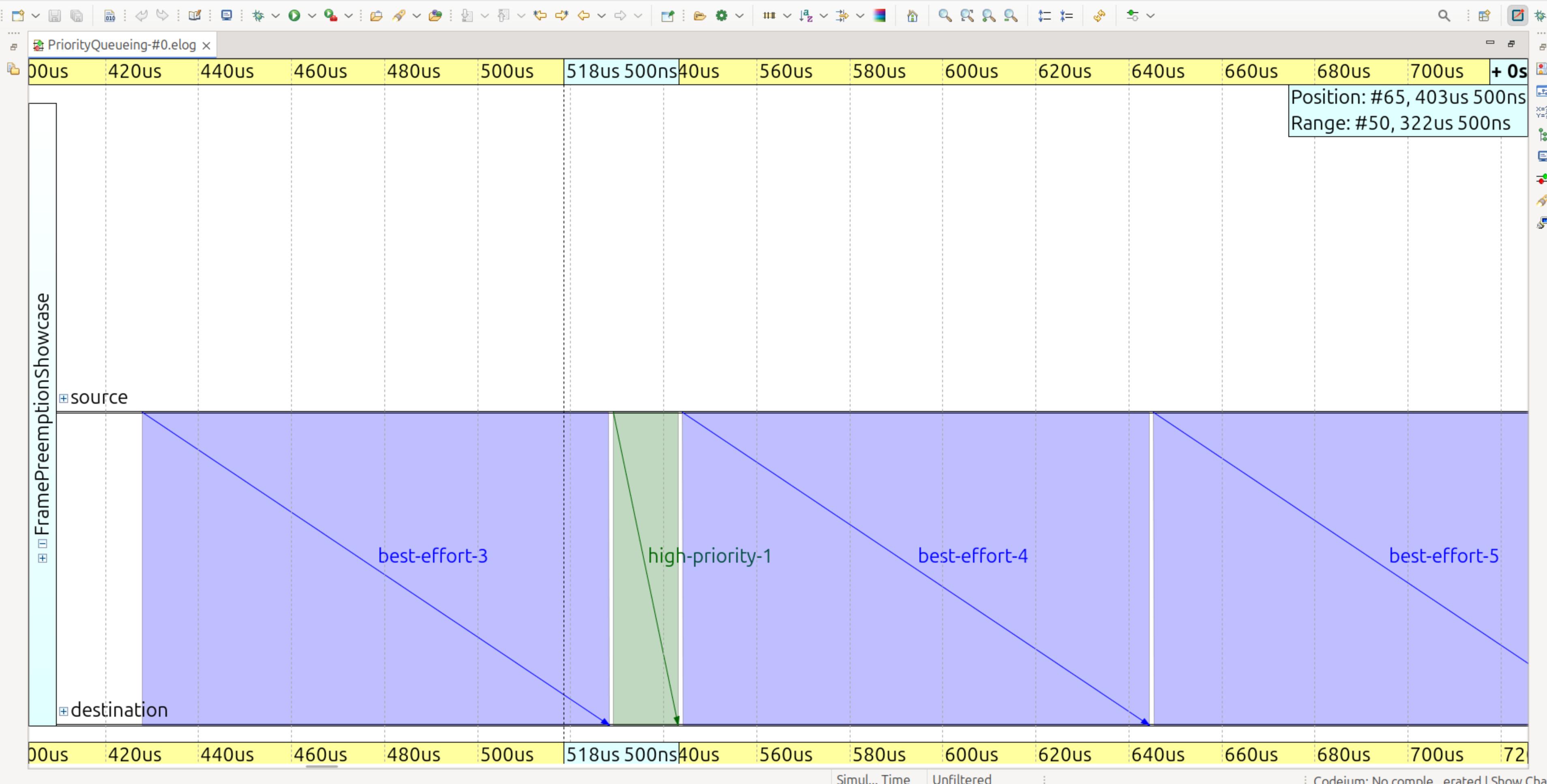
3D

FramePreemptionShowcase
in (cGate) <--> parent
out (cGate) --- service
displayStringTextField
packetCapacity (cParam)
dataCapacity (cParam)
dropperClass (cParam)
numQueues (cParam)
(LocalSignalFilter)
(LocalSignalFilter)

Zoom:1.33x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	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) 120
#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) 120
#82	0.000'490'412'145	^ --> .	best-effort-4	10.0.0.1:1025	10.0.0.2:1000	UDP	1246 B	(UNKNOWN) 120
#82	0.000'490'412'145	. --> classifier	best-effort-4	10.0.0.1:1025	10.0.0.2:1000	UDP	1246 B	(UNKNOWN) 120
#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) 120
#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) 120
#91	0.000'529'141'908	scheduler --> .	high-priority-1	10.0.0.1:1026	10.0.0.2:1001	UDP	166 B	(UNKNOWN) 120

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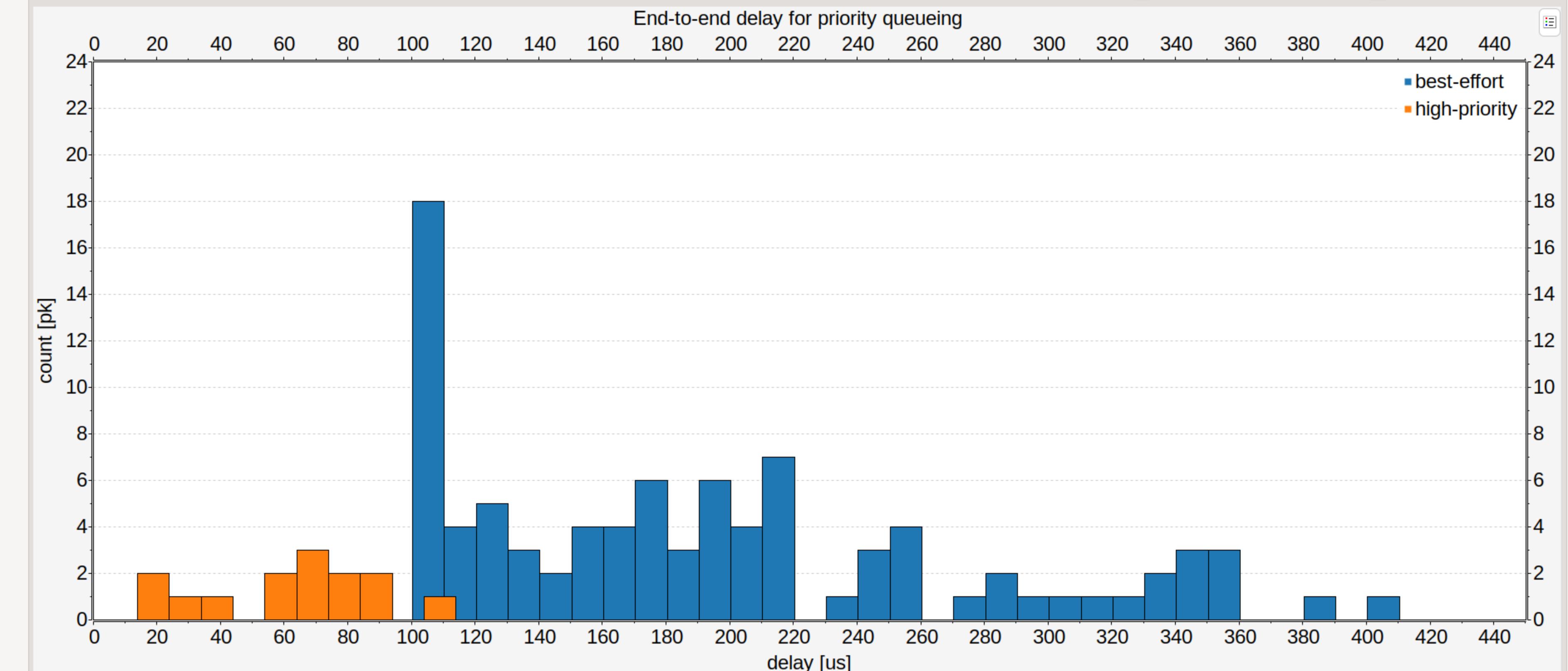


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PriorityQueueing-#0.elog FramePreemption.anf

End-to-end delay for priority queueing



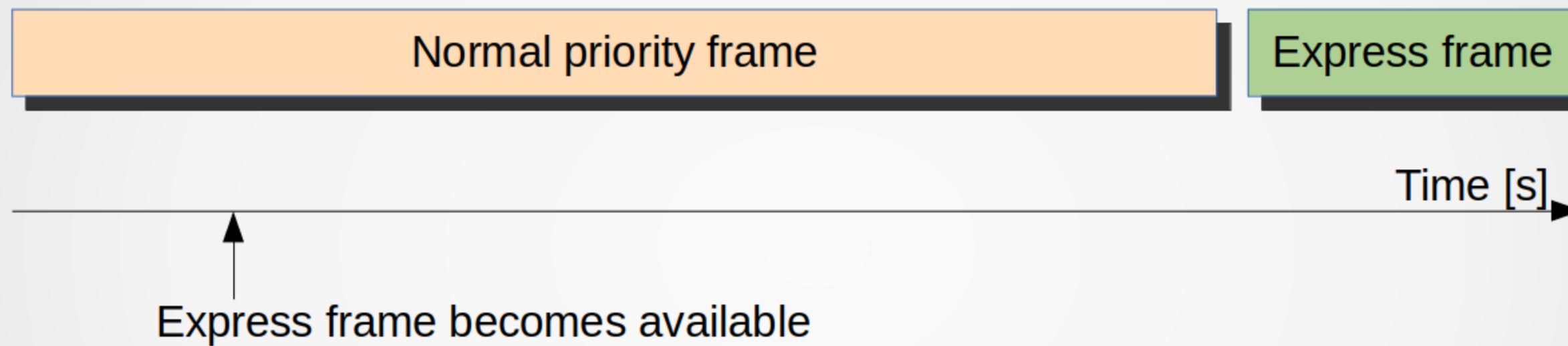
Inputs Browse Data Charts End-to-end delay for priority queueing x

Selected: Chart 'End-to-end delay for priority queueing'

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Frame Preemption

- Long frame delays high priority frame



- Reduce latency by interrupting transmission



File Edit Source Navigate Search Project Run Window Help



PriorityQueueing-#0.elog

FramePreemption.anf

FramePreemption.ini x

```
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 preempt
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

File Simulate Inspect View Help

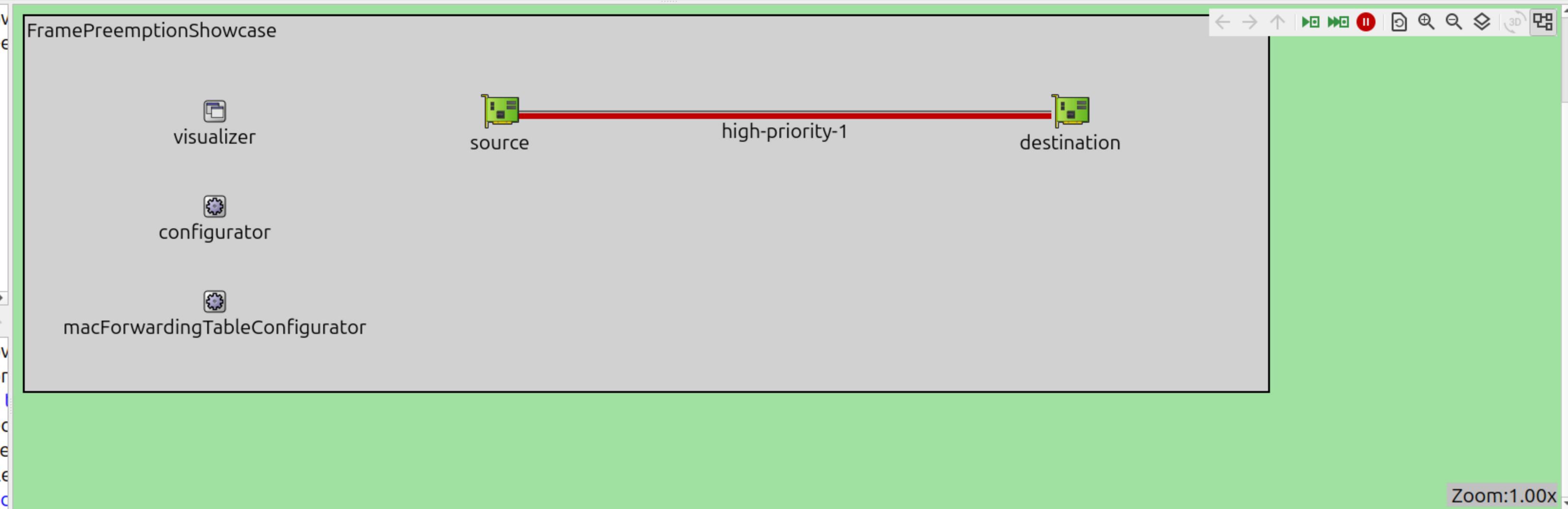


next: #80 | 0s 000ms 476us 260ns 511ps |

Next: Timer (inet::ClockEvent, id=6)

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

[]



FramePreemptionShowcase

- displayStringTextFor
- hasGlobalArp (cPar)
- visualizer (Integrated)
- configurator (Ipv4Net)
- macForwardingTable
- source (TsnDevice) id
- destination (TsnDevice)
- canvas (cCanvas) 19 t

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	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) (in
#54	0.000'291'867'573	source --> destination	best-effort-2			Ethernet PHY	1254 B	(UNKNOWN) (in
#57	0.000'392'187'573	source --> destination	best-effort-2:end			Ethernet PHY	1254 B	(UNKNOWN) (in
#68	0.000'427'861'908	source --> destination	best-effort-3			Ethernet PHY	1254 B	(UNKNOWN) (in
#74	0.000'473'504'914	source --> destination	best-effort-3-frag0:progress			Ethernet PHY	583 B	(UNKNOWN) (in
#76	0.000'474'501'908	source --> destination	best-effort-3-frag0:end			Ethernet PHY	583 B	(UNKNOWN) (in
#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) 120

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

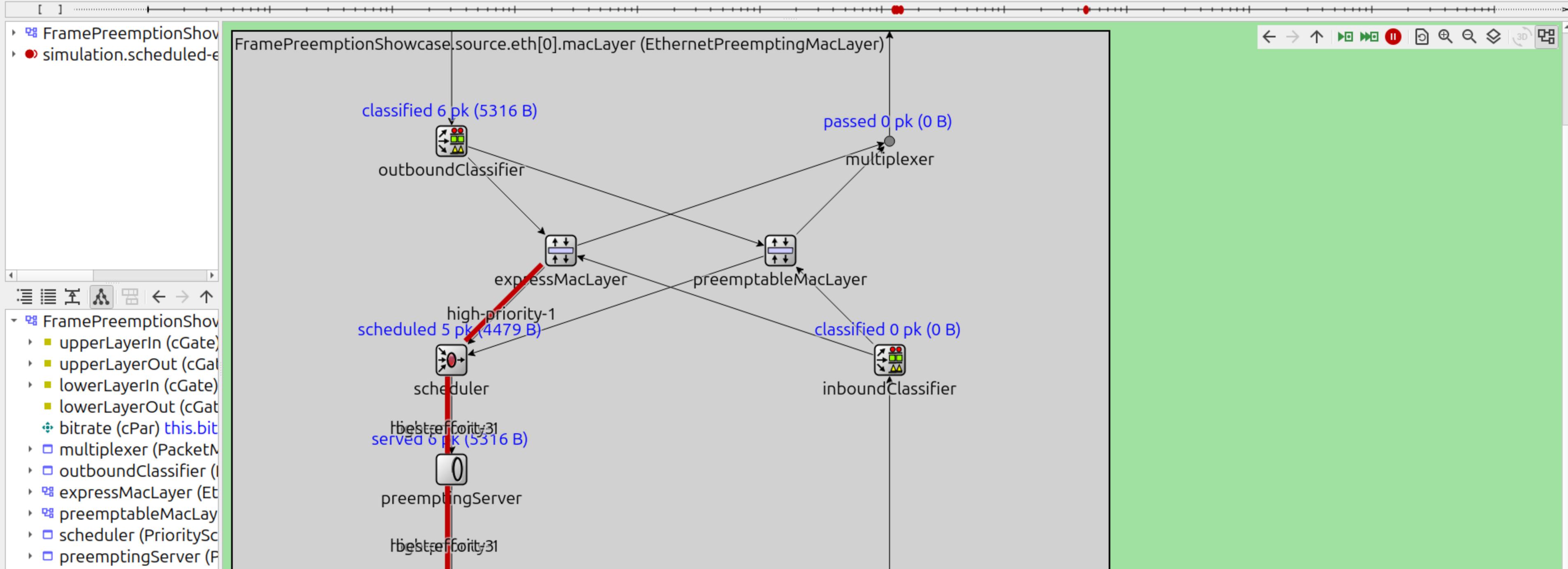
File Simulate Inspect View Help



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

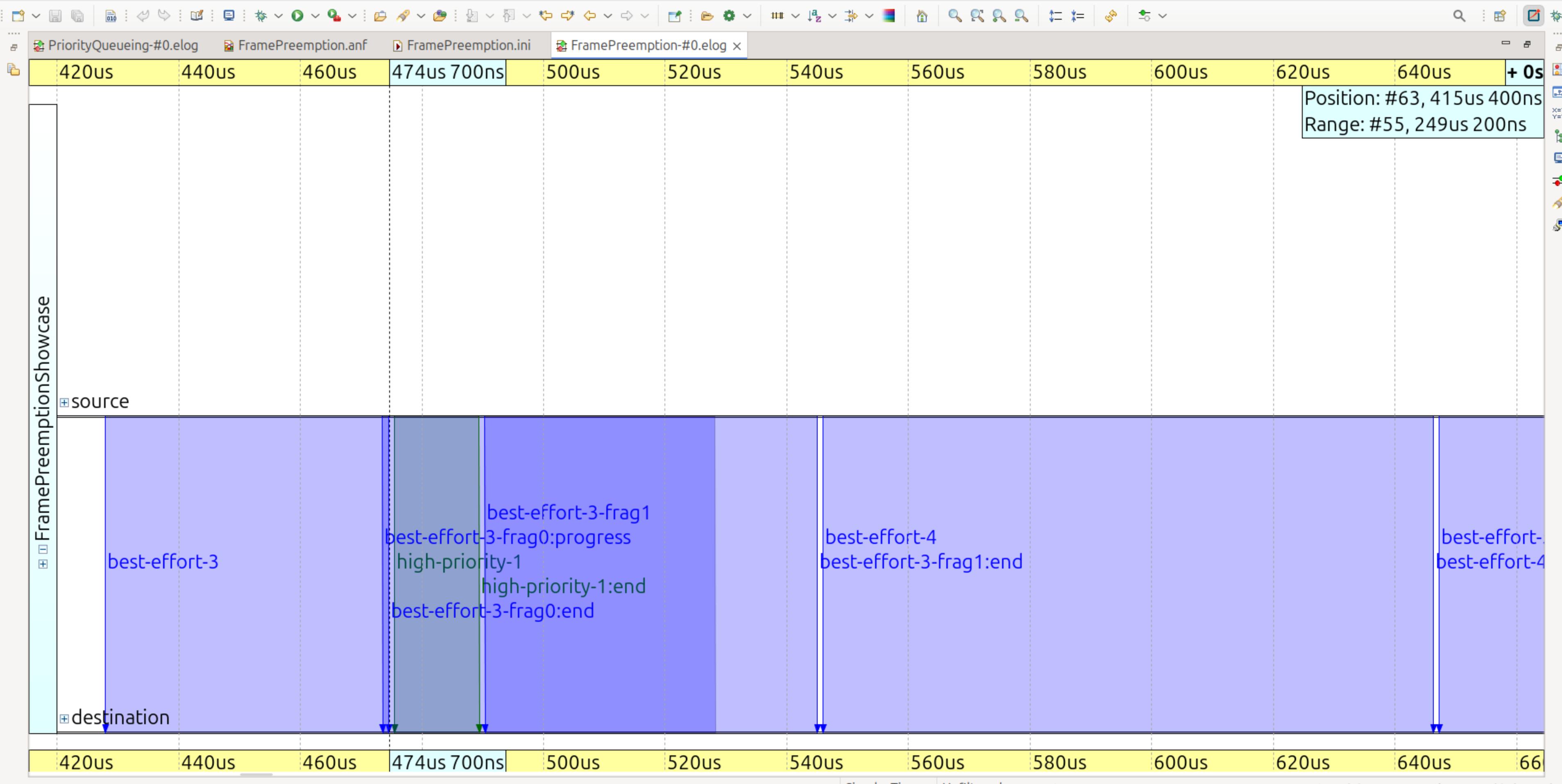
Next: Timer (inet::ClockEvent, id=

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



Zoom:1.33x

File Edit Navigate Search Project Run Window Help



File Edit Navigate Search Project Run Window Help

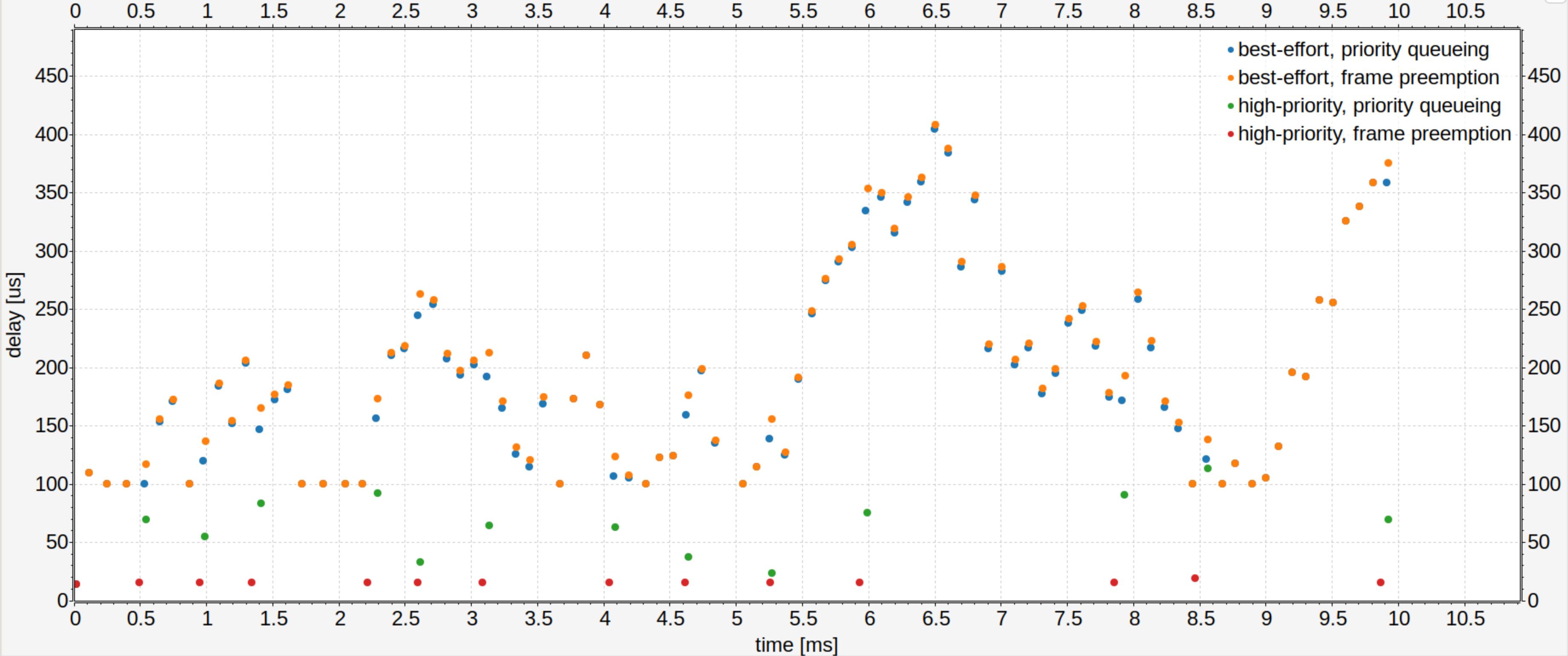


FrameReplication.ini FramePreemption.anf x

End-to-end delay comparison



mean bit life time per packet



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

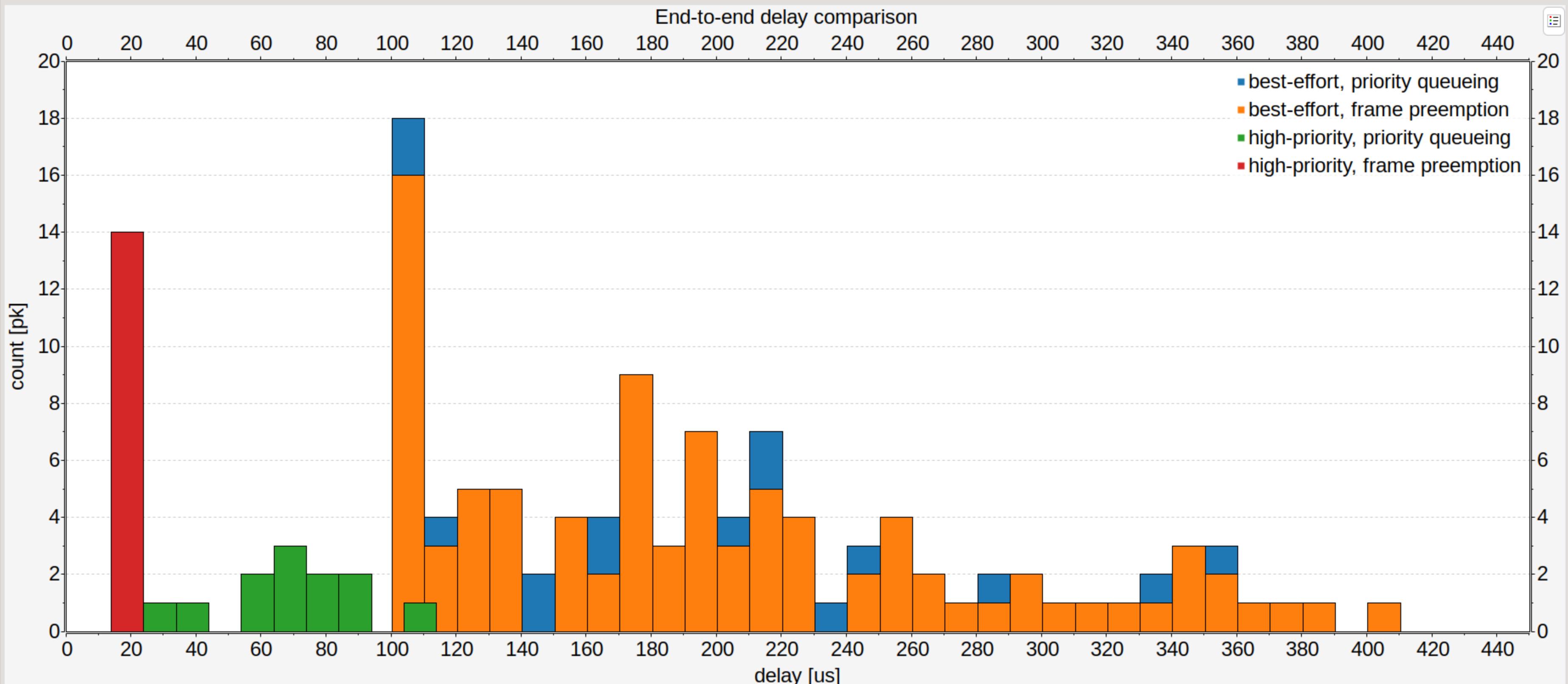
Selected: Chart 'End-to-end delay comparison'

Codeium | Show Chat

File Edit Navigate Search Project Run Window Help

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

End-to-end delay comparison



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

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

Codeium: No comple...erated | Show Chat

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

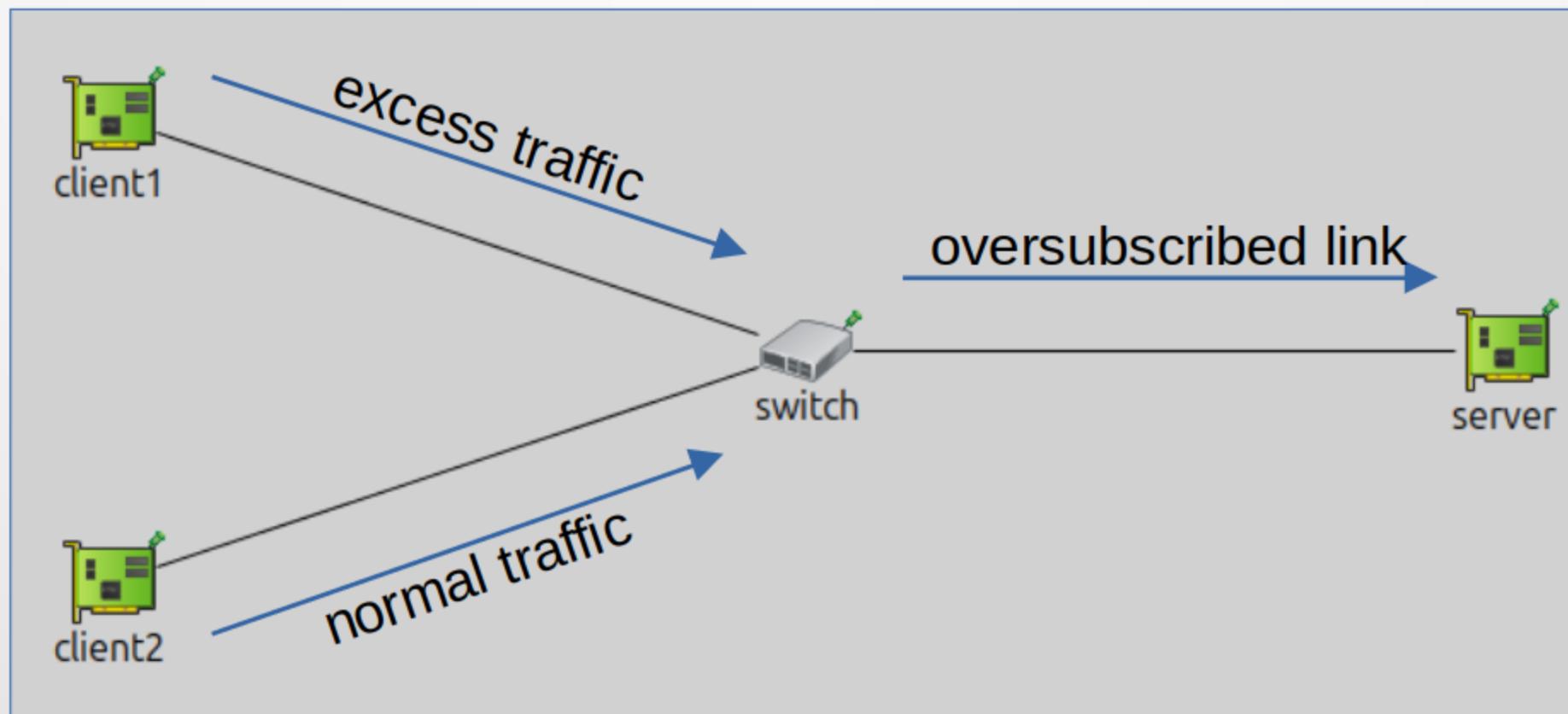
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Incoming Excess Traffic

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



File Edit Source Navigate Search Project Run Window Help



StreamFiltering.ini x

```
1 [General]
2 abstract = true
3 network = StreamFilteringShowcase
4 sim-time-limit = 1s
5 result-dir = "results/wip"
6
7 # configure Ethernet speed
8 *.*.eth[*].bitrate = 100Mbps
9
10 # configure client applications
11 *.client*.numApps = 1
12 *.client*.app[*].typename = "UdpSourceApp"
13 *.client1.app[0].display-name = "excess traffic"
14 *.client2.app[0].display-name = "normal traffic"
15 *.client*.app[*].io.destAddress = "server"
16 *.client1.app[0].io.destPort = 1000
17 *.client2.app[0].io.destPort = 1001
18 *.client1.app[0].io.displayStringTextFormat = "{numSent} excess traffic"
19 *.client2.app[0].io.displayStringTextFormat = "{numSent} normal traffic"
20
21 # configure excess traffic stream from ~40Mbps to ~110Mbps
22 *.client1.app[0].source.packetLength = 1000B
23 *.client1.app[0].source.productionInterval = 200us + replaceUnit(sin(dropUnit(simTime()) * 10)), "ms") / 8
24
25 # configure normal traffic stream ~20Mbps
26 *.client2.app[0].source.packetLength = 500B
27 *.client2.app[0].source.productionInterval = 250us
28
29 # configure server applications
```

Form Source

Writable

Insert

1:1:0

Codeium: No comple...erated | Show Chat

File Simulate Inspect View Help



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

Next: n/a

In: n/a

At: n/a

- StreamFilteringShowcase
- simulation.scheduled-e

StreamFilteringShowcase

visualizer

5526 excess traffic



4000 normal traffic



5524 excess traffic

configurator

4001 normal traffic



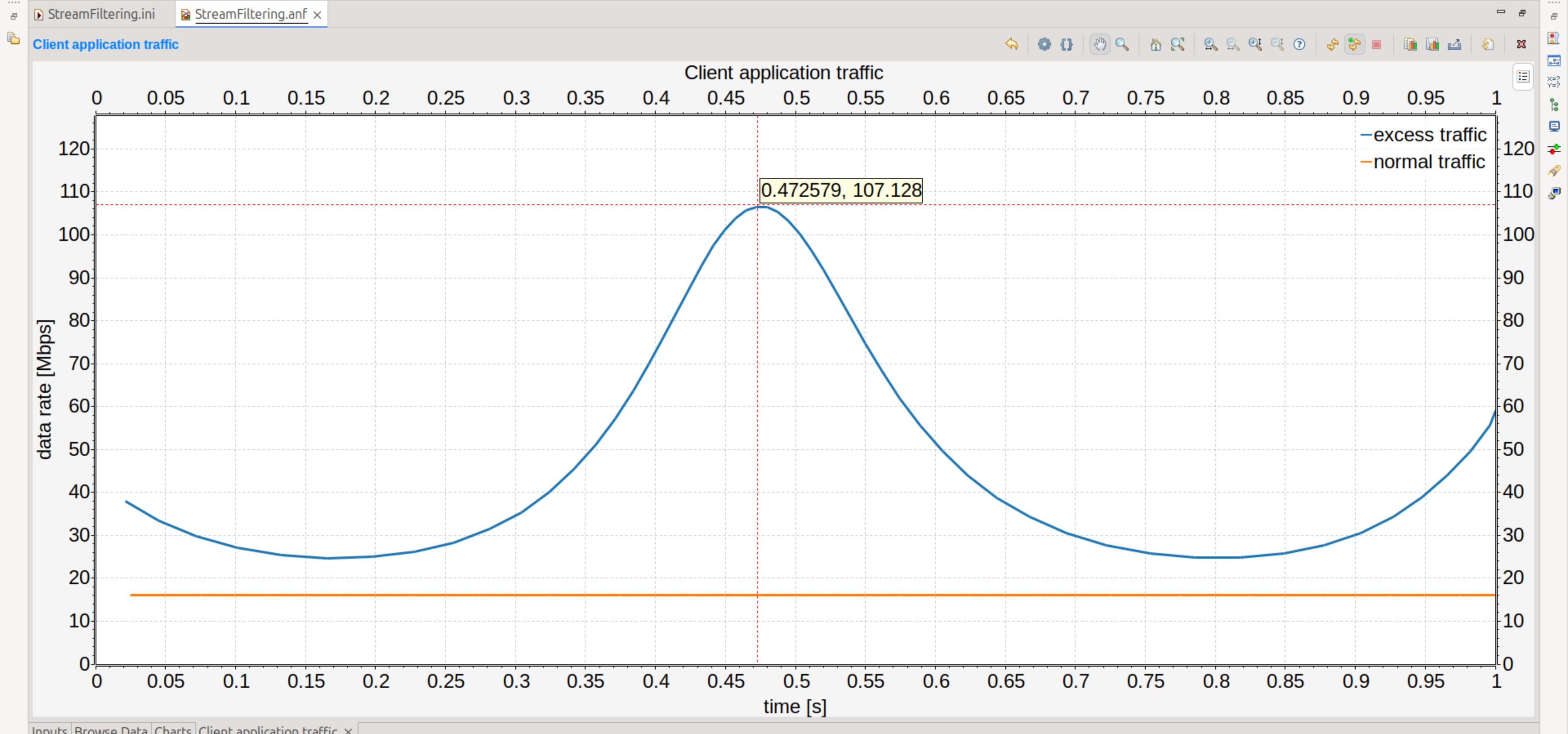
macForwardingTableConfigurator



- StreamFilteringShowcase
 - displayStringTextFor
 - hasGlobalArp (cPar)
- visualizer (Integrated)
- configurator (Ipv4Ne
- macForwardingTable
- client1 (TsnDevice) id
- client2 (TsnDevice) id
- switch (TsnSwitch) id
- server (TsnDevice) id

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	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	(UNKNOWN) 100
#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) 100
#1739	0.010'250	client2 --> switch	normal traffic-41	10.0.0.2:1025	10.0.0.3:1001 UDP		554 B	(UNKNOWN) 500
#1750	0.010'294'370	switch --> server	normal traffic-41	10.0.0.2:1025	10.0.0.3:1001 UDP		554 B	(UNKNOWN) 500
#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) 100
#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) 100
#1785	0.010'500	client2 --> switch	normal traffic-42	10.0.0.2:1025	10.0.0.3:1001 UDP		554 B	(UNKNOWN) 500

File Edit Navigate Search Project Run Window Help

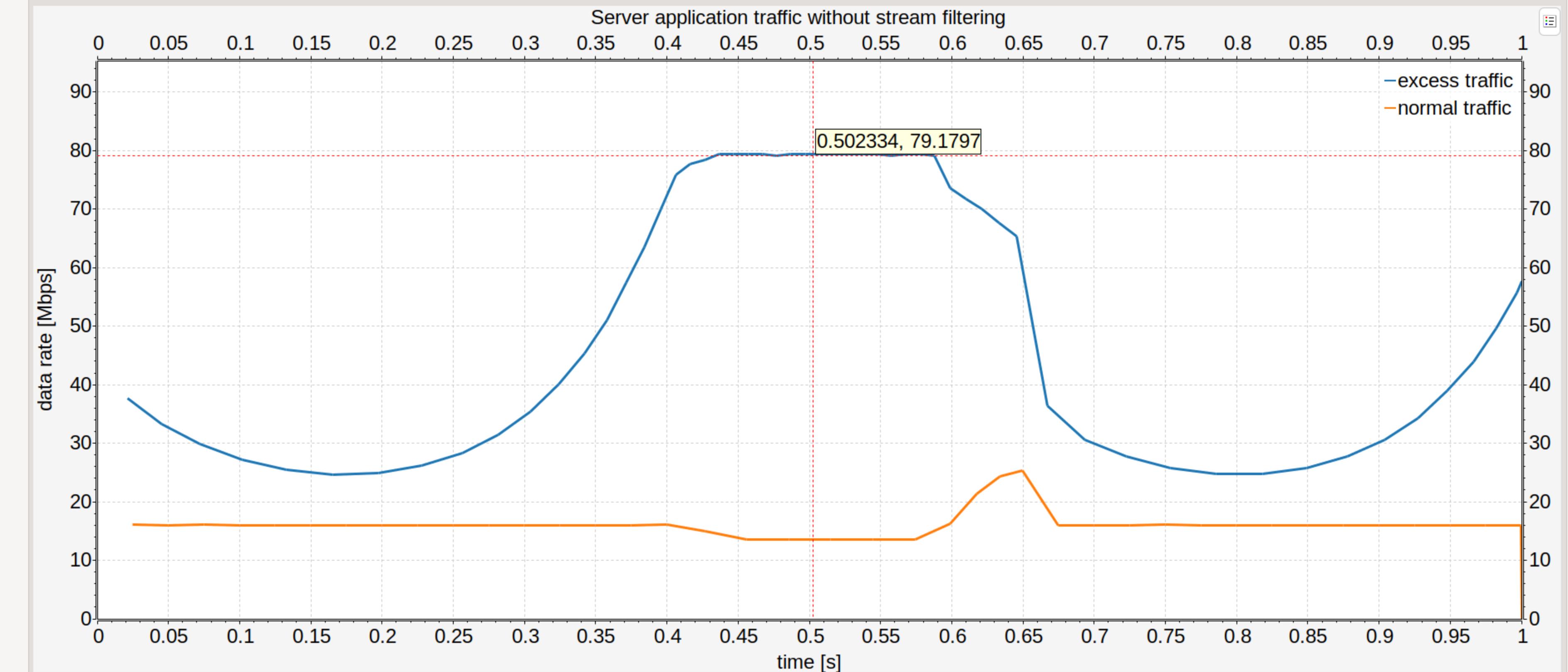


File Edit Navigate Search Project Run Window Help



StreamFiltering.ini StreamFiltering.anf x

Server application traffic without stream filtering



Inputs Browse Data Charts Client application traffic

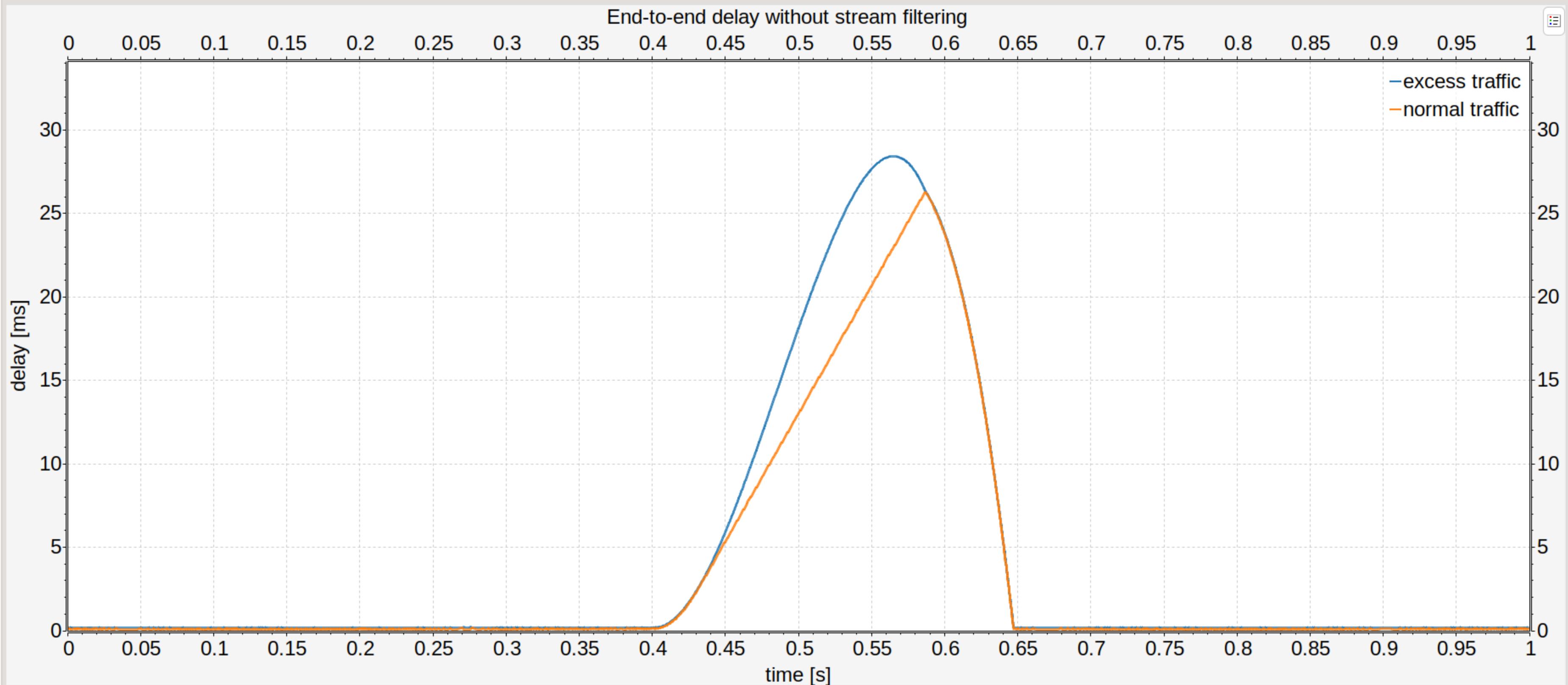
Server application traffic without stream filtering x

File Edit Navigate Search Project Run Window Help



StreamFiltering.ini StreamFiltering.anf x

End-to-end delay without stream filtering



Inputs Browse Data Charts Client application traffic

Server application traffic without stream filtering

End-to-end delay without stream filtering x

Per-Stream Filtering

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



File Edit Source Navigate Search Project Run Window Help



```
StreamFiltering.ini x 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

File Edit Source Refactor Navigate Search Project Run Window Help



```
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

```
14
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_F
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 }
```

File Simulate Inspect View Help



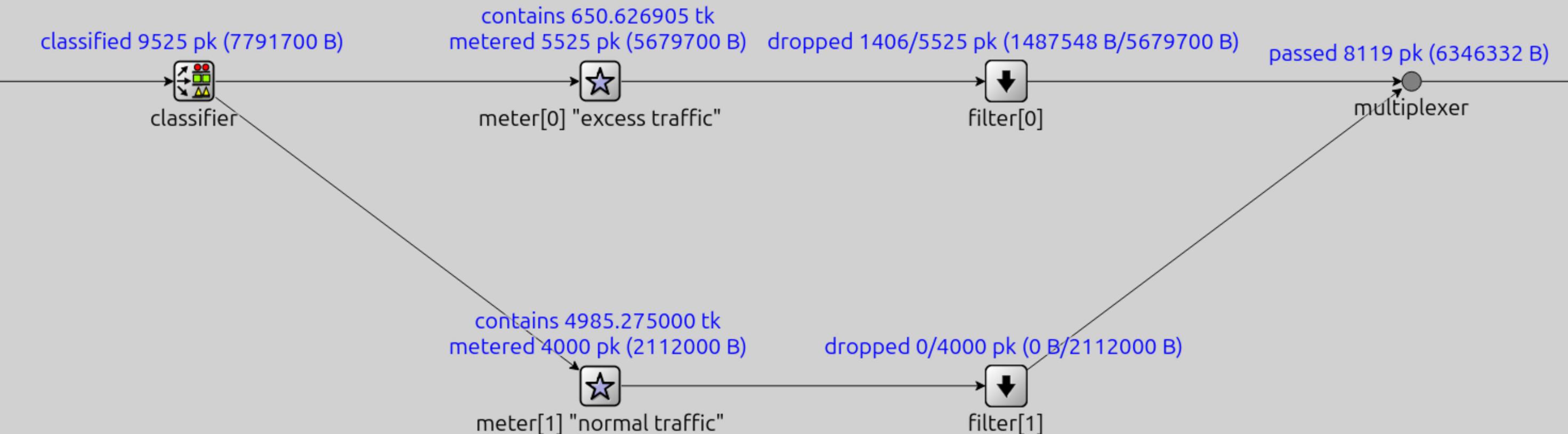
next: #188 339 | 1s 000ms 000us 000ns 000ps

Next: n/a

In: n/a

At: n/a

StreamFilteringShowcase
simulation.scheduled-eve



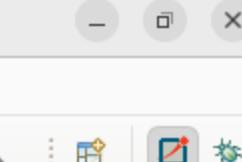
pa

StreamFilteringShowcase
builtInAnimationsAllowe
canvas = nullptr (omnetpp
className = 'omnetpp::c
componentType (cDyna
displayName = " [...]" (str
displayString = p=200,10
fullName = 'ingress' (str
fullPath = 'StreamFilterin
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' [...] (str

Zoom:1.90x

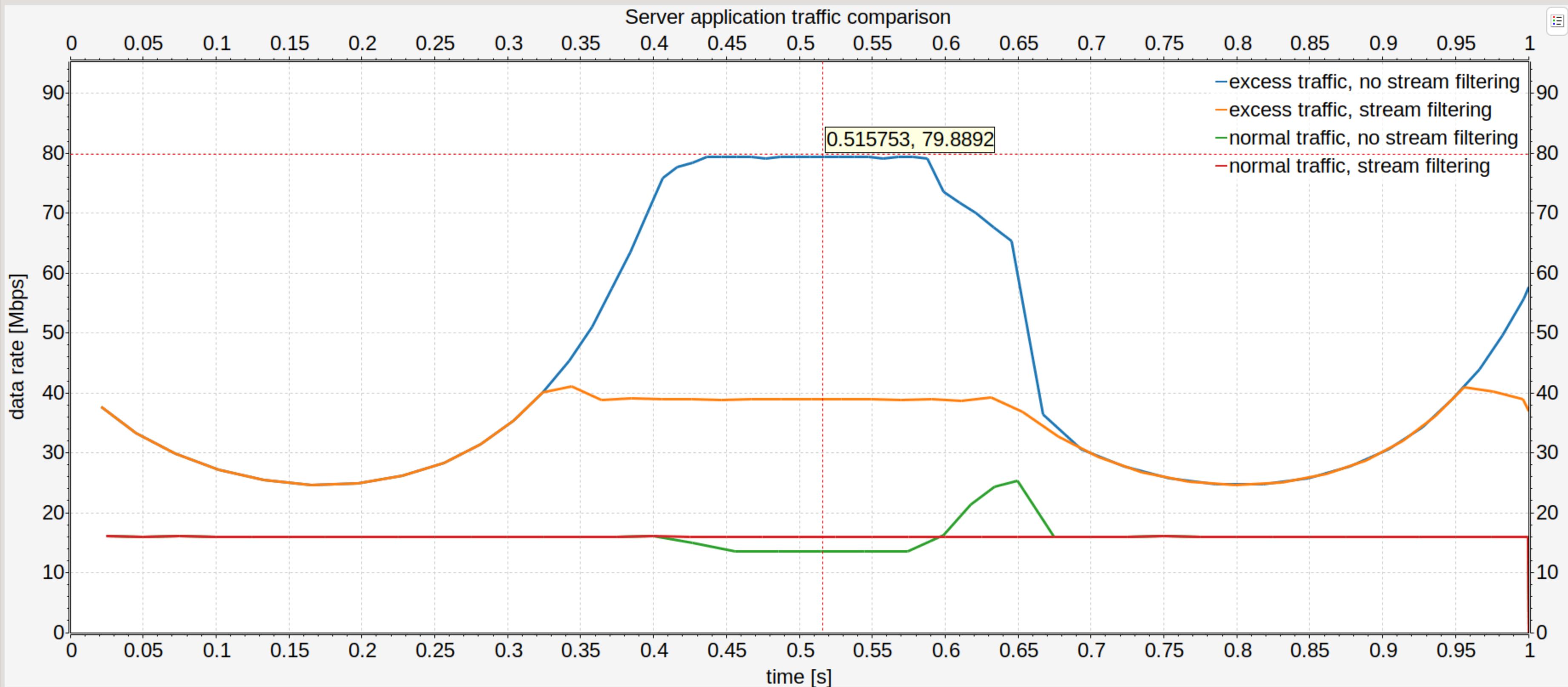
Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	Type	Length	Info
#9209	0.051'794'690	multiplexer --> barrier	normal traffic-207	10.0.0.2:1025	10.0.0.3:1001 UDP		528 B	
#9269	0.051'794'690	barrier --> .	normal traffic-207	10.0.0.2:1025	10.0.0.3:1001 UDP		528 B	
#9287	0.051'857'734'509	. --> 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)

File Edit Navigate Search Project Run Window Help



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

Server application traffic comparison



Inputs Browse Data Charts Client application traffic

Server application traffic without stream filtering

End-to-end delay without stream filtering

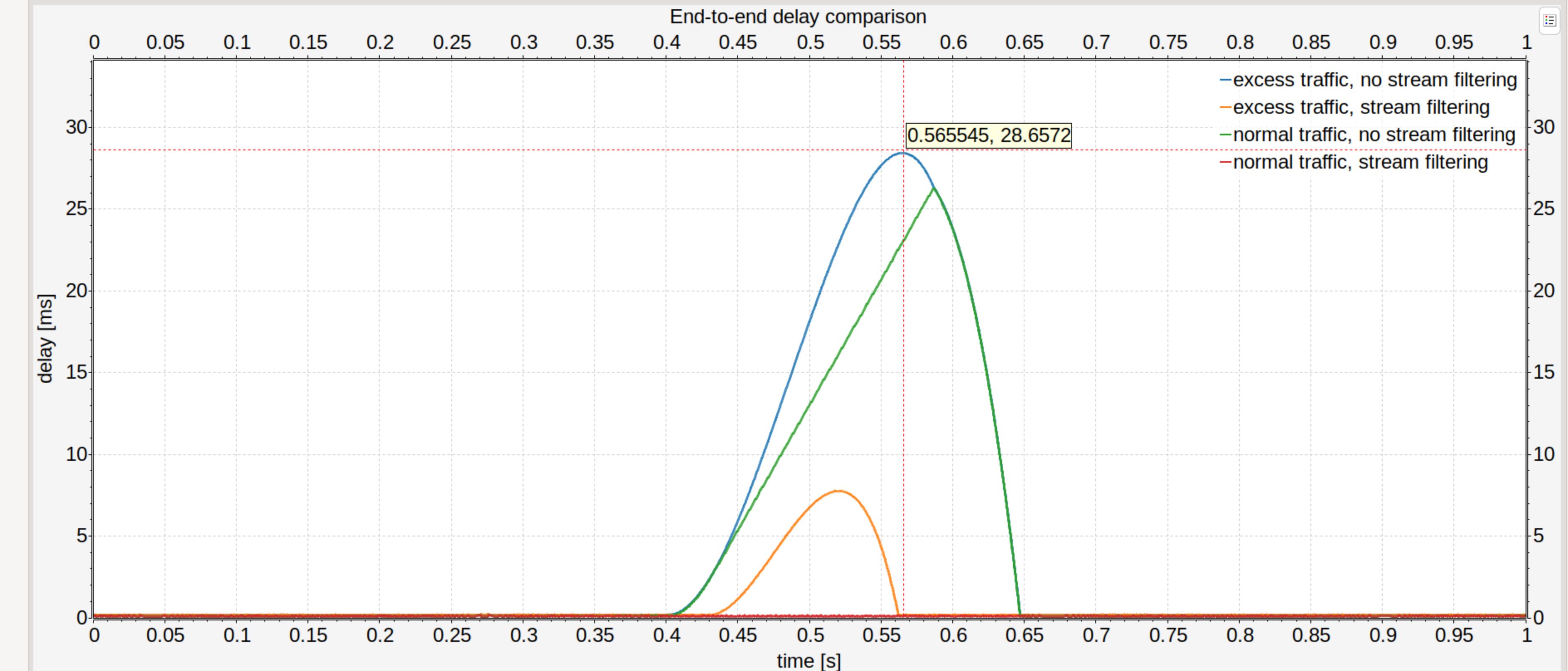
Server application traffic comparison

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'

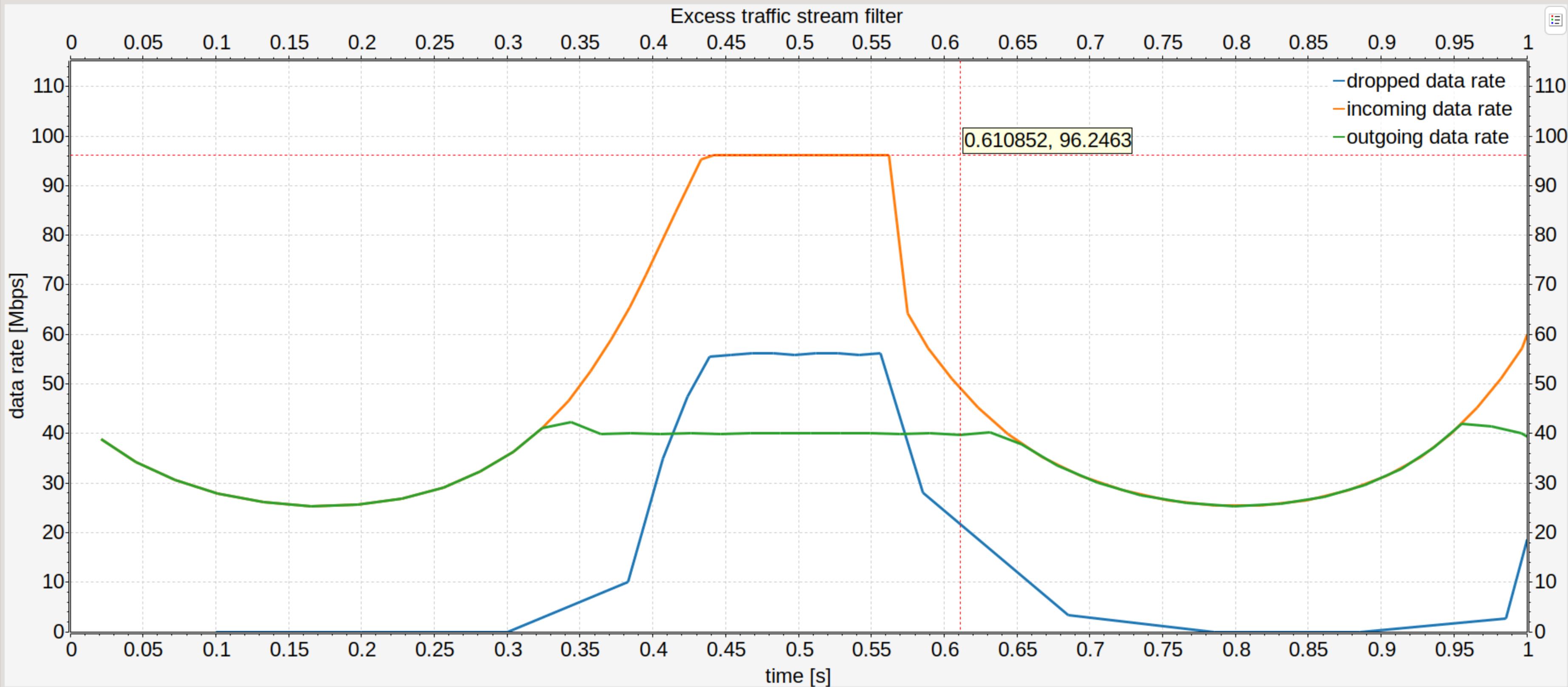
Codeium: No comple...erated | Show Chat

File Edit Navigate Search Project Run Window Help



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

Excess traffic stream filter



Inputs Browse Data Charts Client application traffic

Server application traffic without stream filter...

End-to-end delay without stream filtering

Server application traffic comparison

End-to-end delay comparison

Excess traffic stream filter

Selected: Chart 'Excess traffic stream filter'

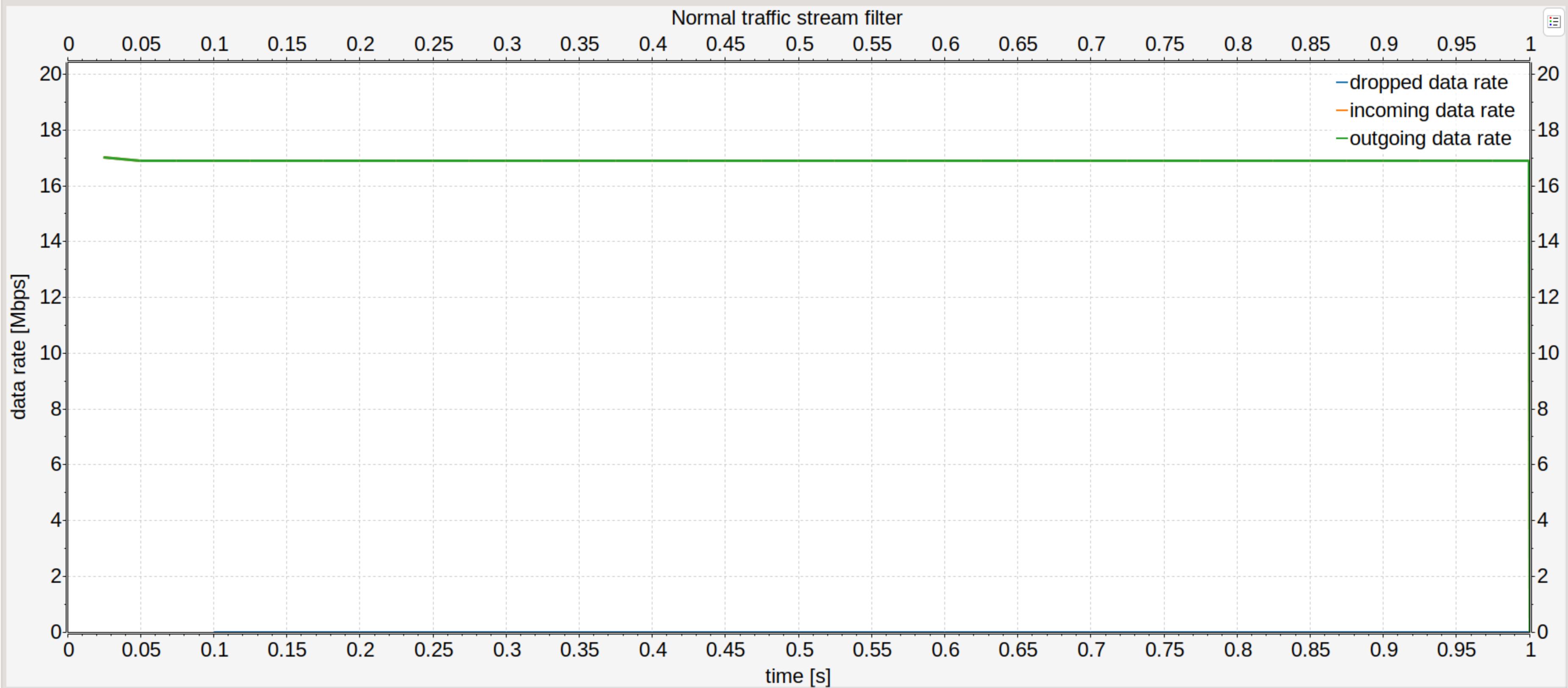
Codeium: No comple...erated | Show Chat

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

Selected: Chart 'Normal traffic stream filter'

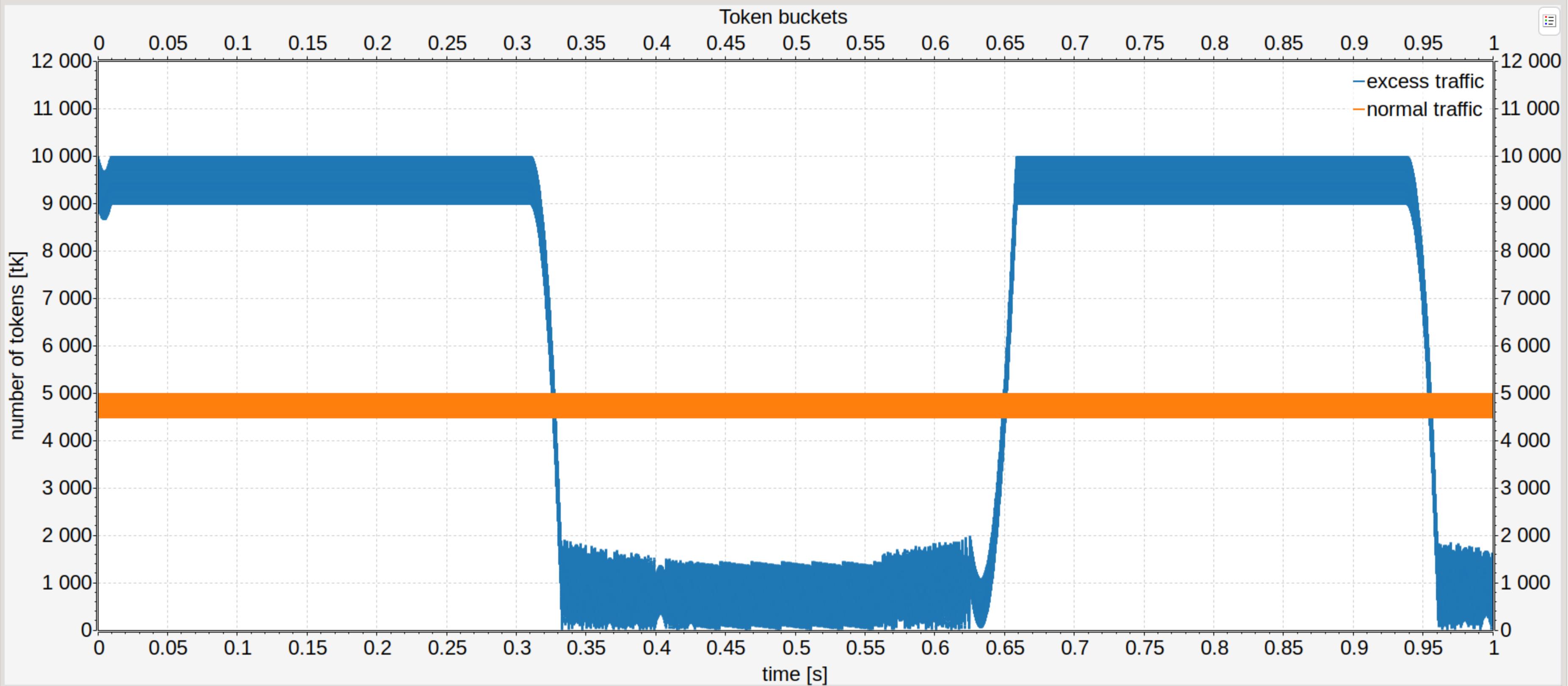
Codeium: No comple...erated | Show Chat

File Edit Navigate Search Project Run Window Help



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

Token buckets



Inputs Browse Data Charts Client application traffic... Server application traffic... End-to-end delay without... Server application traffic... End-to-end delay compar... Excess traffic stream fil... Normal traffic stream fil... Token buckets X

Selected: Chart 'Token buckets'

Codeium: No comple...erated | Show Chat

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

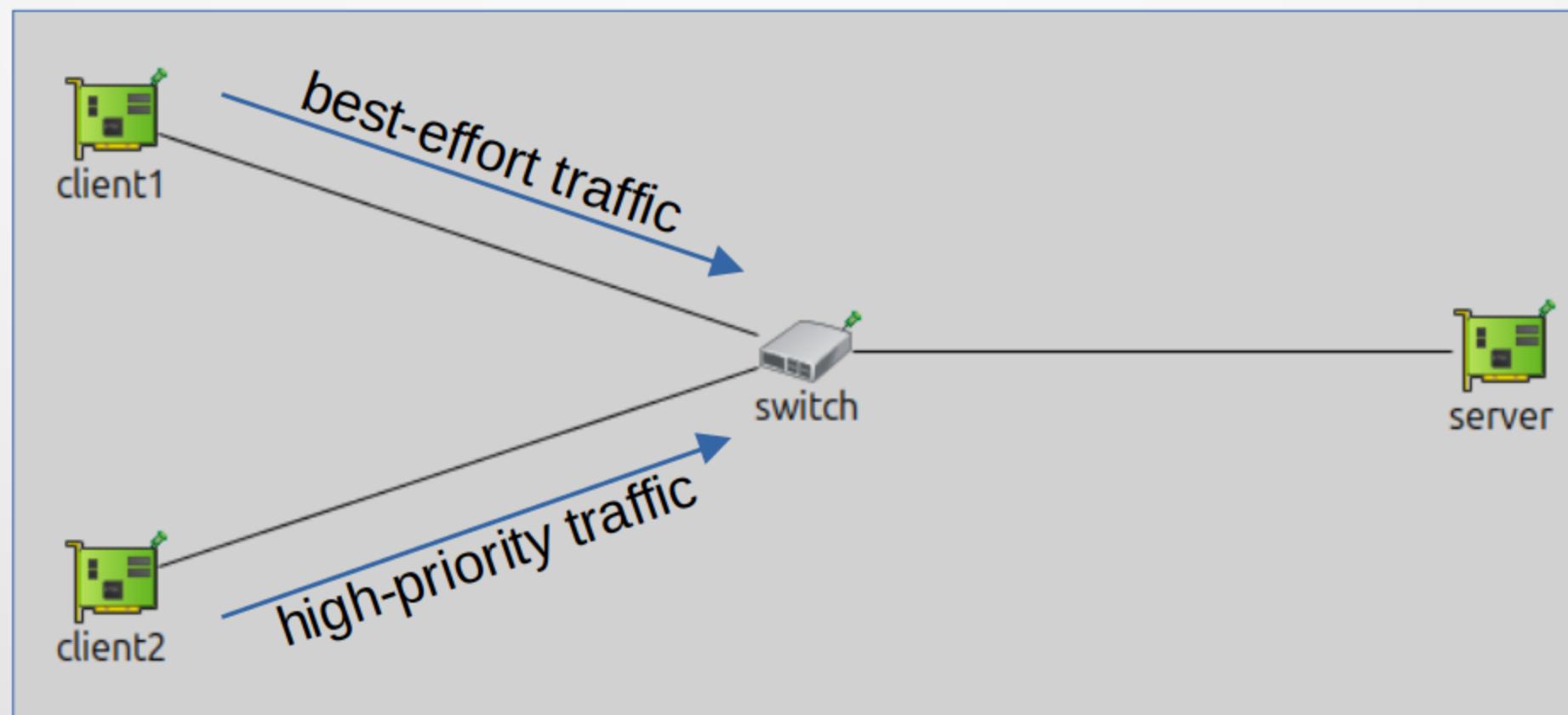
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Outgoing Traffic Contention

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



File Edit Source Navigate Search Project Run Window Help



TrafficShaping.ini x

```
7
8 # configure Ethernet speed
9 *.*.eth[*].bitrate = 100Mbps
10
11 # configure client applications
12 *.client*.numApps = 1
13 *.client*.app[*].typename = "UdpSourceApp"
14 *.client1.app[0].display-name = "best-effort"
15 *.client2.app[0].display-name = "high-priority"
16 *.client*.app[*].io.destAddress = "server"
17 *.client1.app[0].io.destPort = 1000
18 *.client2.app[0].io.destPort = 1001
19 *.client1.app[0].io.displayStringTextFormat = "{numSent} best-effort"
20 *.client2.app[0].io.displayStringTextFormat = "{numSent} high-priority"
21 *.client1.app[0].source.packetLength = 1500B - 54B # 54B = 8B (UDP) + 20B (IP) + 14B (ETH MAC) + 4B (ETH FCS) + 8B (ETH PHY)
22 *.client2.app[0].source.packetLength = 64B - 54B # 54B = 8B (UDP) + 20B (IP) + 14B (ETH MAC) + 4B (ETH FCS) + 8B (ETH PHY)
23 *.client1.app[0].source.productionInterval = exponential(200us) # ~60 Mbps
24 *.client2.app[0].source.productionInterval = 1ms # ~512 kbps
25
26 # configure server applications
27 *.server.numApps = 2
28 *.server.app[*].typename = "UdpSinkApp"
29 *.server.app[0].display-name = "best-effort"
30 *.server.app[1].display-name = "high-priority"
31 *.server.app[0].io.localPort = 1000
32 *.server.app[1].io.localPort = 1001
33 *.server.app[0].io.displayStringTextFormat = "{numReceived} best-effort"
34 *.server.app[1].io.displayStringTextFormat = "{numReceived} high-priority"
35
36 # display number of packets sent and received on network nodes
```

Form Source

Writable

Insert

1:1:0

Codeium: No comple...erated | Show Chat

File Simulate Inspect View Help



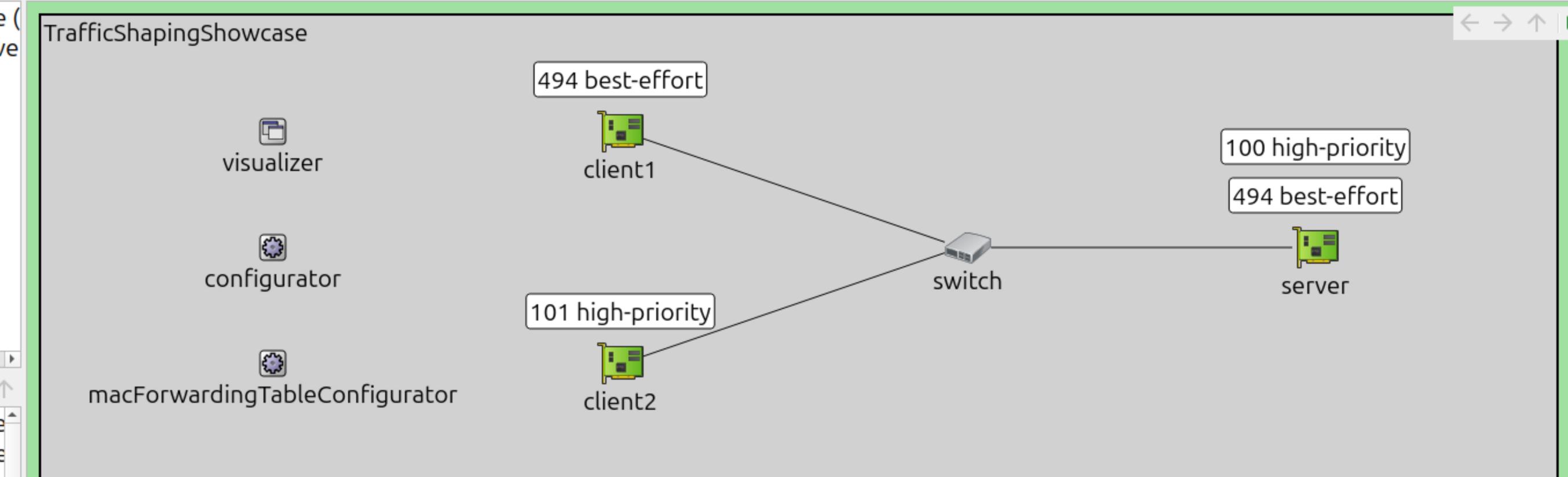
next: #11115 0s 100ms 000us 000ns 000ps

Next: n/a

In: n/a

At: n/a

- ▶ TrafficShapingShowcase (
- simulation.scheduled-eve



Zoom:1.00x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	Type	Length	Info
#11048	0.099	484 891 607	switch --> server	best-effort-490	10.0.0.1:1025	10.0.0.3:1000 UDP	1500 B	
#11050	0.099	485 801 607	client1 --> switch	best-effort-491	10.0.0.1:1025	10.0.0.3:1000 UDP	1500 B	
#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		

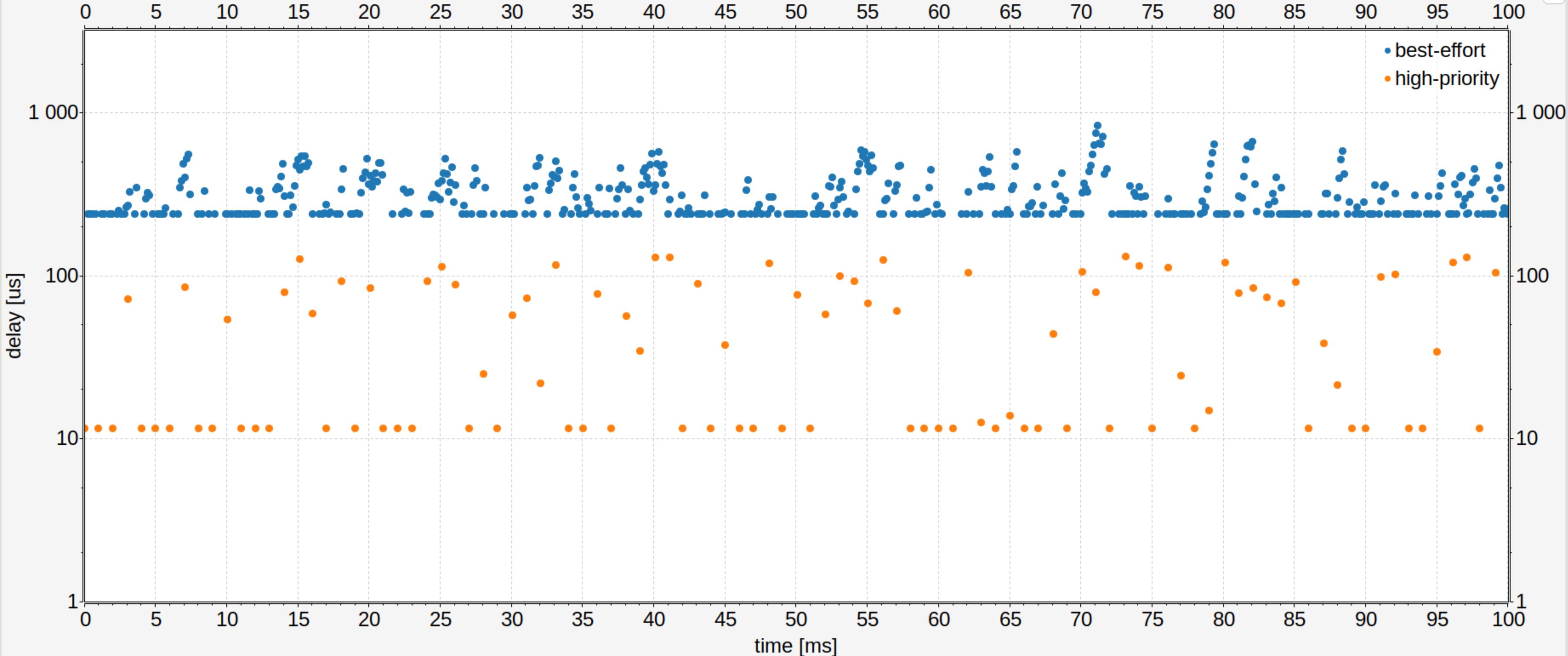
File Edit Navigate Search Project Run Window Help



TrafficShaping.ini TrafficShaping.anf x

End-to-end delay without traffic shaping

End-to-end delay without traffic shaping



Inputs Browse Data Charts End-to-end delay without traffic shaping x

Selected: Chart 'End-to-end delay without traffic shaping'

Codeium: No comple...erated | Show Chat

Time-Aware Shaping

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



File Edit Source Navigate Search Project Run Window Help



TrafficShaping.ini x TrafficShaping.anf

```
i55 *.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  
i59 *.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  
i69 *.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"  
i72 *.switch.eth[*].macLayer.queue.transmissionGate[0].initiallyOpen = false  
i73 *.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  
i78 *.visualizer.gateScheduleVisualizer.displayGateSchedules = true  
i79 *.visualizer.gateScheduleVisualizer.gateFilter = "**.eth[1].**"  
i80 *.visualizer.gateScheduleVisualizer.width = 200  
81 *.visualizer.gateScheduleVisualizer.height = 24  
82 *.visualizer.gateScheduleVisualizer.placementHint = "top"  
83
```

Form Source

File Simulate Inspect View Help



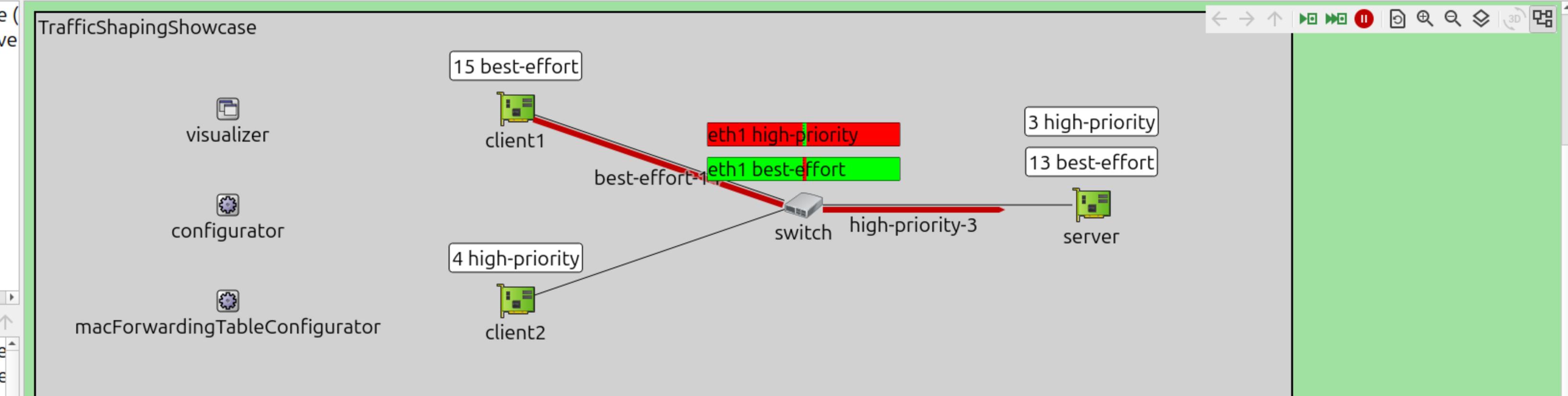
next: #397 | 0s 003ms 005us 846ns 540ps | +

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)

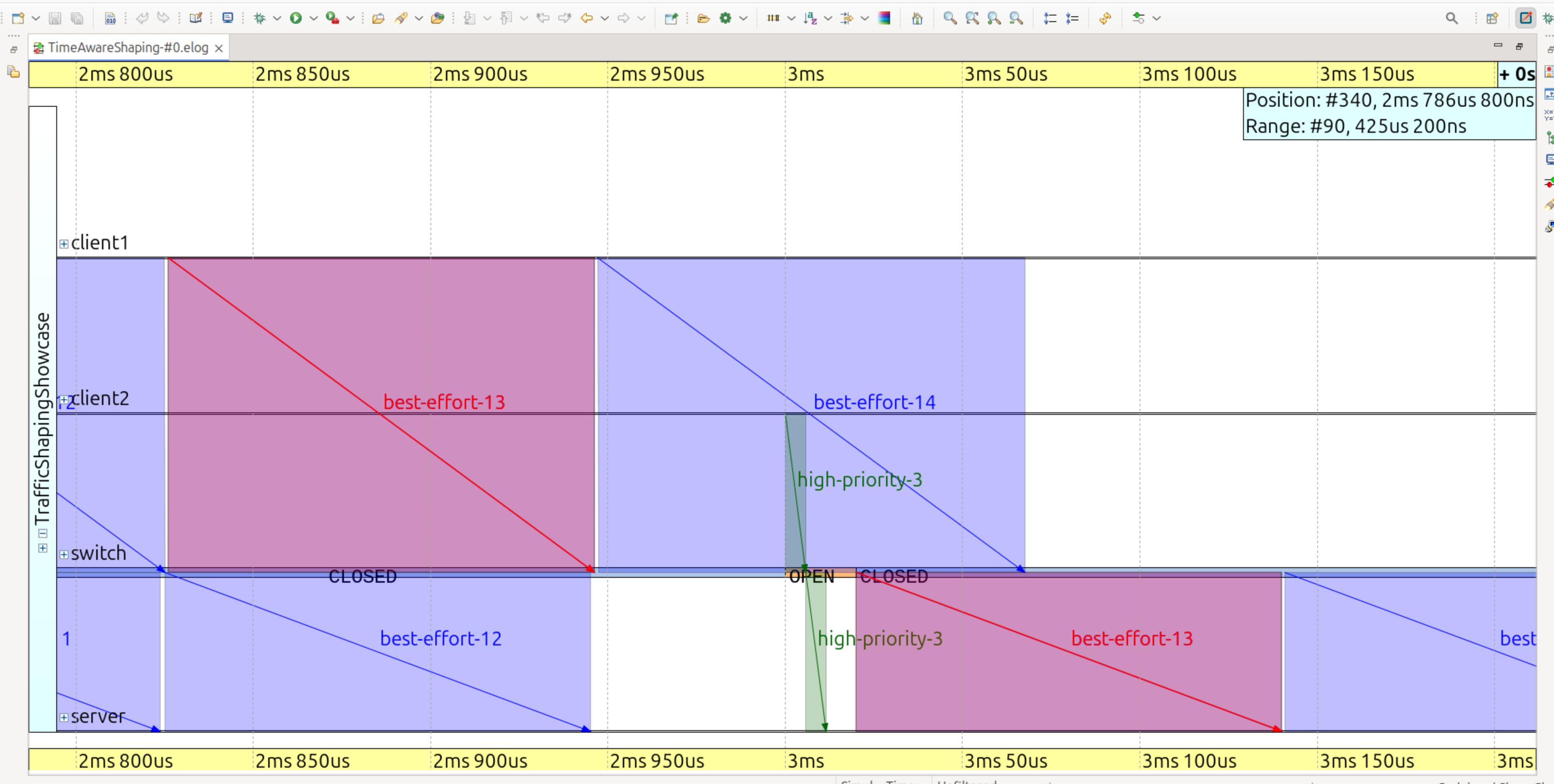


TrafficShapingShowcase
builtinAnimationsAllowe
canvas (cCanvas) canvas
className = 'inet::Netwo
componentType (cDyna
displayName = " [...] (str
displayString [...] (omne
fullName = 'TrafficShapi
fullPath = 'TrafficShapi
gates[0] (omnetpp::cGat
id = 1 (int)
index = <not a vector> (i
info = 'id=1' (string)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

Zoom:1.00x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	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)

File Edit Navigate Search Project Run Window Help



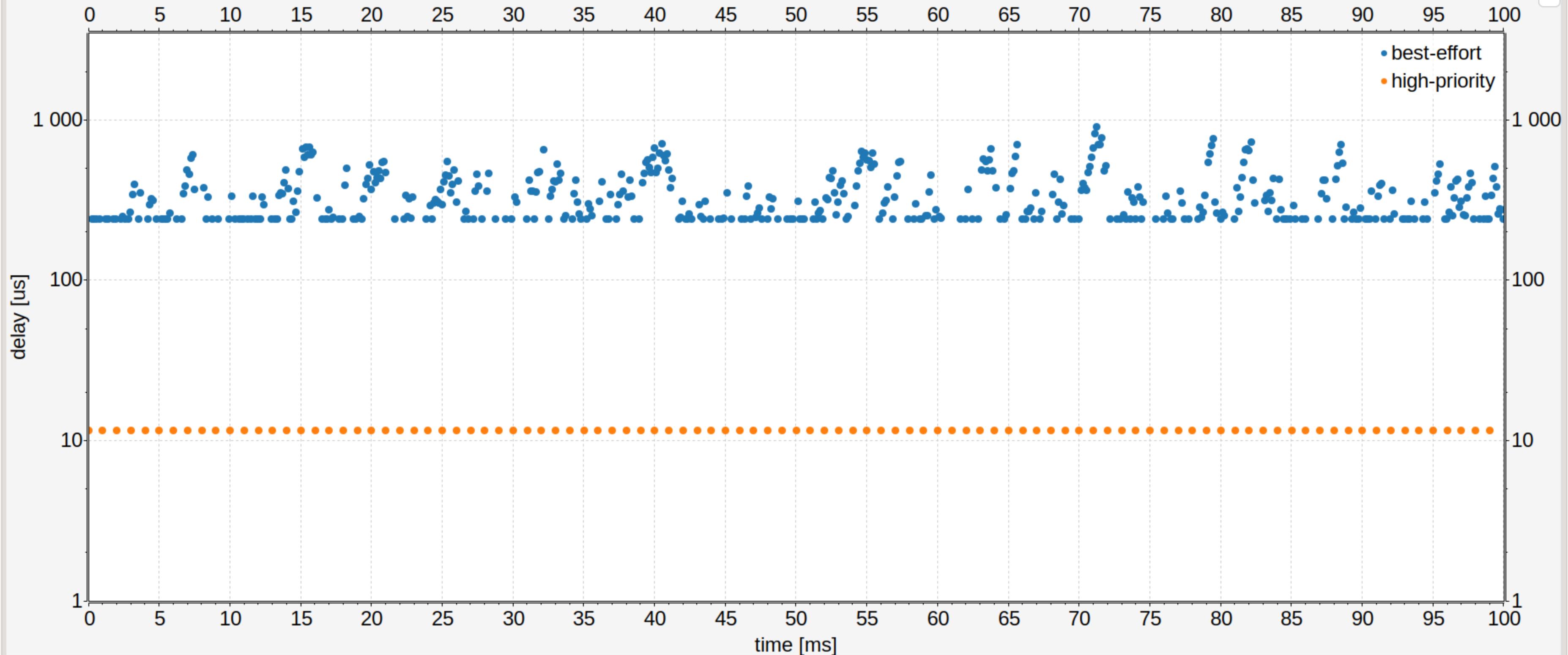
File Edit Navigate Search Project Run Window Help



TrafficShaping.ini TrafficShaping.anf x

End-to-end delay with time-aware shaping

End-to-end delay with time-aware shaping



Inputs Browse Data Charts End-to-end delay without traffic shaping

End-to-end delay with time-aware shaping x

Selected: Chart 'End-to-end delay with time-aware shaping'

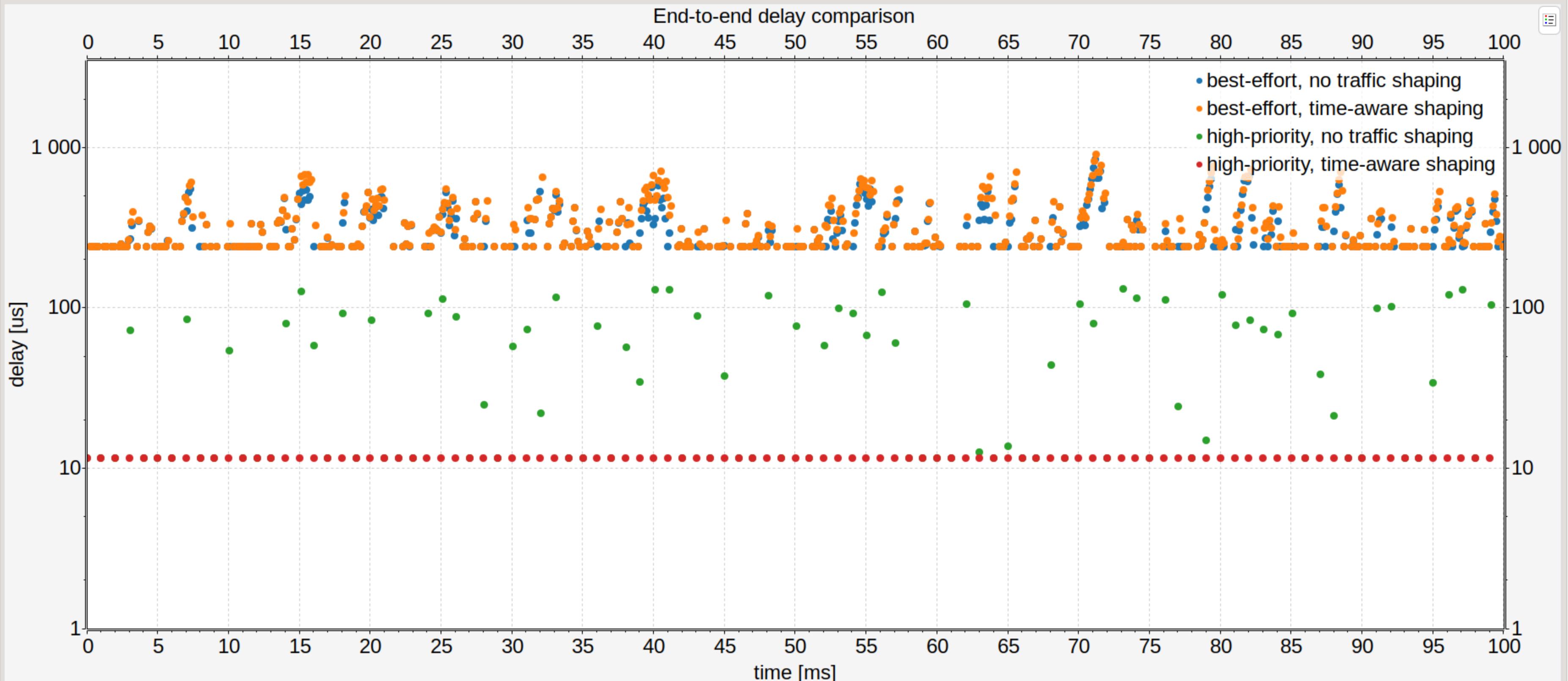
Codeium: No comple...erated | Show Chat

File Edit Navigate Search Project Run Window Help



TrafficShaping.ini TrafficShaping.anf x

End-to-end delay comparison



Inputs Browse Data Charts End-to-end delay without traffic shaping

End-to-end delay with time-aware shaping

End-to-end delay comparison x

File Edit Navigate Search Project Run Window Help

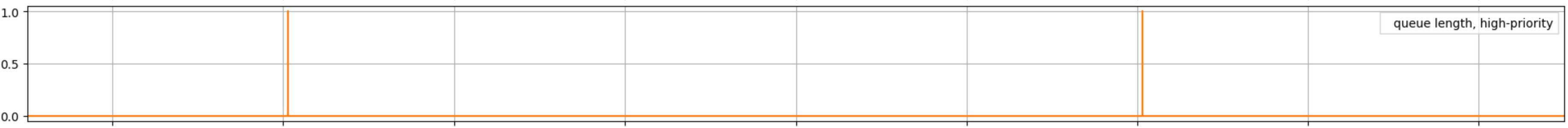


TrafficShaping.ini TrafficShaping.anf x

Queue lengths and gate states



Queue lengths and gate states



39.8 40.0 40.2 40.4 40.6 40.8 41.0 41.2 41.4

time [ms]

Inputs Browse Data Charts End-to-end delay without traffic shaping

End-to-end delay with time-aware shaping

End-to-end delay comparison

Queue lengths and gate states x

Selected: Chart 'Queue lengths and gate states'

Codeium: No comple...erated | Show Chat

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

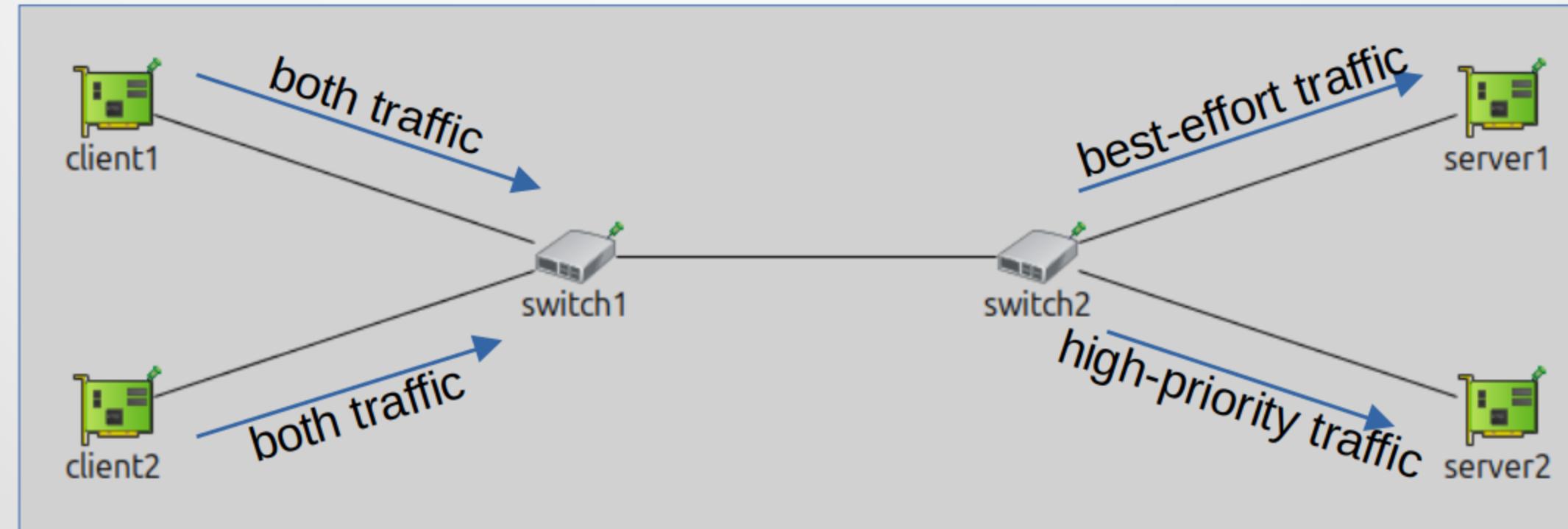
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

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



File Edit Source Navigate Search Project Run Window Help



```
GateScheduling.ini x
83 *.visualizer.introVisualizer.modules = *.client.app[1..10] OR *.server1.app[0..1].10 OR *.server2.app[2..5].10
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.eth[1].**.transmissionGate[1]"
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
```

Form Source

File Simulate Inspect View Help



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

Next: n/a

In: n/a

At: n/a

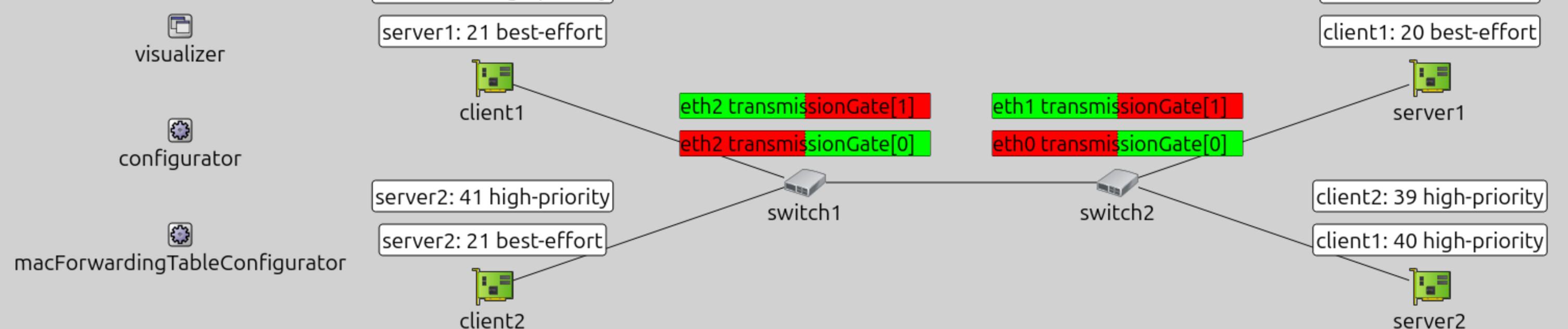
[]

[]

- GateSchedulingShowcase
- simulation.scheduled-eve

[]

GateSchedulingShowcase



visualizer

configurator

macForwardingTableConfigurator

Zoom:1.00x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	Type	Length	Info
#3390	0.009' 800	switch1 --> server1	client1-best-effort-19	10.0.0.1:1025	10.0.0.3:1000 UDP		1058 B	
#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)

File Simulate Inspect View Help



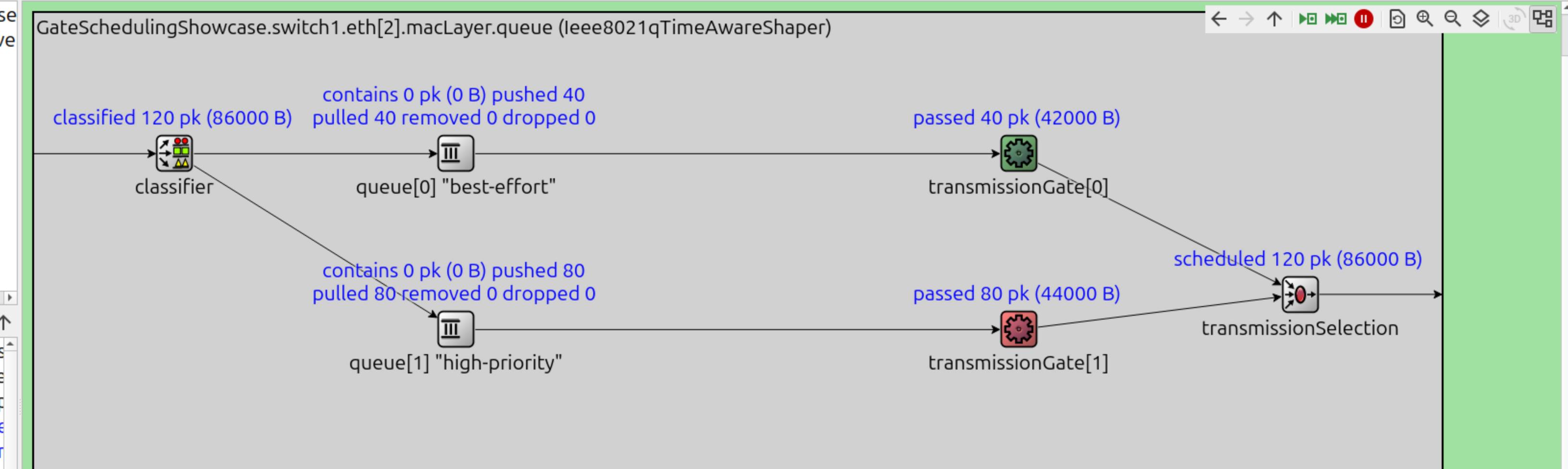
next: #3 474 | 0s 010ms 000us 000ns 000ps

Next: n/a

In: n/a

At: n/a

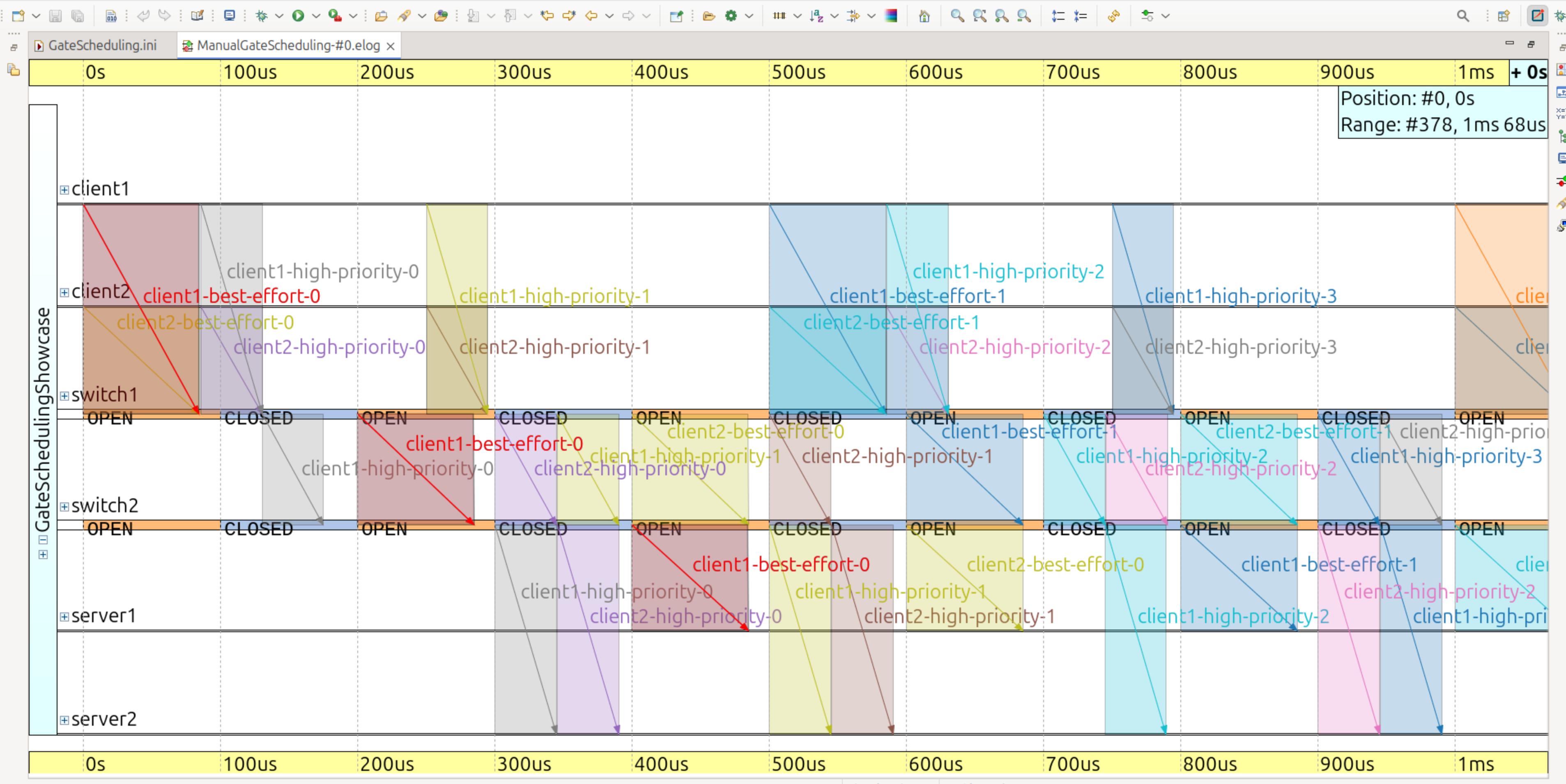
► GateSchedulingShowcase
● simulation.scheduled-eve



Zoom:1.46x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	Type	Length	Info
#3395	0.009'800	transmissionSelection --> transmissionSelection	client2-best-effort-19	10.0.0.2:1025	10.0.0.3:1001	UDP	1050	L
#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	(UNKNOWN)
#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	(UNKNOWN)
#3429	0.009'945'600	transmissionSelection --> .	client2-high-priority-39	10.0.0.2:1026	10.0.0.4:1003	UDP	550 B	(UNKNOWN)

File Edit Navigate Search Project Run Window Help



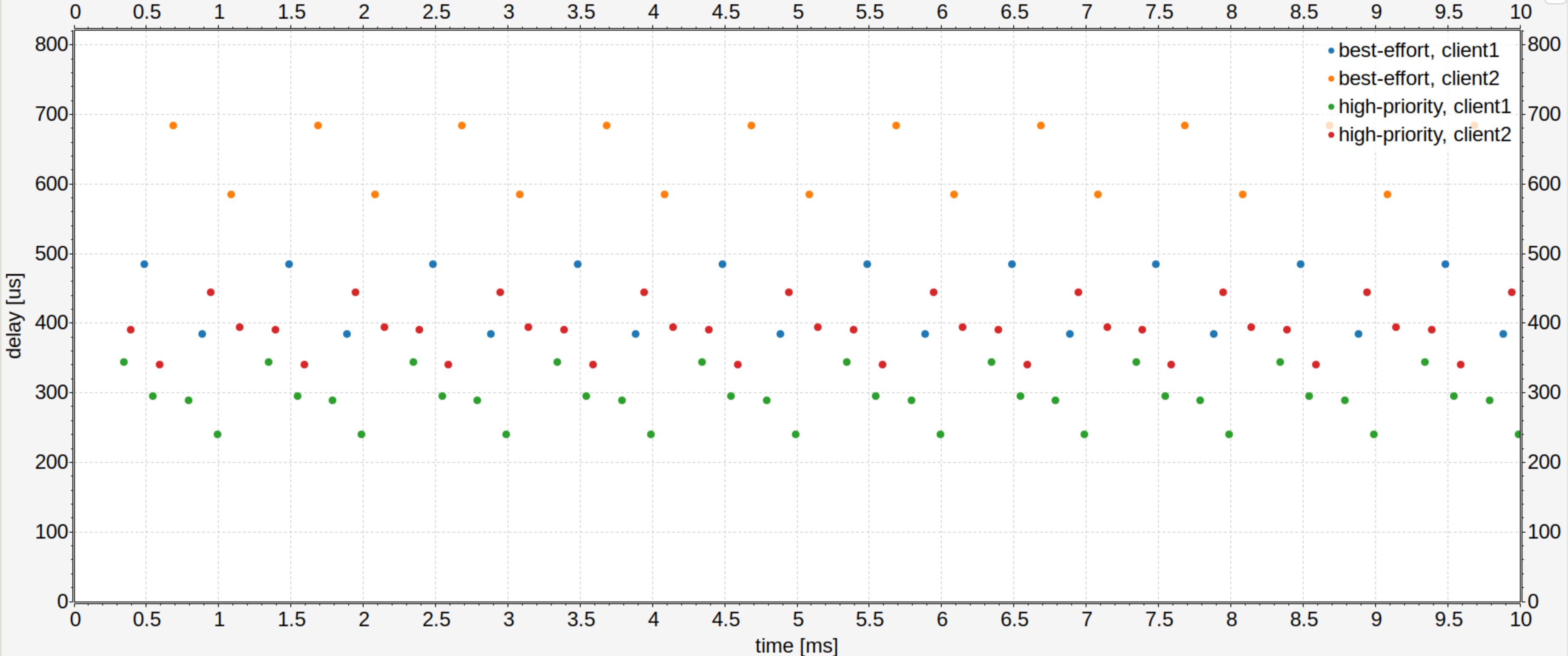
File Edit Navigate Search Project Run Window Help



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

Manual gate scheduling end-to-end delay

Manual gate scheduling end-to-end delay



Inputs Browse Data Charts Manual gate scheduling end-to-end delay x

Selected: Chart 'Manual gate scheduling end-to-end delay'

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

File Edit Source Navigate Search Project Run Window Help



```
GateScheduling.ini x 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, packetI
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, packetI
120 ... {pcp: 4, gateIndex: 1, application: "app[1]", source: "client2", destination: "server2", packetLength: 500B + 58B, packetI
121
```

Form Source

File Simulate Inspect View Help



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

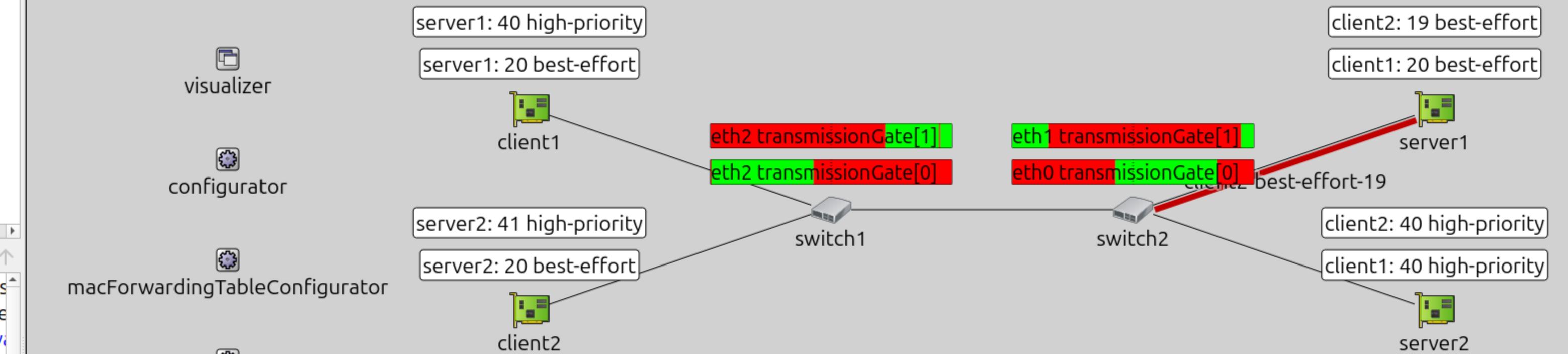
Next: n/a

In: n/a

At: n/a

► GateSchedulingShowcase
● simulation.scheduled-eve

GateSchedulingShowcase



visualizer

configurator

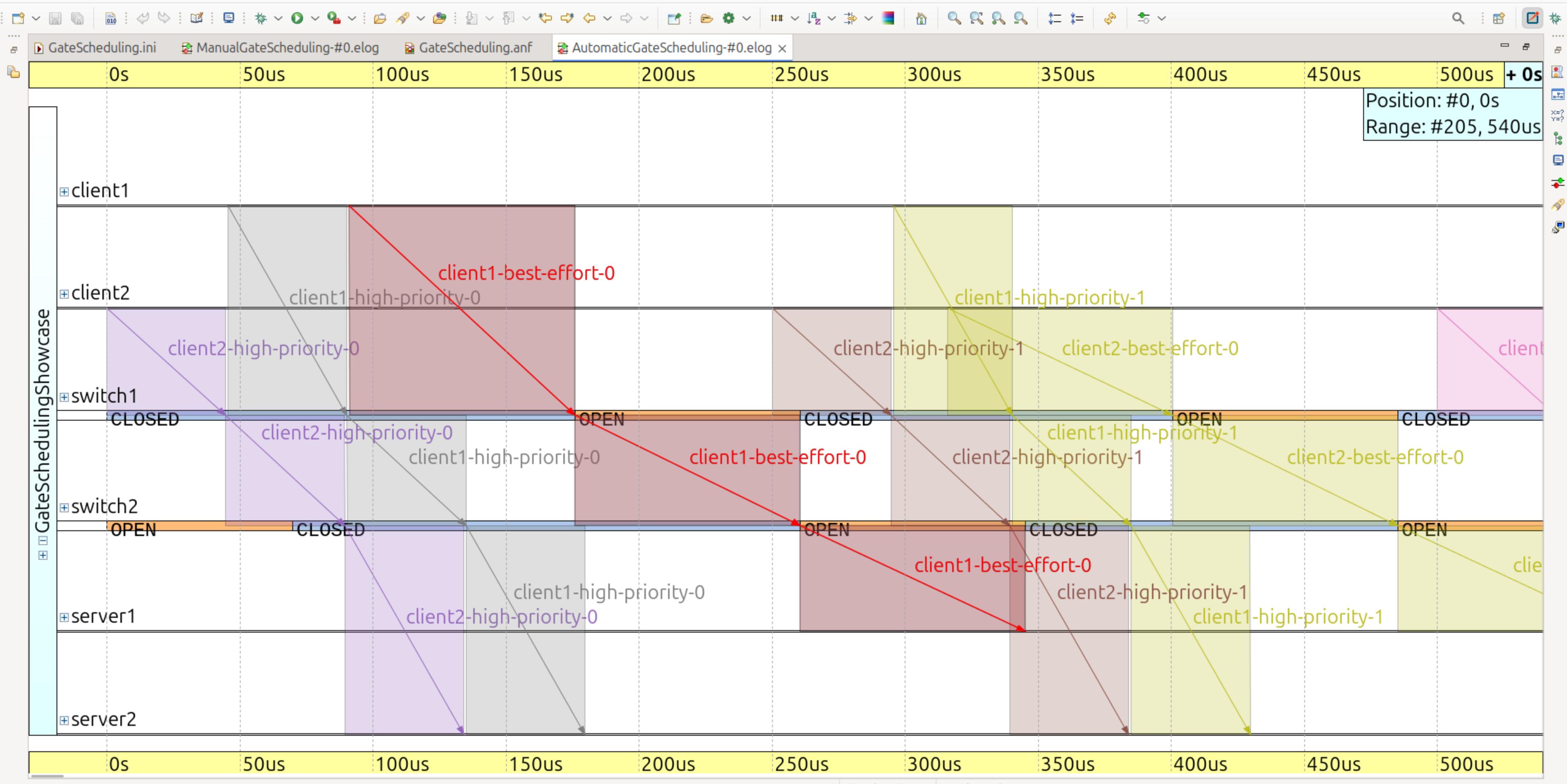
macForwardingTableConfigurator

gateScheduleConfigurator

Zoom:1.00x

Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	Type	Length	Info
#3472	0.009'795'000	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)

File Edit Navigate Search Project Run Window Help



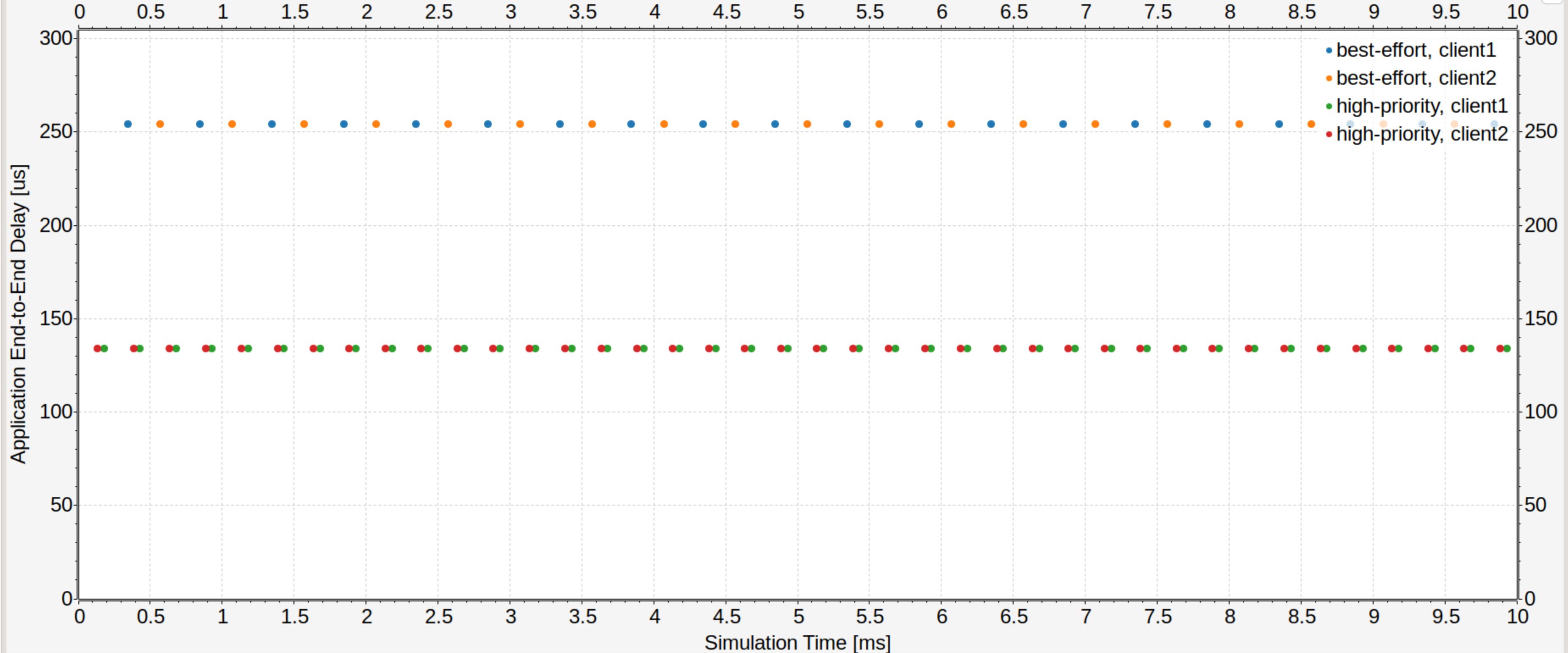
File Edit Navigate Search Project Run Window Help



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

Automatic gate scheduling end-to-end delay

Application End-to-End Delay



Inputs Browse Data Charts Manual gate scheduling end-to-end delay

Automatic gate scheduling end-to-end delay x

Selected: Chart 'Automatic gate scheduling end-to-end delay'

Codeium: No comple...erated | Show Chat

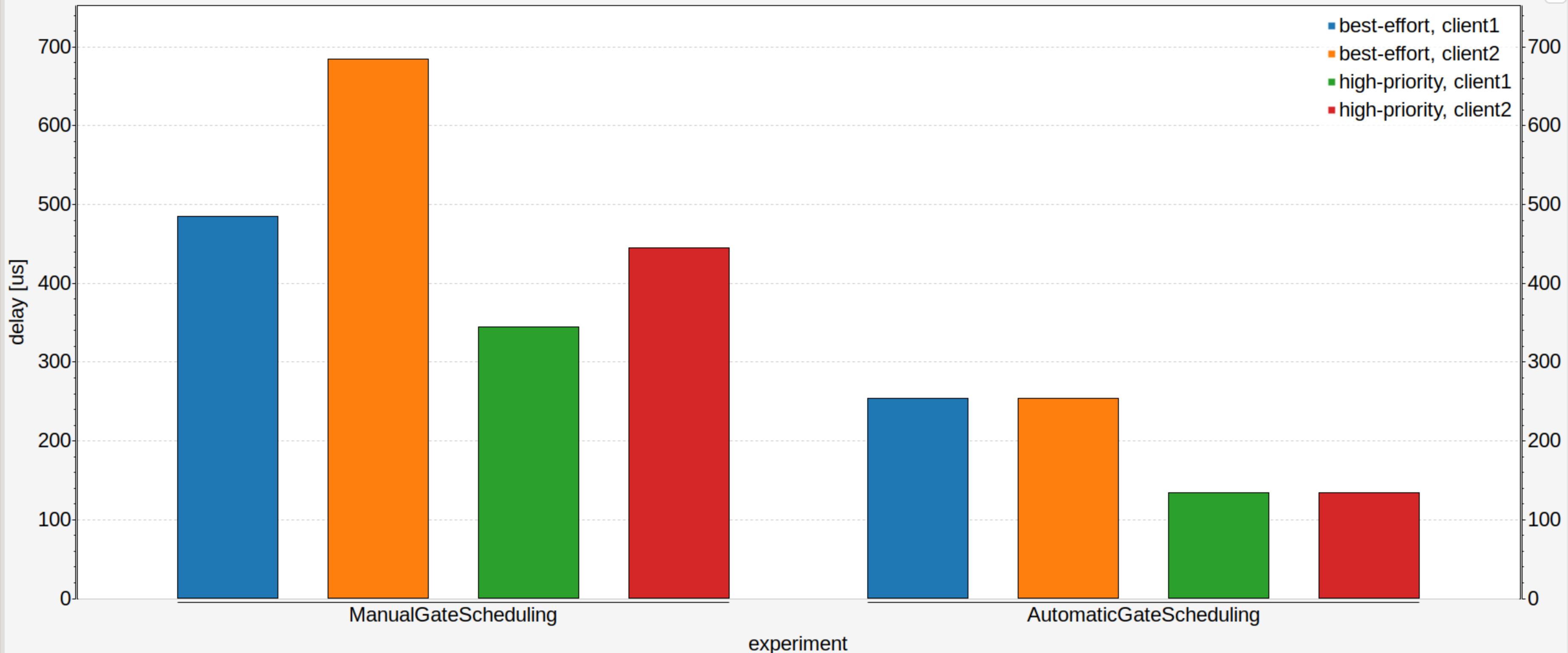
File Edit Navigate Search Project Run Window Help



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

End-to-end delay maximum comparison

End-to-end delay maximum comparison



Inputs Browse Data Charts Manual gate scheduling end-to-end delay

Automatic gate scheduling end-to-end delay

End-to-end delay maximum comparison x

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

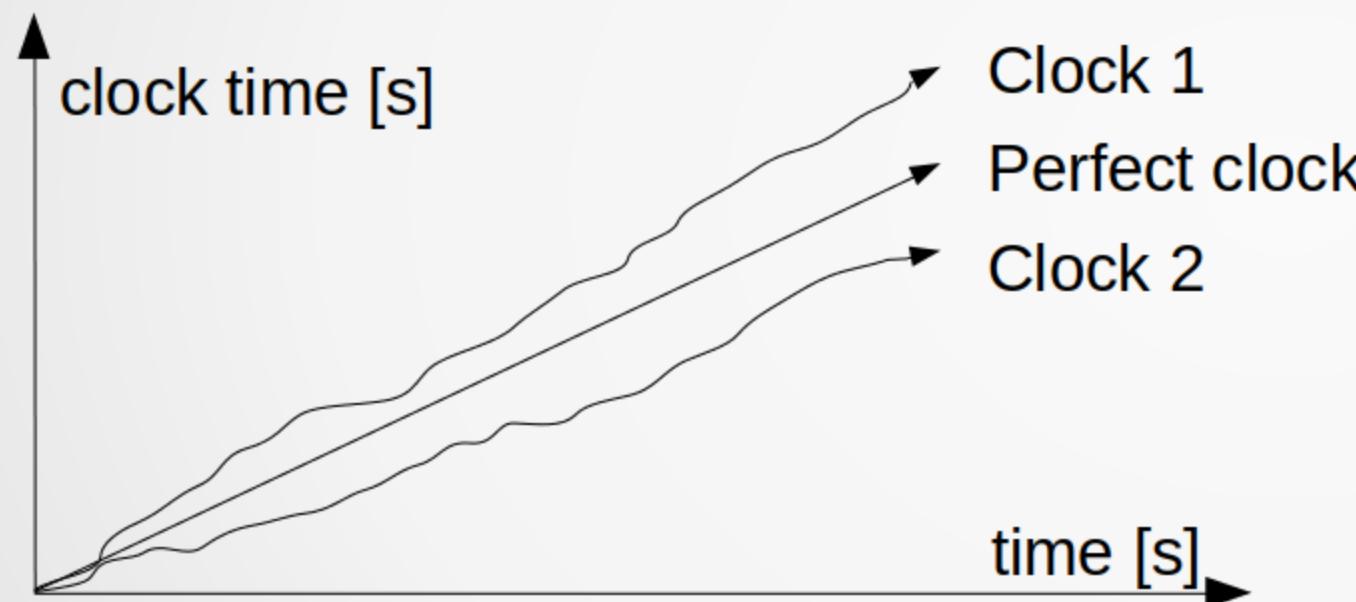
Automatic gate schedule configuration

Time synchronization

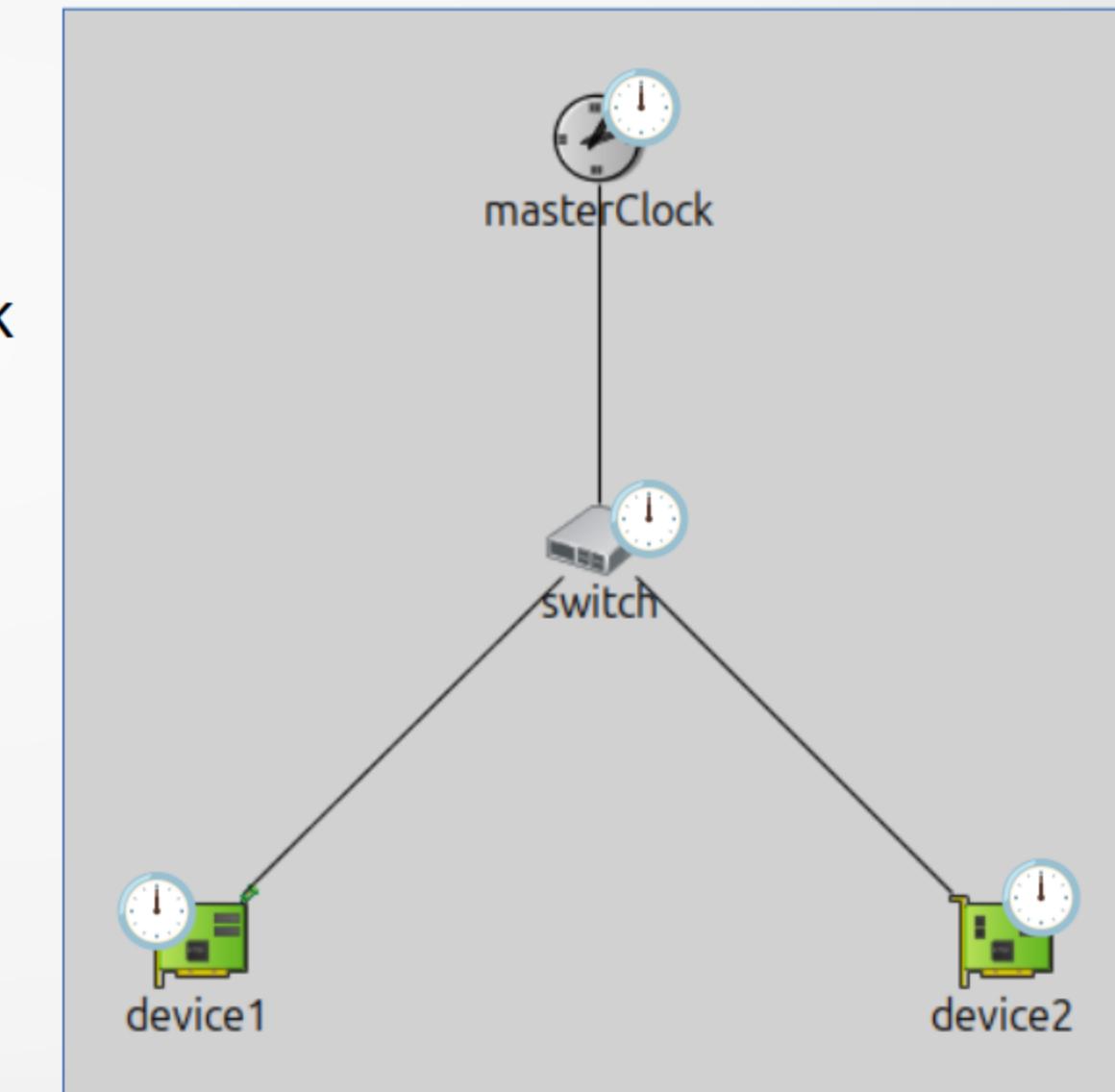
Frame replication and elimination for reliability

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

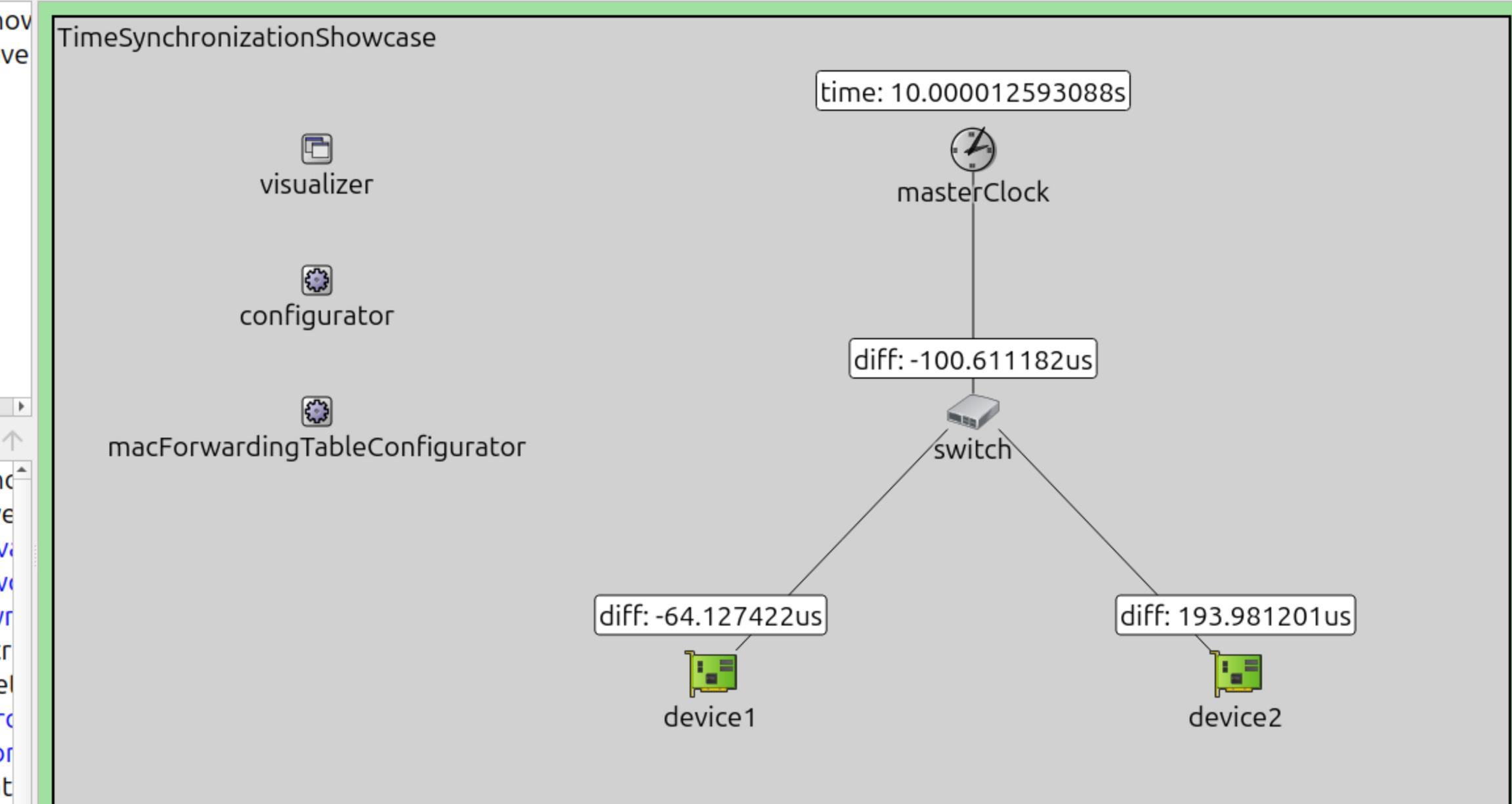


next: #3 208 10s 000ms 000us 000ns 000ps

Next: n/a

In: n/a

At: n/a



Zoom:1.00x

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



NoTimeSynchronization #0: TimeSynchronizationShowca

Msq stats: 4 scheduled / 92 existing / 92 created

File Simulate Inspect View Help

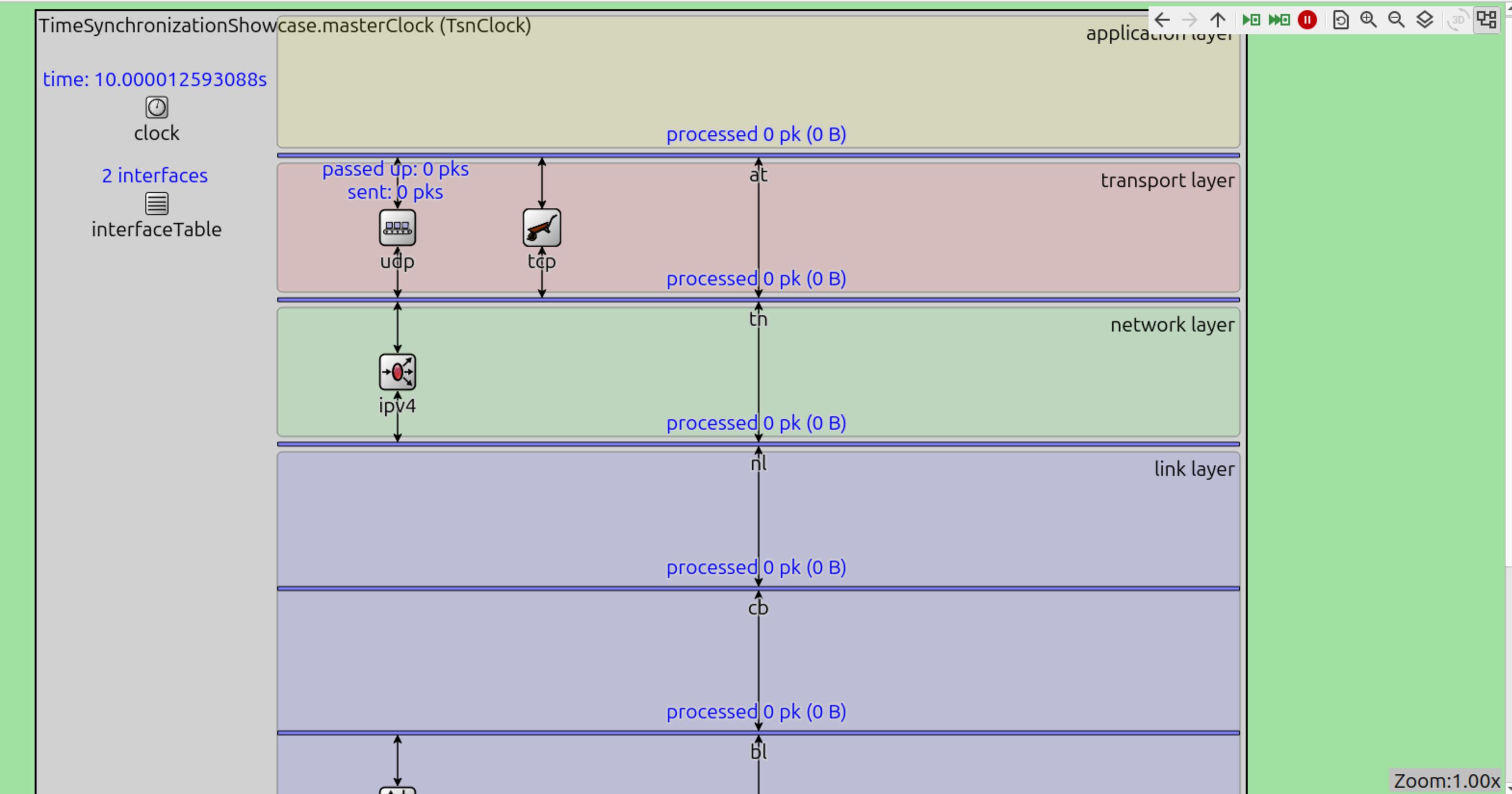
next: #3 208 10s 000ms 000us 000ns 000ps

Next: n/a

In: n/a

At: n/a

- TimeSynchronizationShowcase
- simulation.scheduled-eve



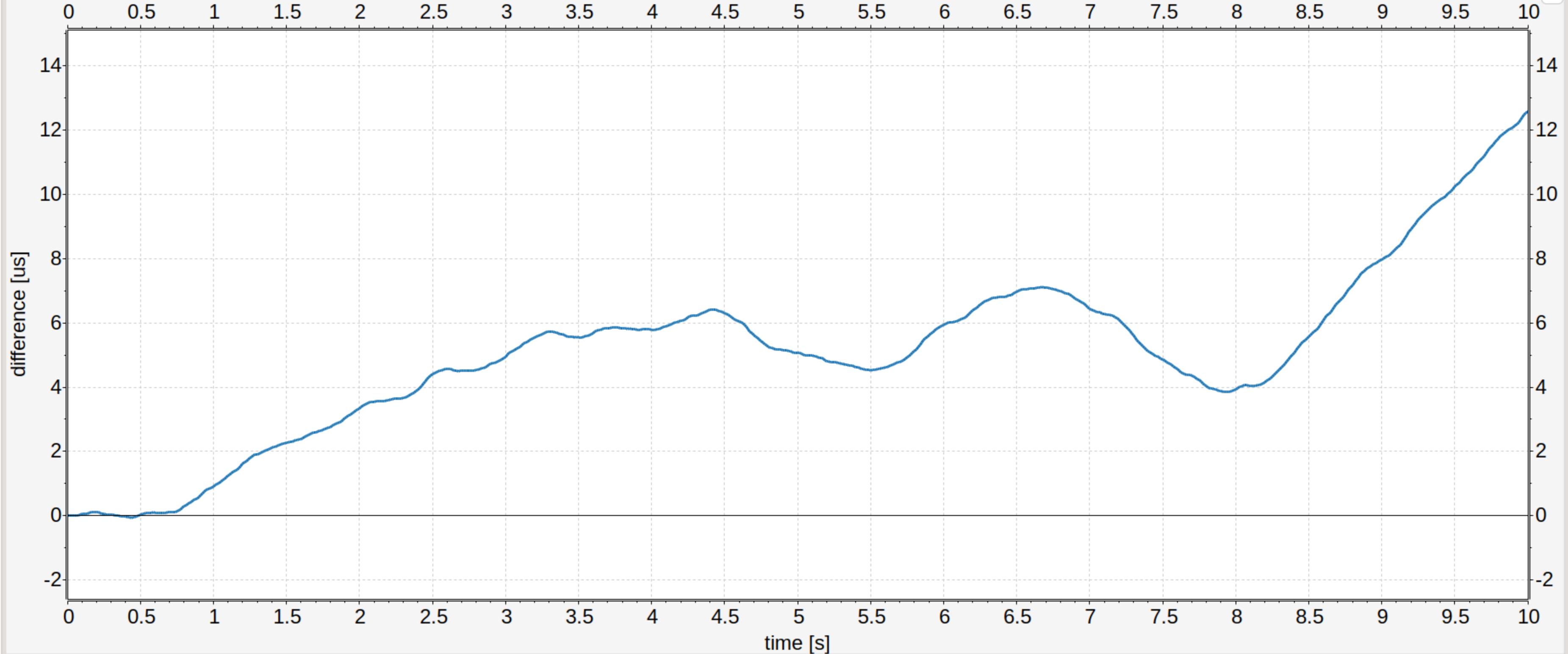
File Edit Navigate Search Project Run Window Help



TimeSynchronization.anf x

Master clock time difference to simulation time

Master clock time difference to simulation time



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

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

Codeium: No comple...erated | Show Chat

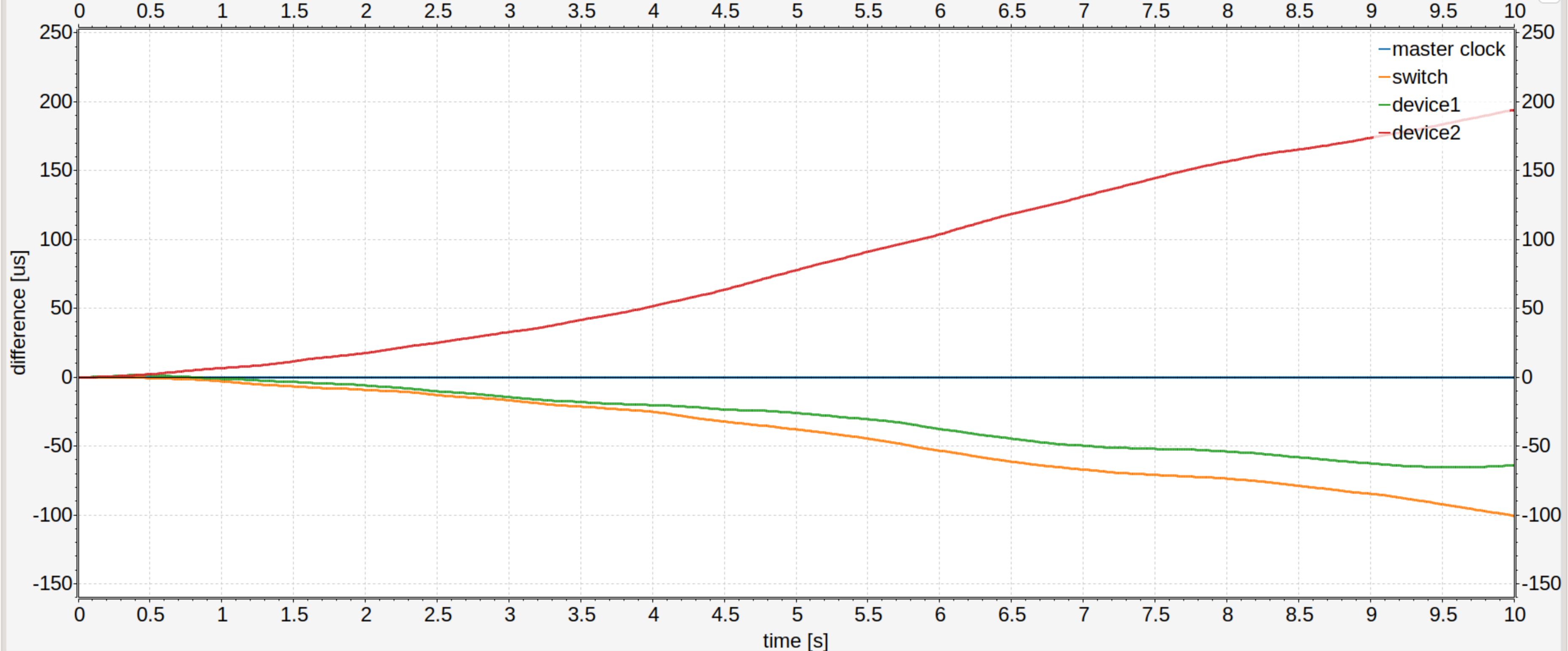
File Edit Navigate Search Project Run Window Help



TimeSynchronization.anf x

Clock time differences without time synchronization

Clock time differences without time synchronization



Inputs Browse Data Charts Master clock time difference to simulation time

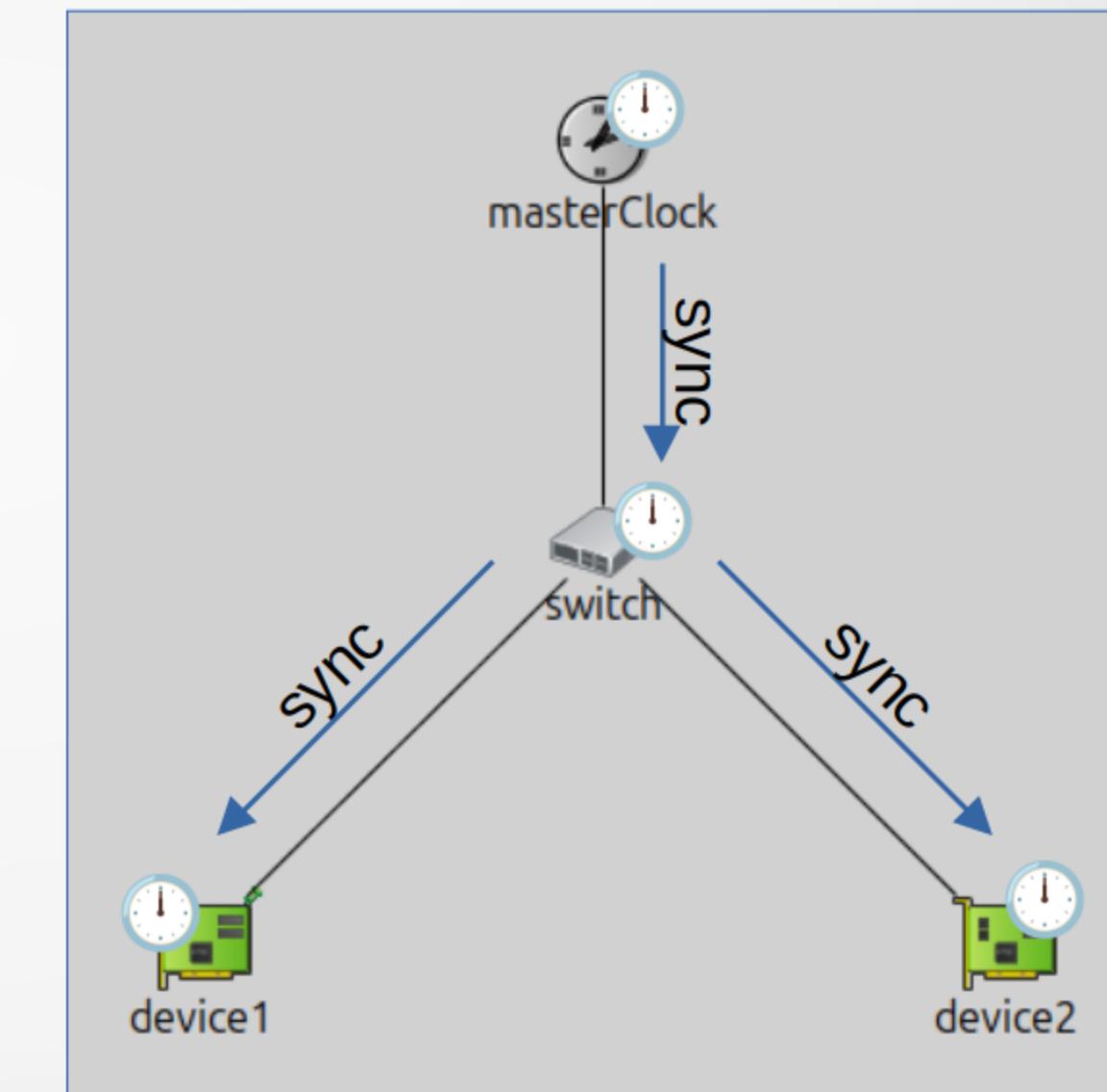
Clock time differences without time synchronization x

Selected: Chart 'Clock time differences without time synchronization'

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



File Edit Source Navigate Search Project Run Window Help



TimeSynchronization.anf

TimeSynchronization.ini x

```
i28 *.visualizer.infoVisualizer.displayInfos = true
i29 *.visualizer.infoVisualizer.placementHint = "top"
i30 *.visualizer.infoVisualizer.modules = "*.*.clock"
31
i32 *.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
i42 *.*.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
```

Form

Source

Writable

Insert

50 : 1 : 1808

Codeium: No comple...erated | Show Chat

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

File Simulate Inspect View Help

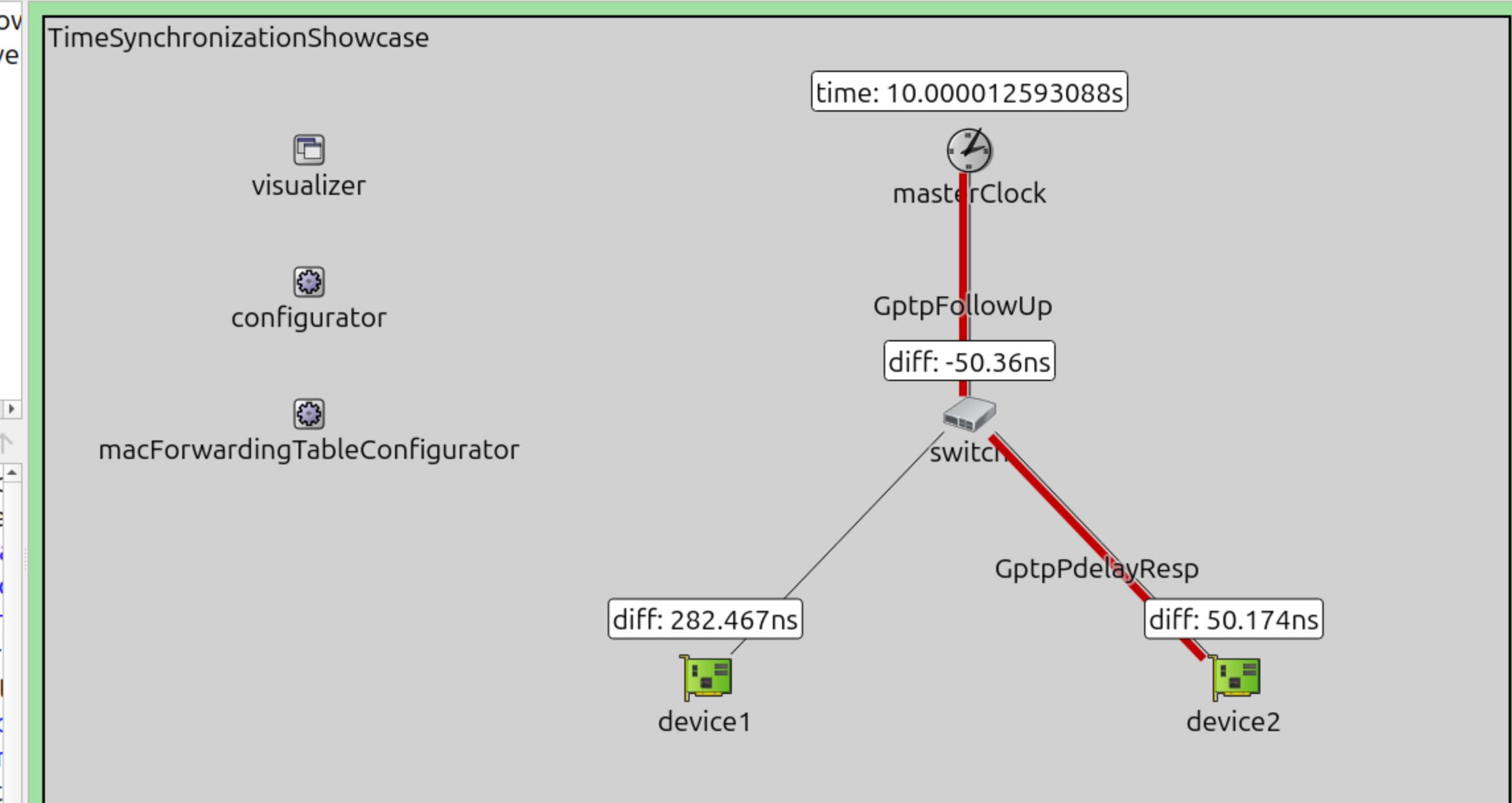


ext: #7 332 10s 000ms 000us 000ns 000ps

Next: n/a

In: n/a

At: n/a



[zoom:1.00x]

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

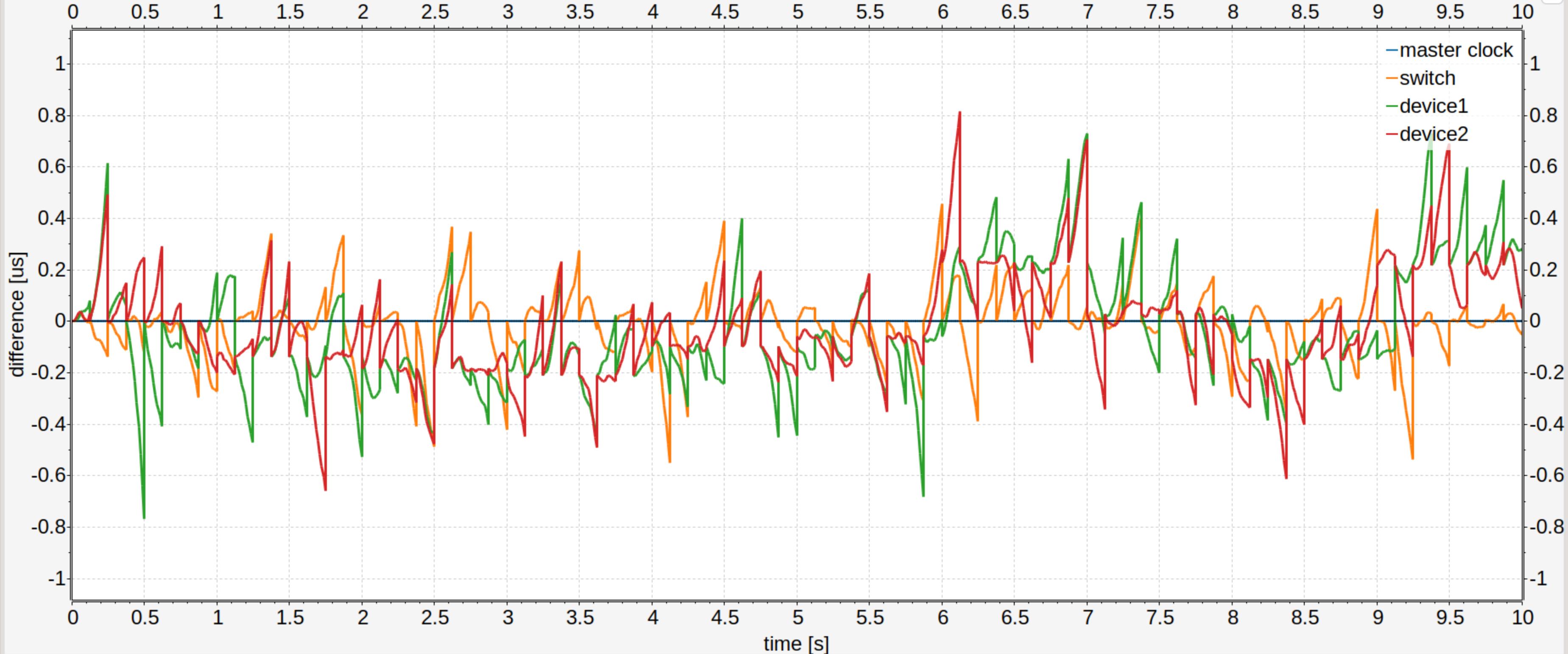
File Edit Navigate Search Project Run Window Help



TimeSynchronization.anf x TimeSynchronization.ini

Clock time differences with gPTP time synchronization

Clock time differences with gPTP time synchronization



Inputs Browse Data Charts Master clock time difference to simulation time

Clock time differences without time synchronization

Clock time differences with gPTP time synchronization x

Selected: Chart 'Clock time differences with gPTP time synchronization'

Simulating WFCS 2025...Run : (0%)

Codeium: No comple...erated | Show Chat

Covered Topics

Cut-through switching

Frame preemption

Per-stream filtering and policing

Scheduling and traffic shaping

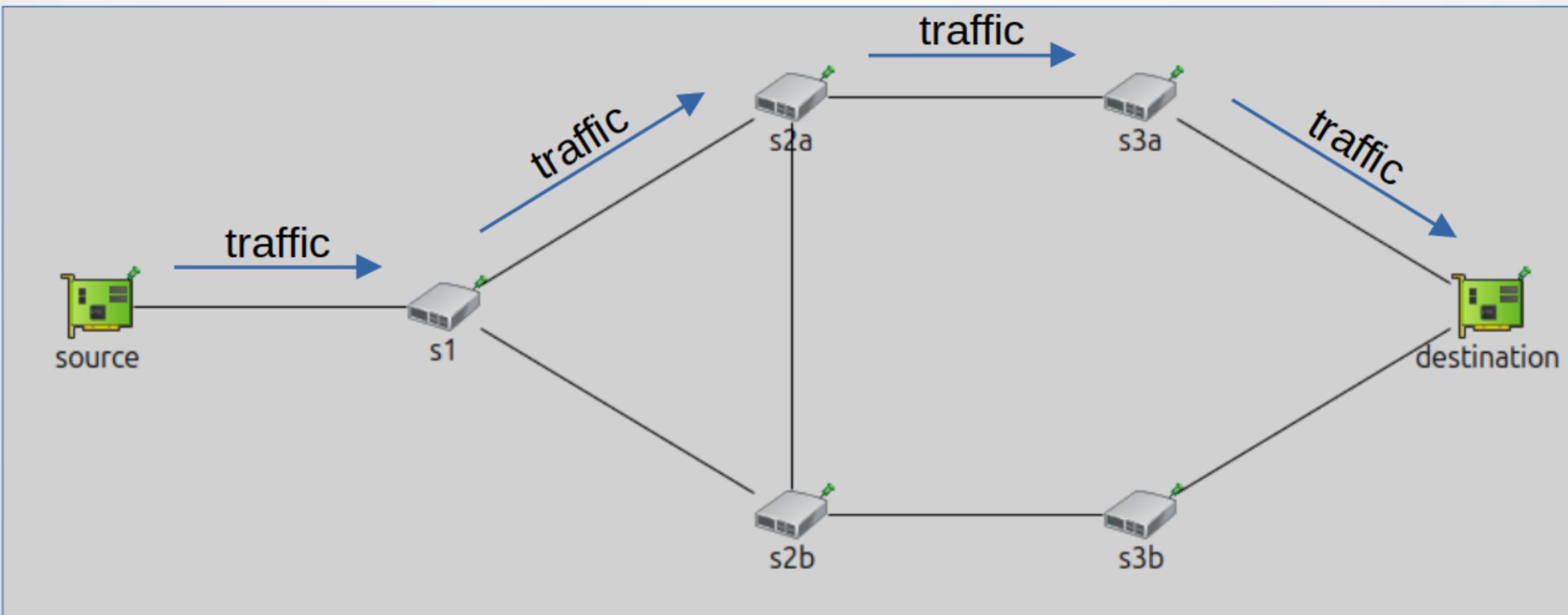
Automatic gate schedule configuration

Time synchronization

Frame replication and elimination for reliability

Node Failure

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



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FrameReplication.ini x 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>
... <at t='20ms'><crash module='s2a' /></at> \
... <at t='80ms'><startup module='s2a' /></at> \
</script>")
29
30
31
32
33 // configuration of nodes and information visualization
```

Form Source

Writable

Insert

26 : 1 : 704

Codeium | Show Chat

File Simulate Inspect View Help



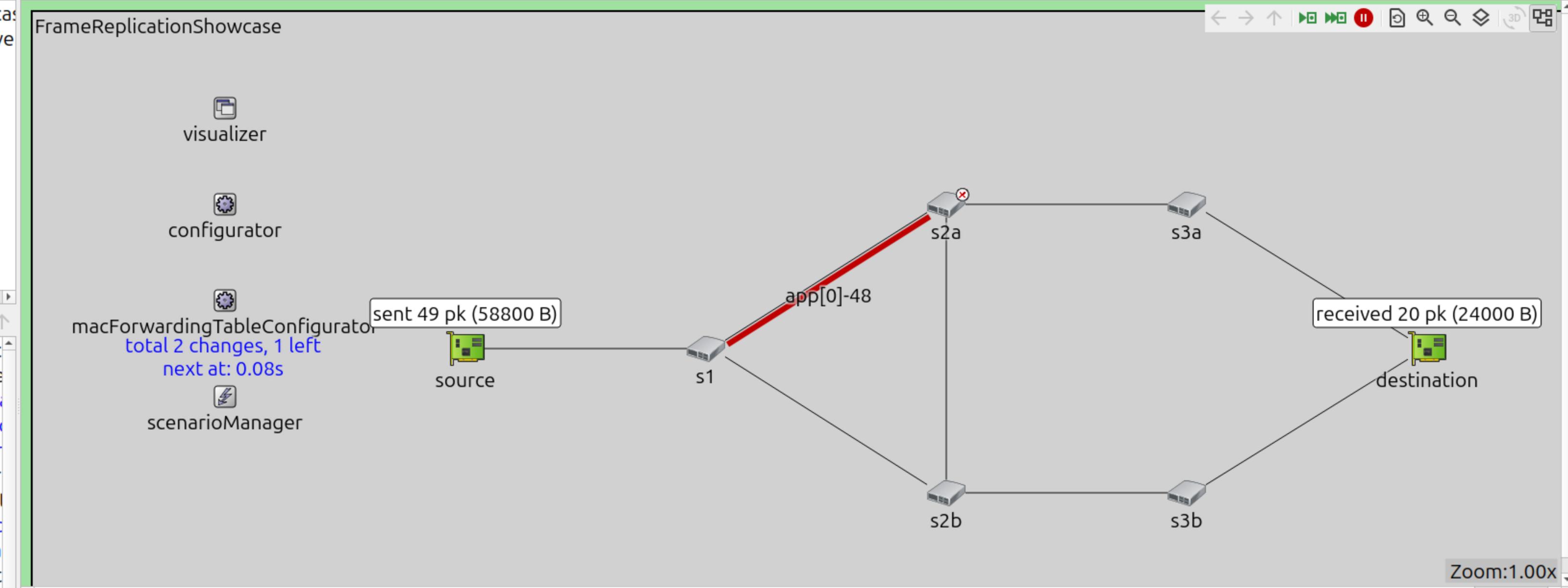
next: #1 032 | 0s 048ms 117us 992ns 820ps

Next: TxEndTimer (inet::ClockEvent, id=34)

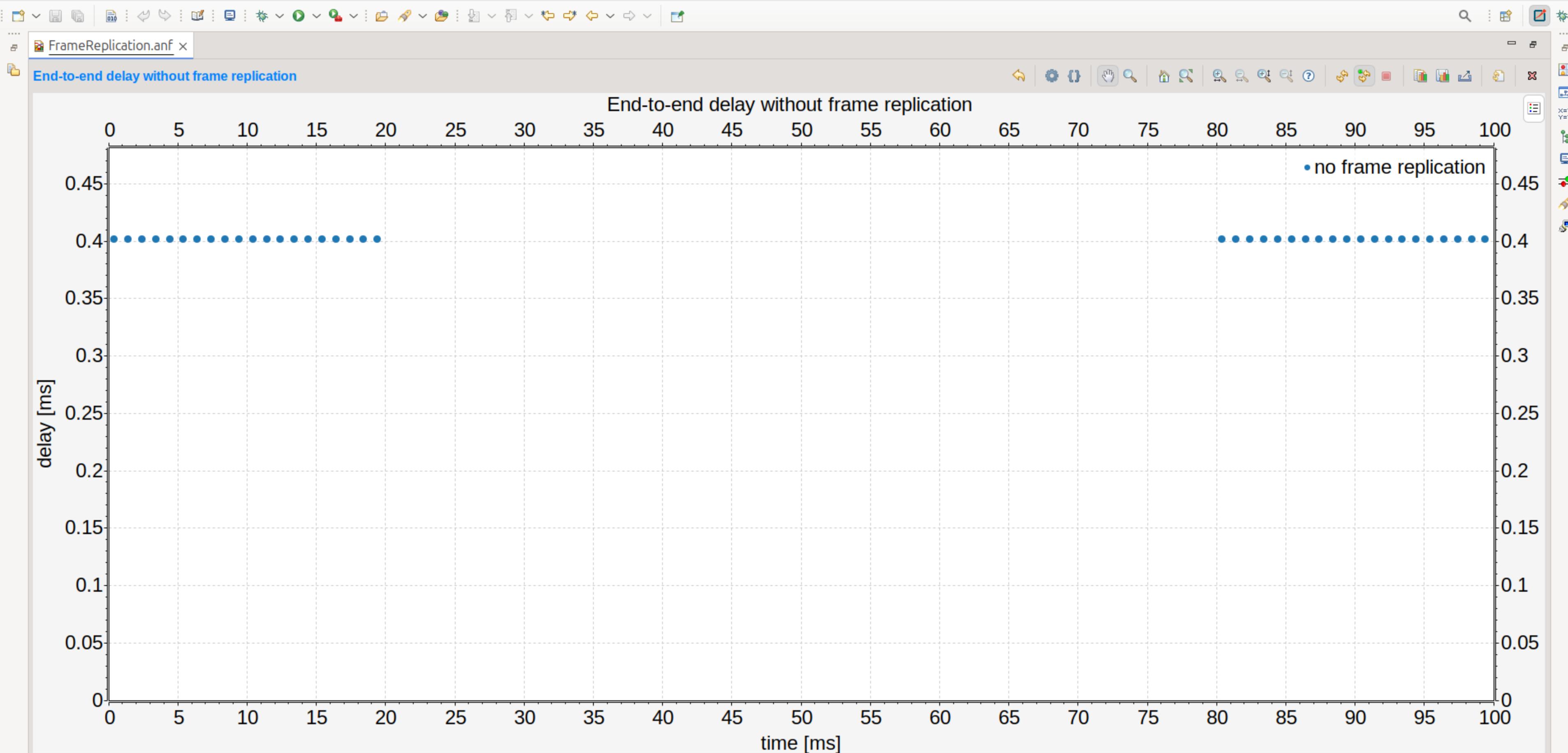
In: FrameReplicationShowcase.s1.eth[0].phyLayer.transmitter (PacketTransmitter, id=227) At: 0.04820069s (now+0.00008269718s)



FrameReplicationShowcase
simulation.scheduled-eve

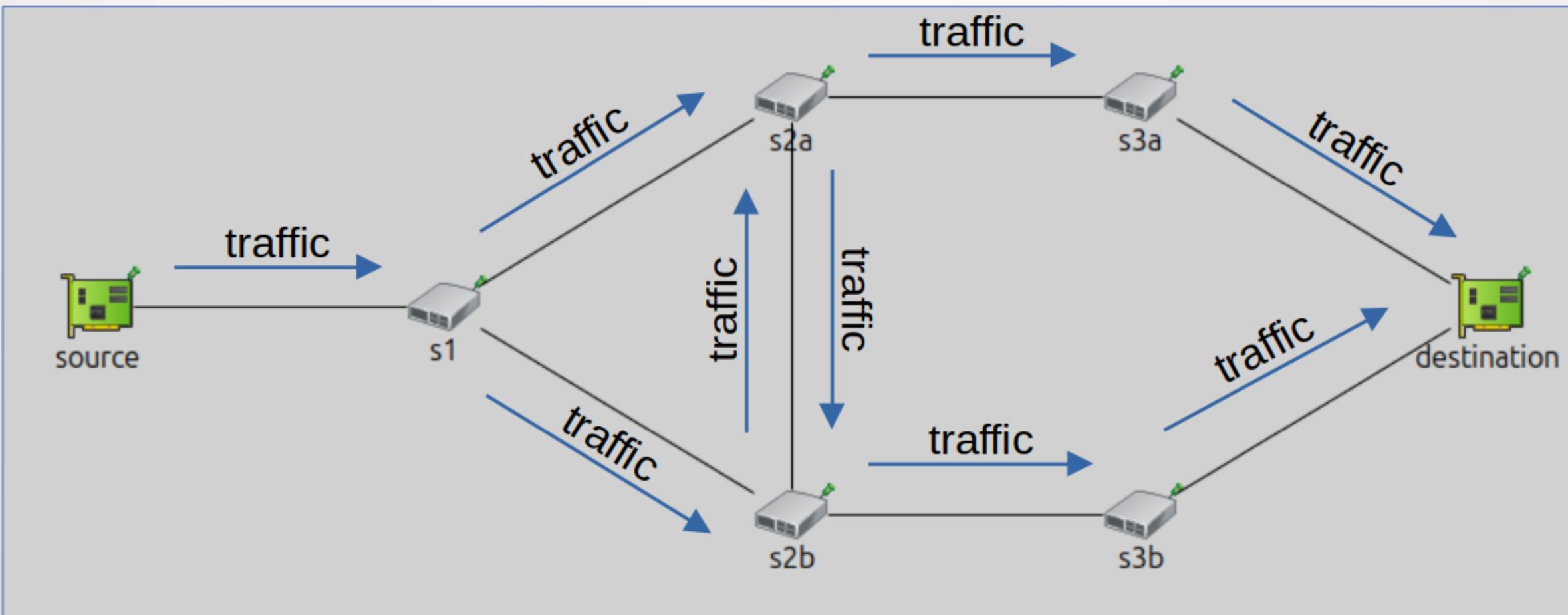


Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	Type	Length	Info
#999	0.046	'100' 370 s1 --> s2a	app[0]-46	10.0.0.1:1025	10.0.0.2:1000	UDP	1254	
#1011	0.047	source --> s1	app[0]-47	10.0.0.1:1025	10.0.0.2:1000	UDP	1254	B (UNKNOWN)
#1014	0.047	'100' 370 s1 --> s2a	app[0]-47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



Frame Replication and Elimination

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



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```
FrameReplication.anf FrameReplication.ini x
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: "destination",
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
```

Form Source

File Simulate Inspect View Help

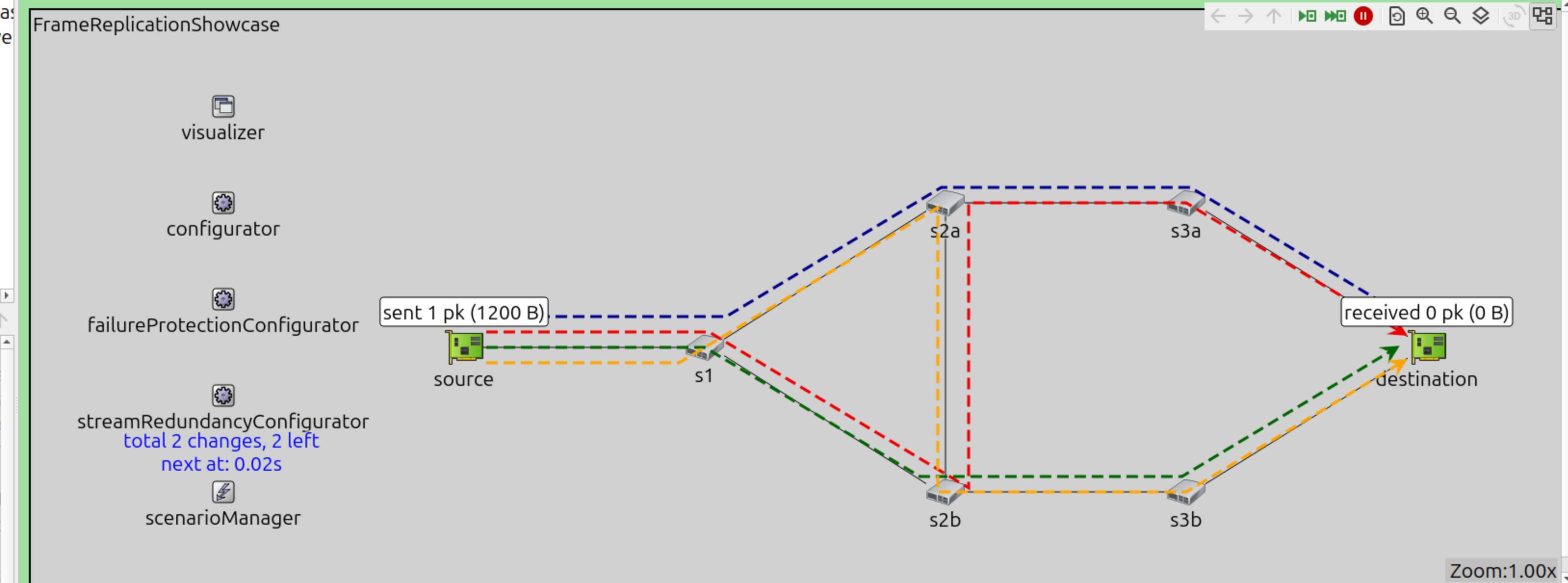


next: #1 0s 000ms 000us 000ns 000ps

Next: ServeTimer (omnetpp::cMessage, id=6)

In: FrameReplicationShowcase.source.eth[0].macLayer.server (InstantServer, id=147) At: 0s (now+0s)

- FrameReplicationShowcase
- simulation.scheduled-events



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



File Simulate Inspect View Help

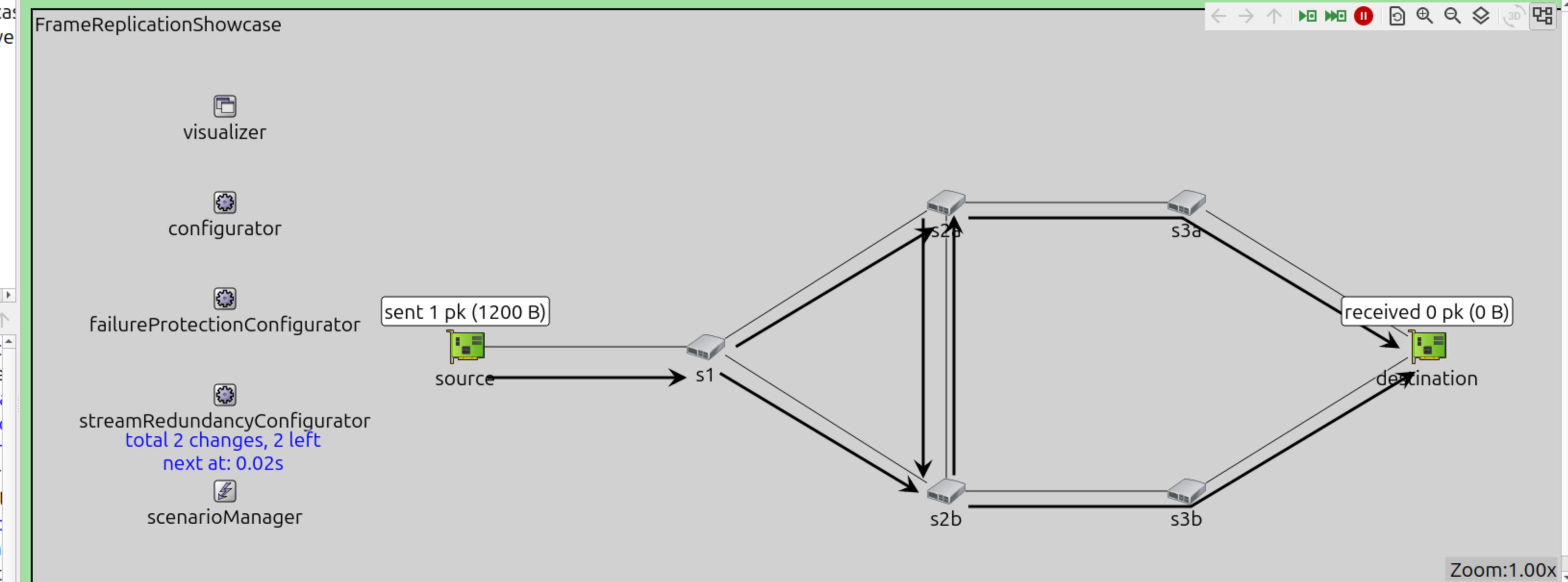


next: #1 0s 000ms 000us 000ns 000ps

Next: ServeTimer (omnetpp::cMessage, id=6)

In: FrameReplicationShowcase.source.eth[0].macLayer.server (InstantServer, id=147) At: 0s (now+0s)

- FrameReplicationShowcase
- simulation.scheduled-events



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

File Simulate Inspect View Help



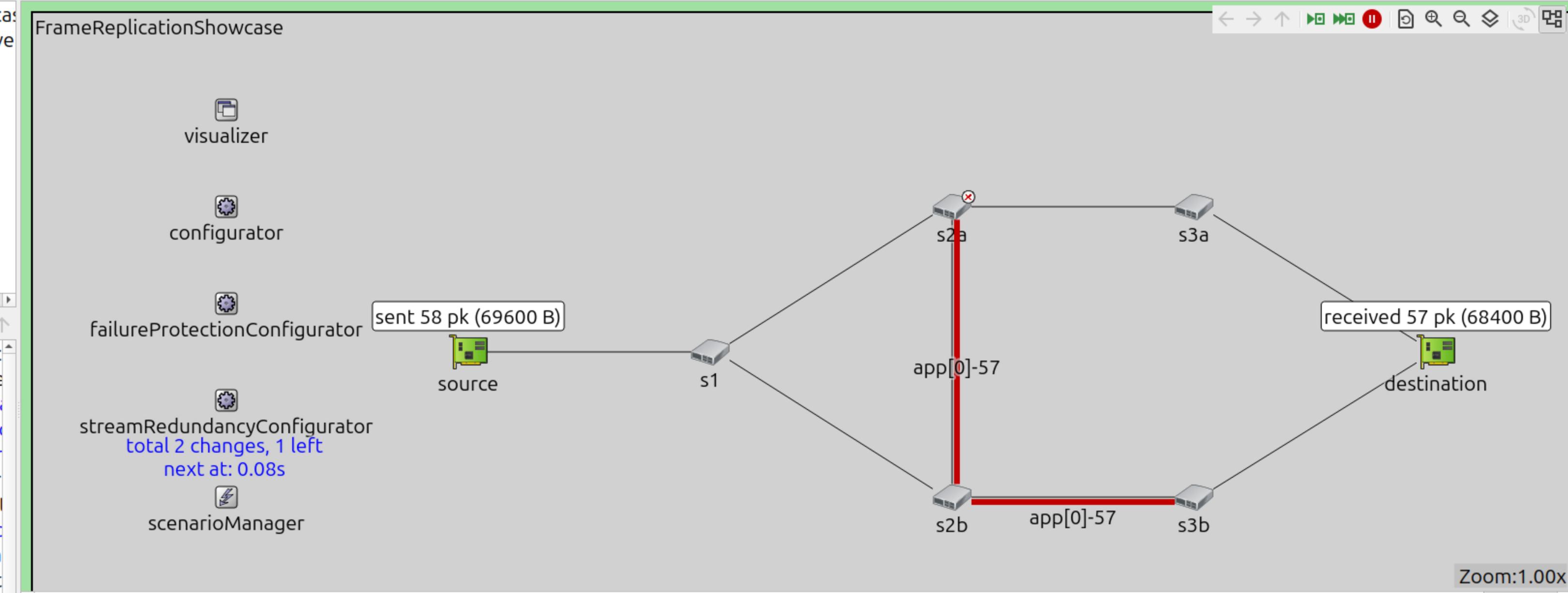
last: #2 561 | 0s 057ms 202us 659ns 978ps

Ev/sec: 381.911

Simsec/sec: 0.00979259

Ev/simsec: 39000

- FrameReplicationShowcase
- simulation.scheduled-eve



Event#	Time	Relevant Hops	Name	TxUpdate? / Source	Length / Des Info / Protocol	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)

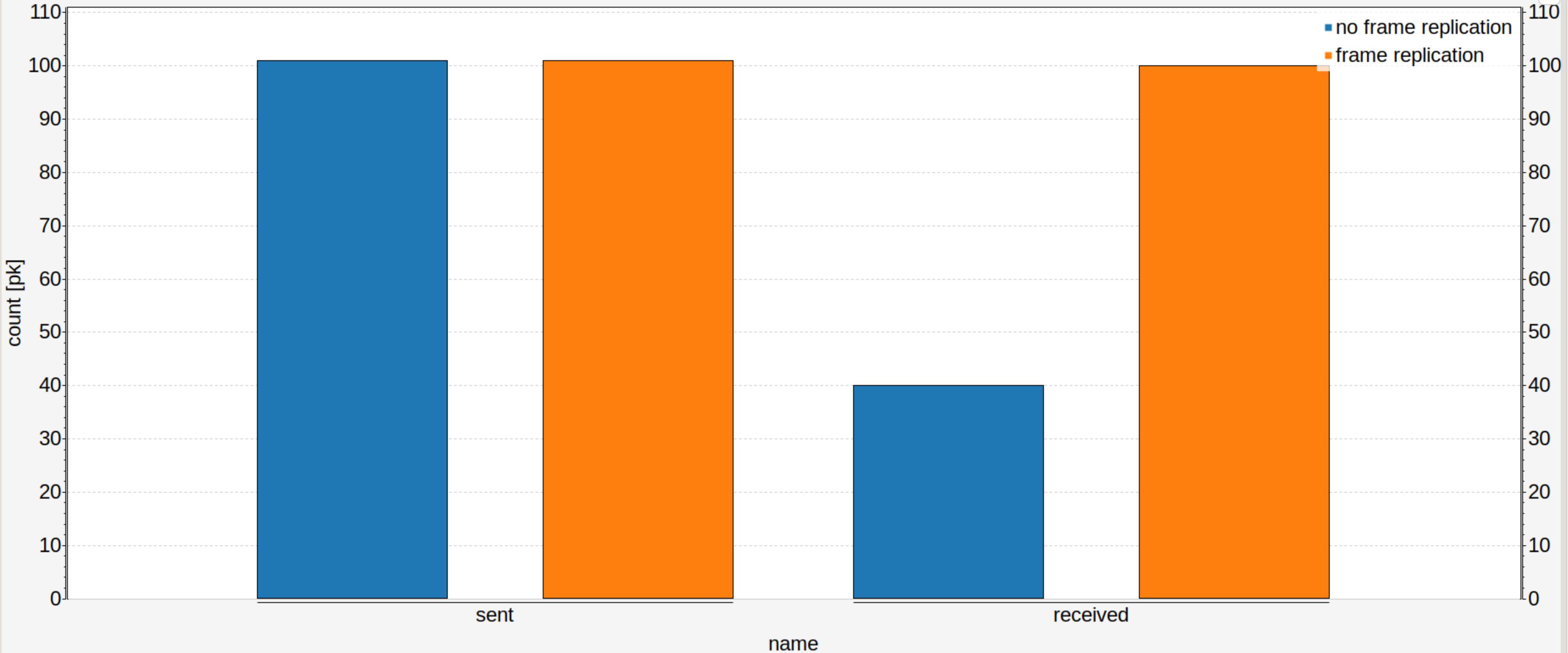
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FrameReplication.anf x FrameReplication.ini

Number of packets sent and received comparison

Number of packets sent and received comparison



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

Number of packets sent and received comparison x

Selected: Chart 'Number of packets sent and received comparison'

Codeium: No comple...erated | Show Chat

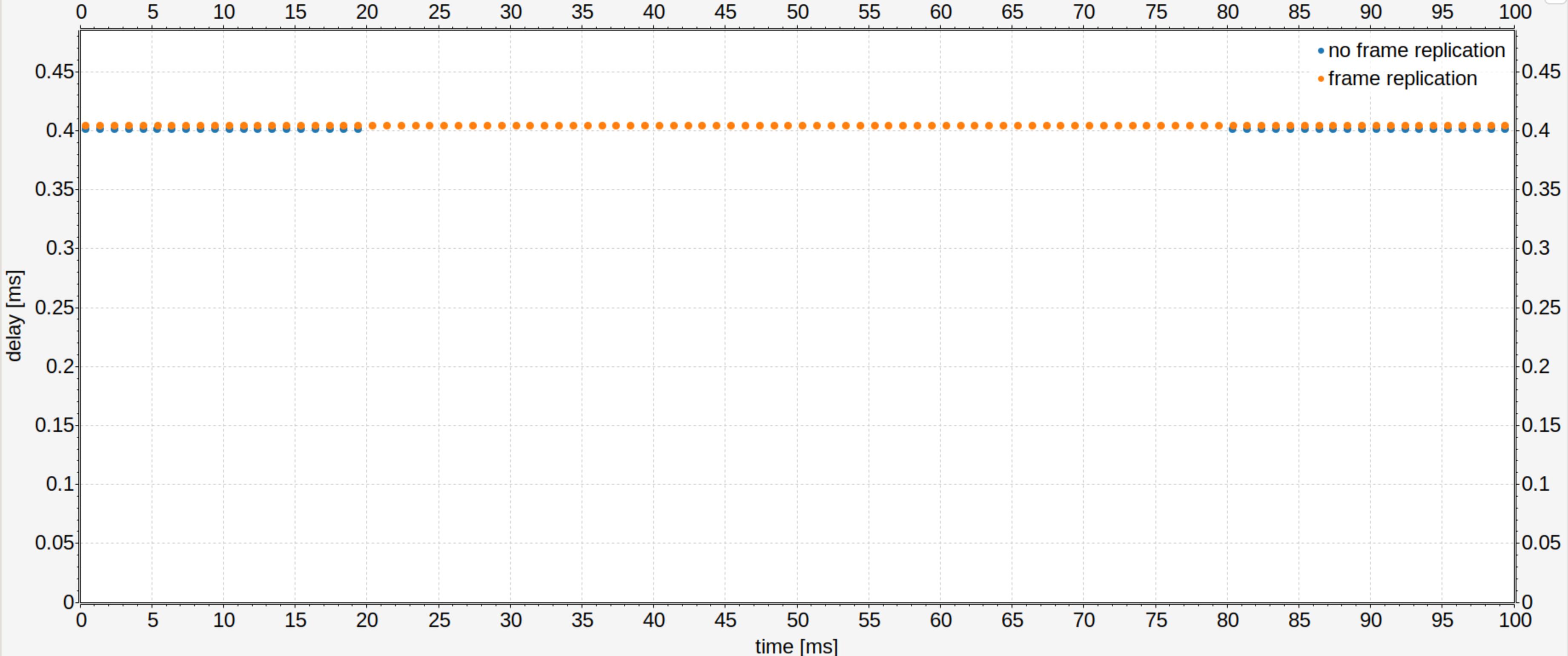
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FrameReplication.anf x FrameReplication.ini

End-to-end delay comparison

End-to-end delay comparison

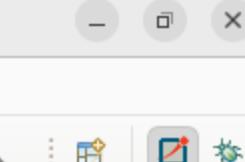


Inputs Browse Data Charts End-to-end delay without frame replication

Number of packets sent and received comparison

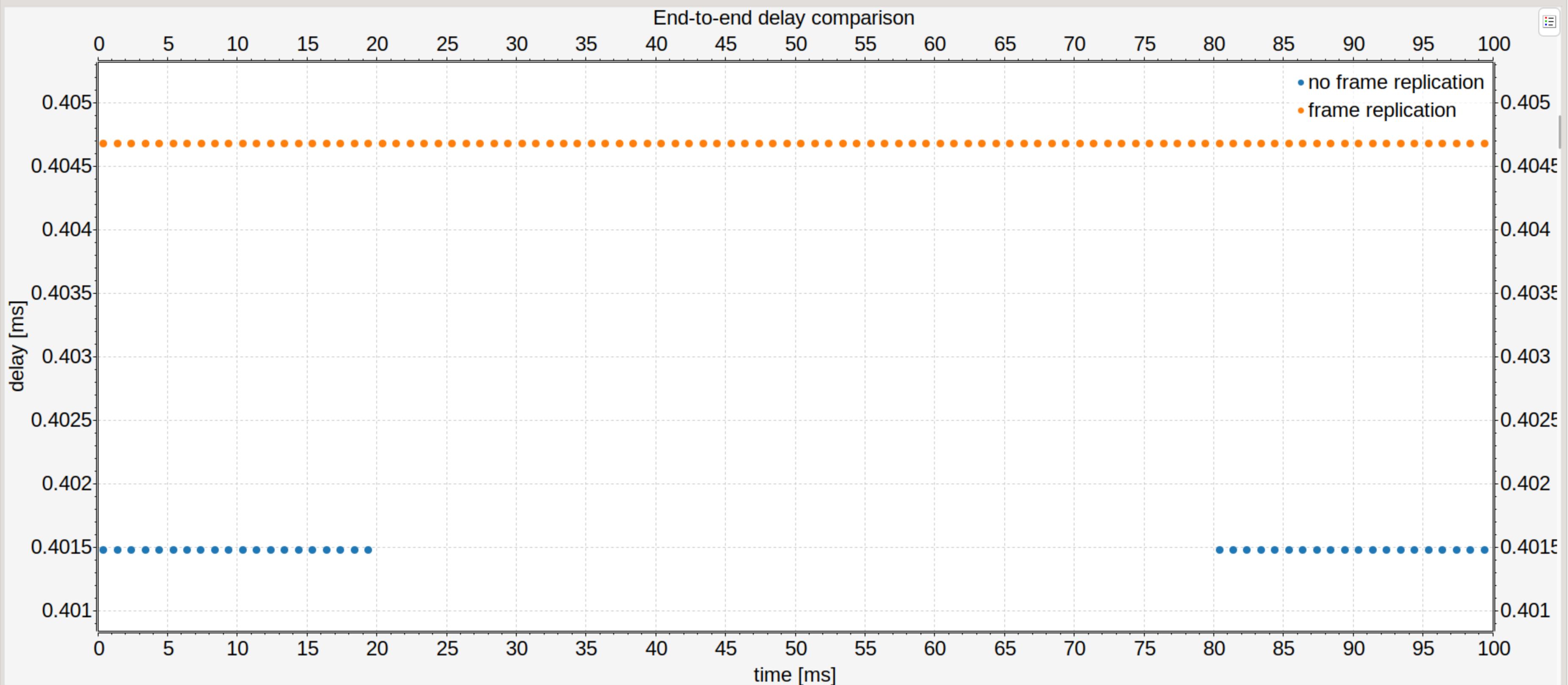
End-to-end delay comparison x

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FrameReplication.anf x FrameReplication.ini

End-to-end delay comparison



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

Number of packets sent and received comparison

End-to-end delay comparison x

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!