Chair of Connected Mobility
TUM School of Computation, Information and Technology
Technical University of Munich

Hierarchical Resource Sharing and Queuing in OMNeT++ and INET Framework

OMNeT++ Summit 2022

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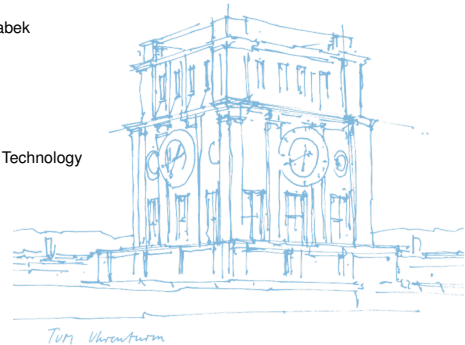

Content

Motivation

- Scheduling algorithms determine the order of packets to dequeue from the queue.
- Hierarchical Token Bucket (HTB) [1] is a hierarchical scheduling algorithm that is in the stock Linux kernel since 2005.
- Hierarchical Link Sharing (HLS) [2] is a new hierarchical scheduling algorithm, implemented in Linux.
- Our goal is to compare HTB and HLS.
- An implementation of HTB into OMNeT++ simulator [3] already exists.
- We implement HLS into OMNeT++, then validate and compare HLS and HTB on OMNeT++.

Research Questions

- How can HLS be implemented into OMNeT++ discrete event simulator?
- How well do HTB and HLS (hierarchical queuing structures) fit within OMNeT++ queuing structure?
- **In what ways is HLS advantageous to use compared to HTB (bandwidth sharing, impact on delay, etc.)?**

Background

Hierarchical Scheduling Algorithms

- Scheduling algorithms that are implemented into Linux kernel are called qdiscs.
- Qdiscs are split into two types: classless and classful.
- Packets arriving at classful qdiscs are filtered into one of the user-defined classes.
- Using these classes, users can control bandwidth sharing between classes.
- Using classes, a hierarchy can be realized.
- FIFO, fq_codel [4] are classless qdiscs, HLS and HTB are classful qdiscs.

Background

Hierarchical Scheduling Algorithms

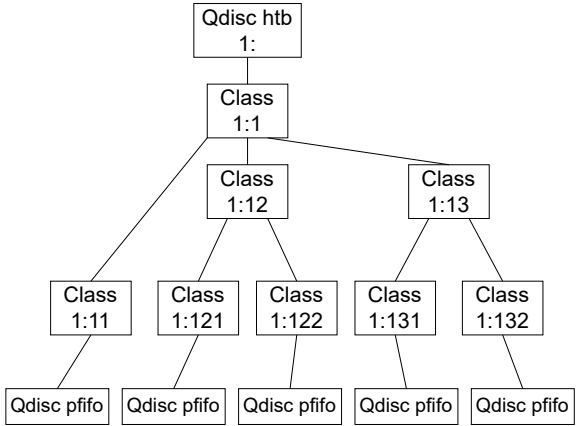

Figure 1: Example classful qdisc hierarchy

Background

Hierarchical Link Sharing (HLS)

- Each class except root has a parameter called weight.
- Each node shares bandwidth to their children proportional to their weights.
- Each class has balance, number of bytes a class is allowed to transmit.
- Classes can be active or idle. An inner class is active if any of its descendants is active.
- HLS works in rounds, in each round balance is propagated from root to active leaf classes.
- Balance is consumed in leaf classes to transmit packets.

- Each class distributes its balance to its active children, starting from top.
- The balance each child gets is proportional to their weight (compared to their siblings).

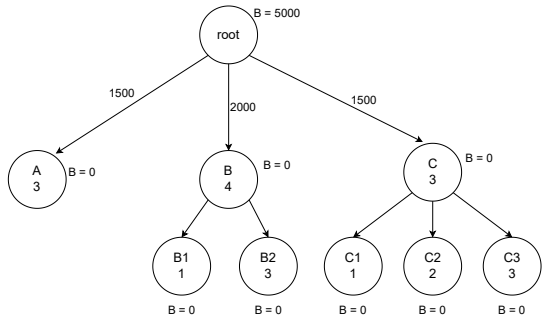

Figure 2: HLS balance distribution

Background

Hierarchical Link Sharing (HLS)

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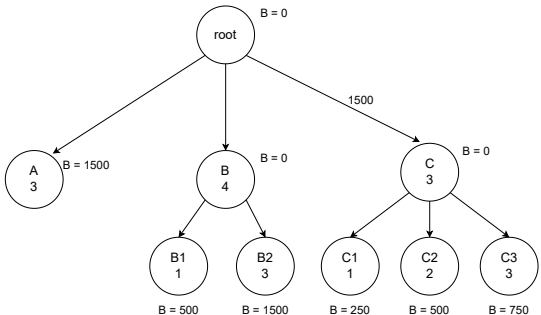


Figure 3: HLS balance distribution

- After the distribution of balance, HLS cycles between each leaf class.
- Dequeues a packet if balance is bigger than next packet byte size.
- Consumed balance is returned to root, to be distributed in the next round.

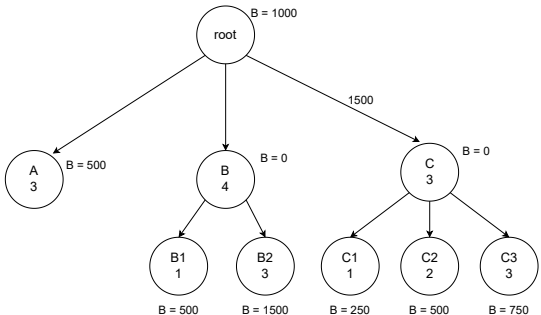


Figure 4: HLS balance distribution

Background

Hierarchical Token Bucket (HTB)

- Each class has parameters guaranteed rate and maximum rate.
- Leaf classes further have parameters priority and quantum value.
- Quantum value determines proportion of bandwidth a class will "borrow" from their ancestor.
- Classes have three modes depending on their current rate: can send (green), can borrow (yellow), and cannot send (red).

- HTB iterates through levels starting from bottom.
- Searches for active green classes with highest priority.
- If the found green class is a leaf, HTB simply dequeues a packet from that leaf class.
- If there are multiple classes to pick from, HTB utilizes a round-robin that consumes the quantum values to dequeue packets.

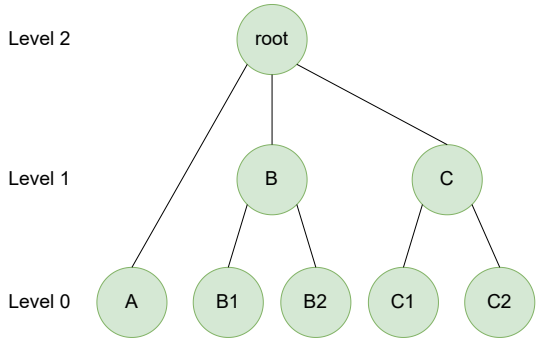


Figure 5: Example HTB Hierarchy

- If the found green class is a an inner class, HTB picks a descendant leaf to "borrow" bandwidth to.
- The bandwidth a class gets from its ancestors will be proportional to their quantum value, enforced through a deficit round-robin.

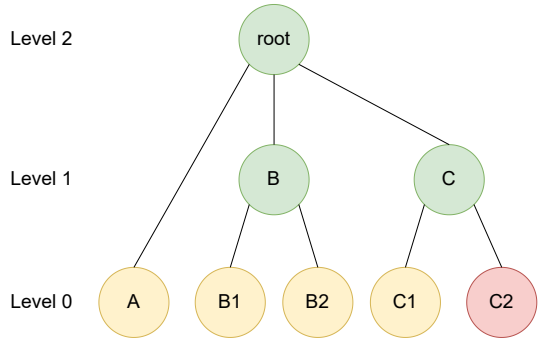


Figure 6: Example HTB Hierarchy

Analysis

Comparison of HLS and HTB

- Both are hierarchical scheduling algorithms.
- HTB has 4 different parameters that control throughput, HLS has only 1.
- HLS does not have a way to replicate the effects of priority and maximum rate parameters of HTB.
- In HLS, the rate a class achieves when every class is active can be thought as the guaranteed rate.
- Quantum values of HTB are by default proportional to their guaranteed rates. If set like this, they behave the similar to weights in HLS.

Analysis

Comparison of HLS and HTB

- HLS goes top-down while sharing bandwidth, so it is independent of condition of its subtrees.
- HTB sharing depends on which and how many descendant leaf classes are in yellow mode.
- In theory, HLS should have better class isolation. Excess bandwidth are contained in the subtrees.

Analysis

Comparison of Linux and OMNeT++ Environment

- OMNeT++ clock does not include overhead generated by classifying and scheduling operations.
- The overhead is not significant enough to diverge results of OMNeT++ and Linux.
- By default OMNeT++ clock is a perfect simulated clock, does not have any clock drift.
- INET 4.4 introduced Time-Sensitive Networking (TSN) features, including device clocks.
- HTB OMNeT++ implementation uses normal simulation clock.
- HTB heavily uses clocks to regulate class modes, so drift can result in very minor differences.
- HLS is unaffected by clock drift.

- Queuing modules are active/passive packet sink/sources.
- Modules communicate using C++ method calls through gates.

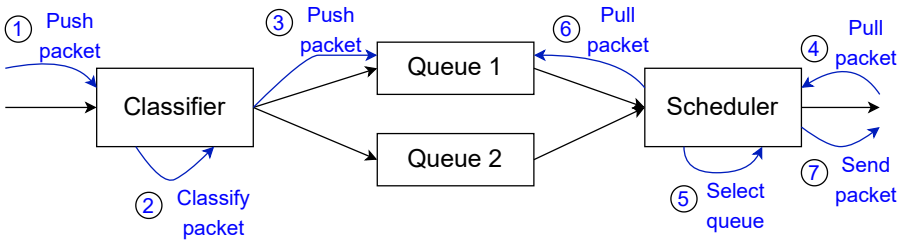


Figure 7: Example flow of a queue with a classifier and scheduler in OMNeT++

Implementation of HLS into OMNeT++/INET

Design

An ideal implementation should have the following properties:

- Should work the same as the qdisc implementation.
- The implementation should be able to use the already available classifiers and queues in INET Framework.
- The leaf packet queue types should be freely selectable. Even HLS can be a leaf queue of itself.

We designed two modules:

- HLSScheduler: Implements HLS functionality, selects which queue to dequeue from for every packet pull request.
- HLSQueue: Combine classifier, queues and scheduler into one compound module.

HLSQueue

The implementation has the same structure as HTB OMNeT++ implementation [3].

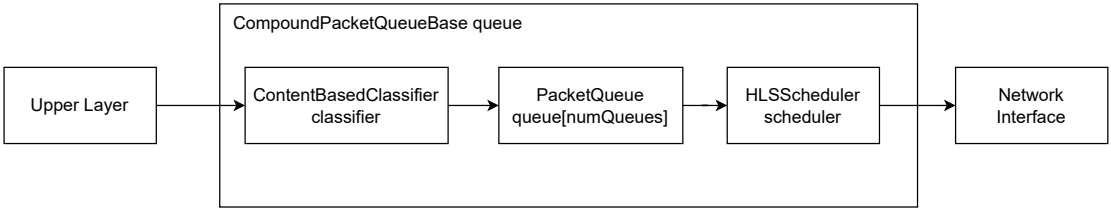


Figure 8: Design of HLSQueue module

CompoundPacketQueueBase handles interaction with upper layer and network interface.

- Outgoing packets are forwarded to classifier.
- Pull packet request from network interface is forwarded to scheduler.
- Hierarchy is set up using an XML file.

- Packets are generated on "Packet Generator" so that the generation time does not affect the scheduling.
- Hardware experiments use iperf3 [5] for packet generation.
- OMNeT++ experiments use UdpBasicApp for packet generation.

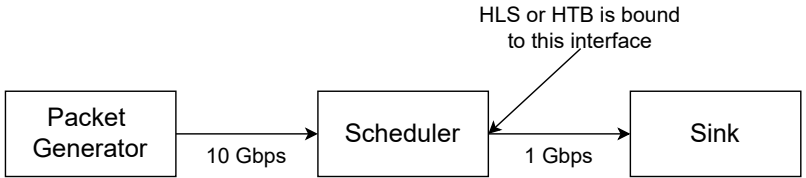
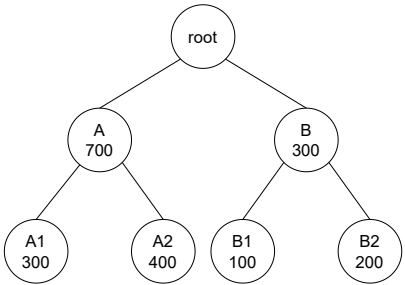


Figure 9: Configuration

Validation of HLS and HTB Against Linux

HLS Validation Test

Figure 10: Hierarchy of HLS validation test.



- Scheduler is set up on a 1 Gbps link.
- Classes should reach throughput in Mbps equal to their weights, i.e. A1 $\rightarrow$ 300 Mbps.

Validation of HLS and HTB Against Linux

HLS Validation Test Results

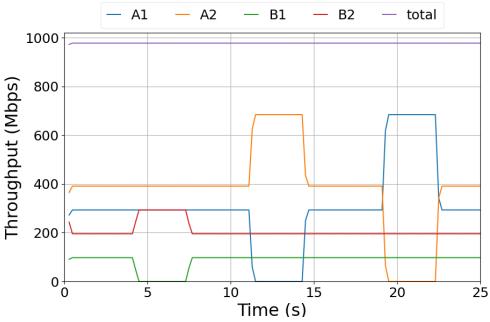


Figure 11: HLS qdisc

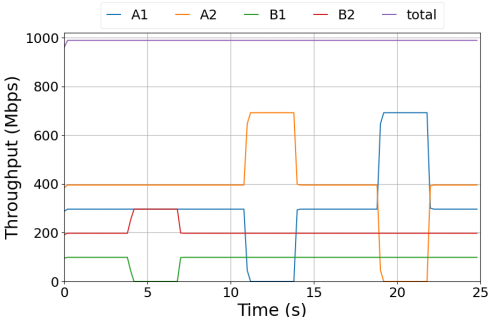
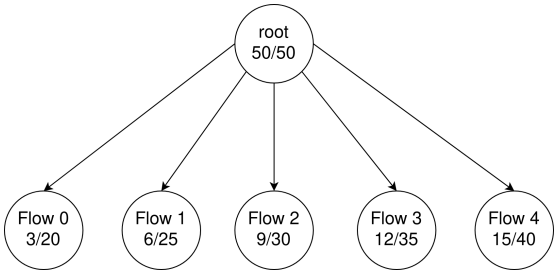


Figure 12: HLS OMNeT++

Validation of HLS and HTB Against Linux

HTB Validation Test

Figure 13: Hierarchy of HTB validation test.



- Guaranteed rate/Maximum rate in Mbps.
- Each flow should reach their guaranteed rate while not exceeding maximum rate.

Validation of HLS and HTB Against Linux

HTB Validation Test Results

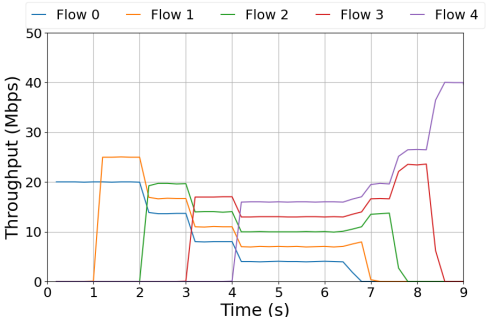


Figure 14: HTB qdisc

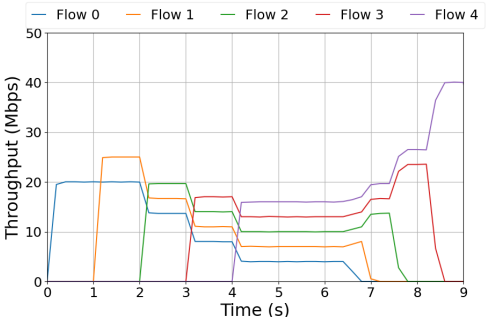


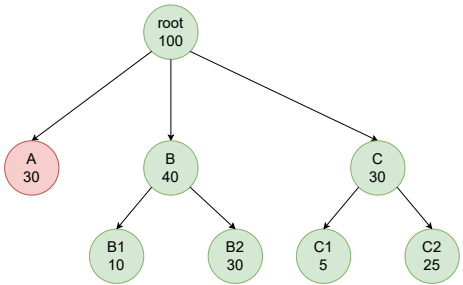
Figure 15: HTB OMNeT++

Experiments on OMNeT++

Bandwidth Sharing Comparison

- Numbers in nodes correspond to weight for HLS and guaranteed rate in Mbps for HTB.
- Quantum values are proportional to guaranteed rates.
- Maximum rate of every node is equal to link rate.
- Red nodes denote idle nodes, green nodes denote active nodes.
- Every active leaf class is generating packets at a speed of 100 Mbps.

Figure 16: Hierarchy used in throughput comparison.



Experiments on OMNeT++

Bandwidth Sharing Comparison

- Throughputs are the same before B2 becomes idle.
- When B2 becomes idle, the throughput of B does not change for HLS, does change for HTB.
- HTB shares the extra bandwidth with every leaf class, HLS gives all the extra bandwidth to B1.

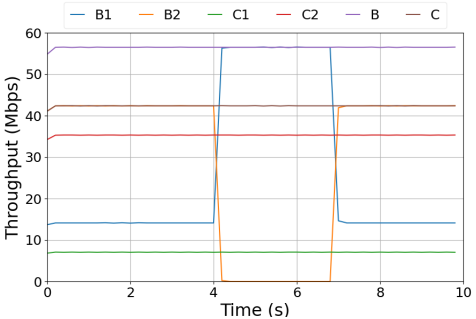


Figure 17: HLS Throughput

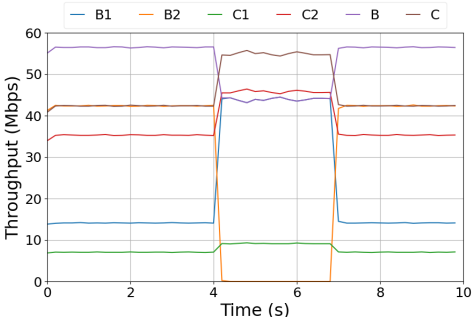


Figure 18: HTB Throughput

Experiments on OMNeT++

Delay During Congestion

- Experiment was done in OMNeT++.
- What happens to the delay of classes that send at or lower than their guaranteed rate during congestion?
- The experiment consists of 4 runs, in each only one of the classes is sending at lower than their guaranteed rate.

Table 1: End-to-end delay on delay during congestion experiment.

Classes	HLS Mean (*ms*)	HTB Mean (*ms*)
A1	1.94	2.37
A2	1.45	2.08
B1	1.48	4.07
B2	1.32	1.63

- In each experiment, the same class achieves the same throughput.

Figure 19: Hierarchy used in HLS and HTB delay experiments.

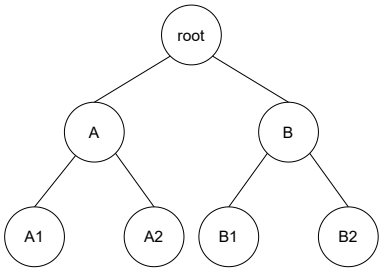


Table 2: Weights used in HLS delay experiments.

Classes	Weights
A	2
B	3
A1	1
A2	3
B1	1
B2	2

Experiments on OMNeT++

Jitter Comparison

- HTB has 2 scenarios:
  - Scenario 1 does not involve borrowing, classes only achieve their guaranteed rates.
  - Scenario 2 has low guaranteed rates, so that classes "borrow" a lot.
- Borrowing has an effect on jitter and delays while using HTB.

Table 3: HTB Scenario 1

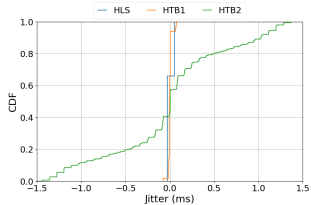
Classes	GR(Mbps)	Quantum
root	100	-
A	40	-
B	60	-
A1	10	1500
A2	30	4500
B1	20	3000
B2	40	6000

Table 4: HTB Scenario 2

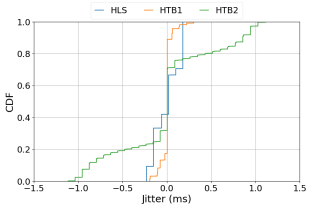
Classes	GR(Mbps)	Quantum
root	100	-
A	4	-
B	6	-
A1	1	1500
A2	3	4500
B1	2	3000
B2	4	6000

Experiments on OMNeT++

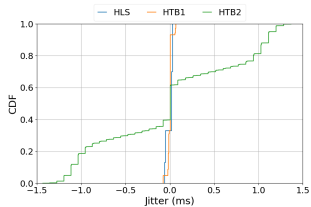
Jitter Comparison



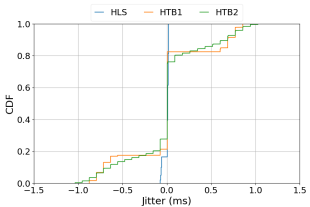
Class A1



Class A2



Class B1



Class B2

Conclusion

- **RQ:** In what ways is HLS advantageous to use compared to HTB (bandwidth sharing, impact on delay, etc.)?
  - HLS achieves class isolation better than HTB. The excess bandwidth from a leaf class in HLS is shared to leaf classes that are as close as possible.
  - The jitter resulting from HTB is higher than HLS.
  - During congestion, the delay of well-behaving classes are lower in HLS compared to HTB.
- In future, using OMNeT++ implementation, a rate limiting feature can be added to HLS and then tested for rate conformance and delay/jitter bounds.

Bibliography

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Backup Slides

Overhead Test

- OMNeT++ does not include scheduling overhead.
- The hierarchies are perfect binary trees.
- UDP packets of size 60 bytes are generated. We compute the number of packets sent per second.

Table 5: Results of overhead analysis experiments.

Qdisc	Packets/s (4 leaves)	Packets/s (128 leaves)
HLS	362240	241970
HTB	365590	226295
pfifo	358880	377945

- HLS scales slightly better than HTB.
- According to [2], classifying packets is the most significant contributor to overhead.
- By default, qdiscs cannot enqueue and dequeue at the same time.
- The overhead is not significant enough for the link data rates we use in OMNeT++ experiments.

Backup Slides

HTB Borrowing Analysis

- Quantum values and priorities of leaf classes are equal.
- Maximum rate of all classes are set to 100 Mbps.
- Every leaf class is generating packets at a speed of 100 Mbps.
- Experiment was done in OMNeT++.

Figure 20: Hierarchy used in HTB borrowing analysis Experiment 1.

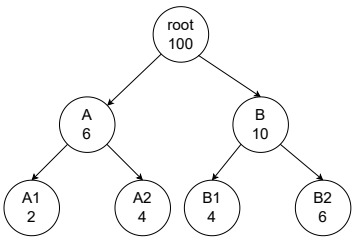
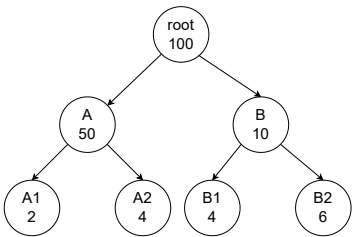


Figure 21: Hierarchy used in HTB borrowing analysis Experiment 2.



HTB Borrowing Analysis

- Colored numbers under the nodes denote how much bandwidth that class borrowed from the corresponding ancestor.
- The guaranteed rate of inner node changed how root distributes bandwidth.
- This can lead to unintended and unpredictable bandwidth sharing.

Figure 22: Experiment 1 results

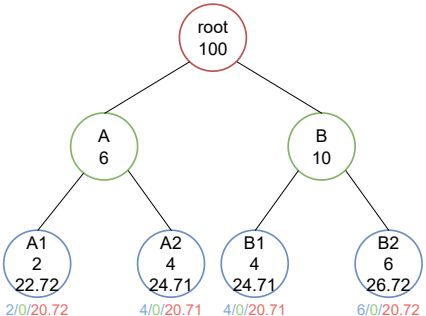


Figure 23: Experiment 2 results

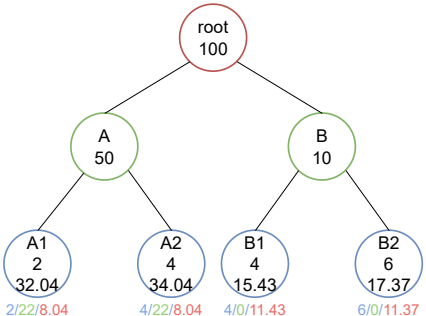
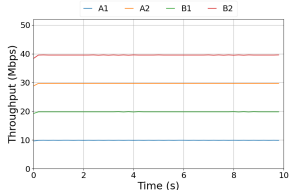
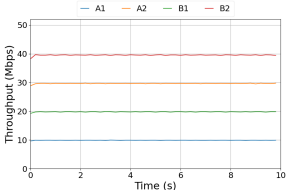


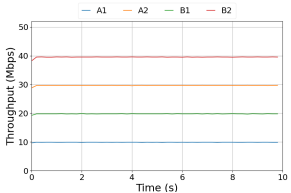
Figure 24: Throughput



HLS



HTB Scenario 1



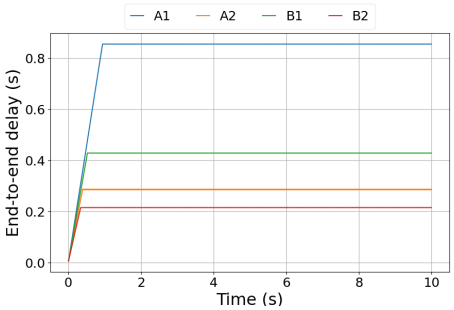
HTB Scenario 2

Backup Slides

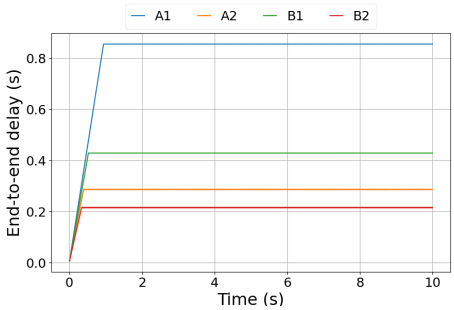
Delay and Jitter

- Qdiscs by default and this OMNeT++ test has FIFO queues with packet size limit of 1000 in leaf classes.
- To minimize delay using UDP it might be beneficial to reduce queue size or use another qdisc as leaf queues.

Figure 25: End-to-end delay



HLS



HTB Scenario 1 and 2