Carousel: Scalable Traffic Shaping at End Hosts

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Rate limiting and isolation between thousands of flows per machine [BwE - SIGCOMM ’15]

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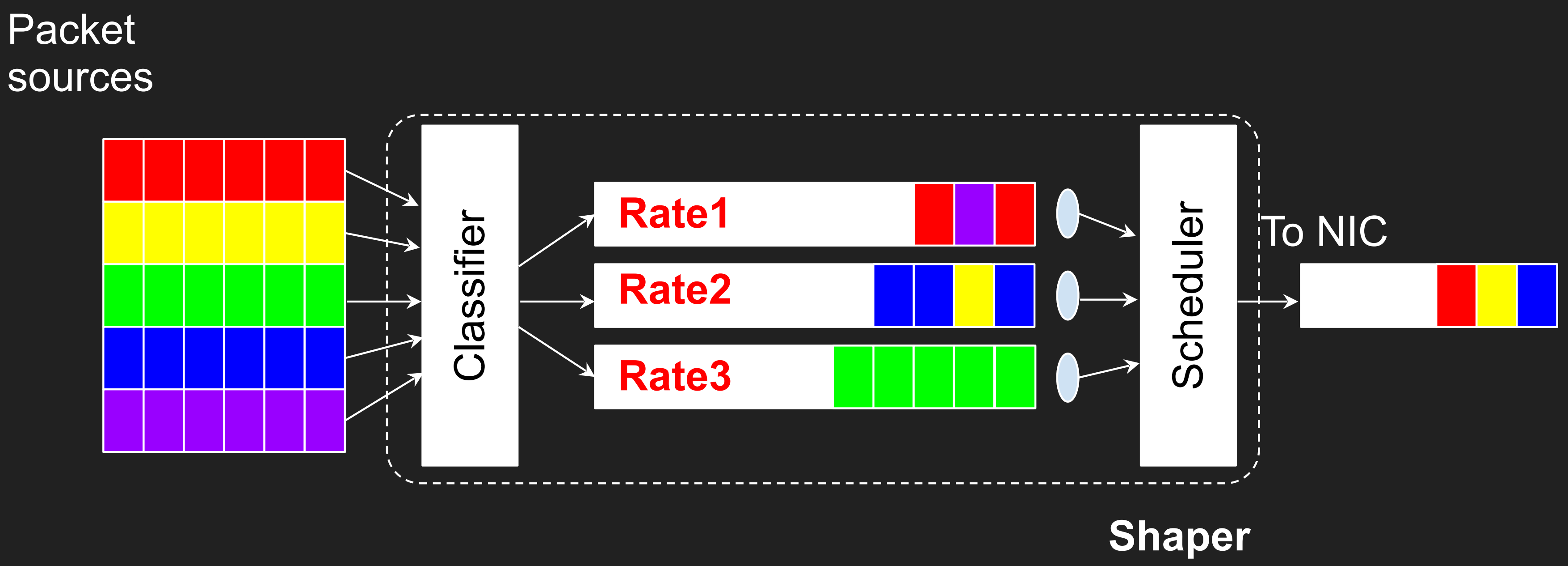
New protocols that require per-flow pacing [TCP BBR and TIMELY - SIGCOMM ’15]

Traffic Shaping



Packet sources

Classifier

Rate1

Rate2

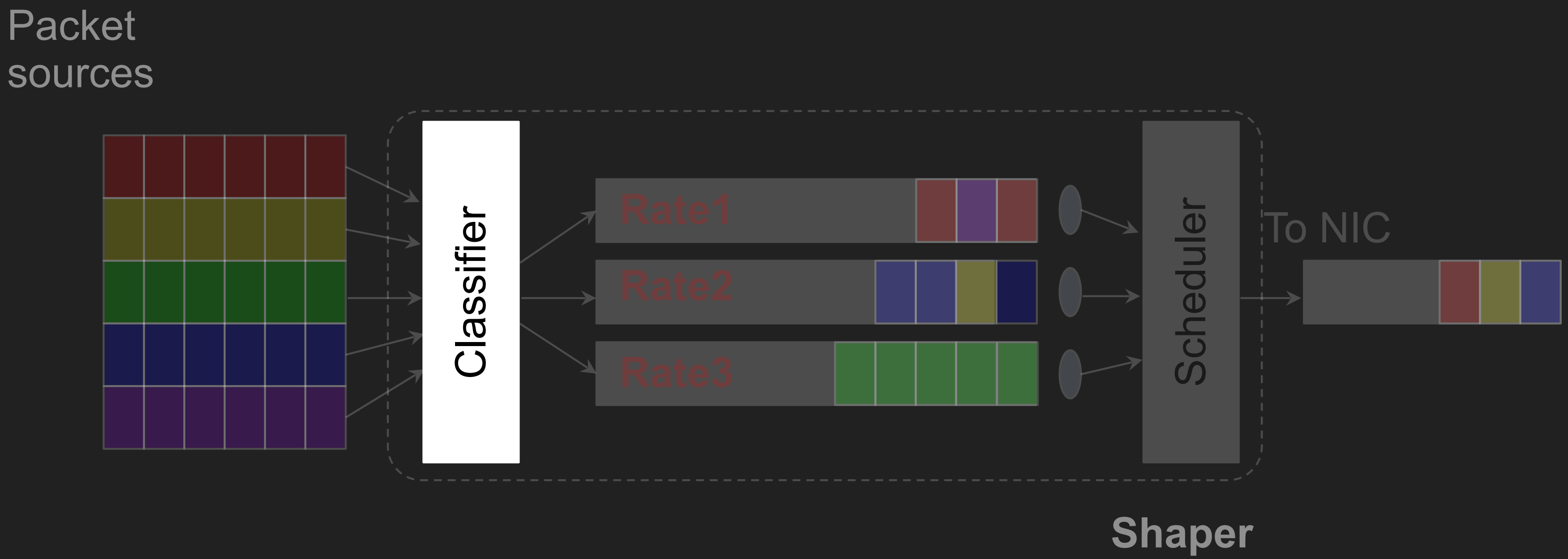
Rate3

Scheduler

To NIC

Shaper

Traffic Shaping



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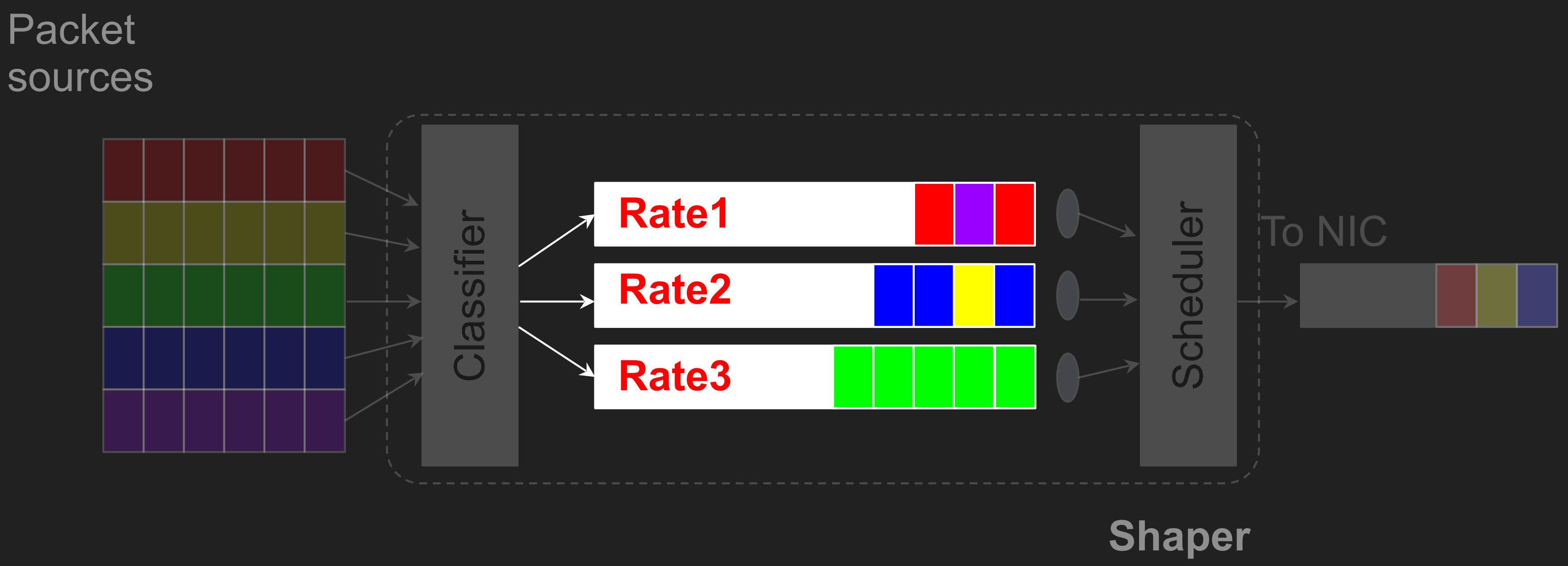

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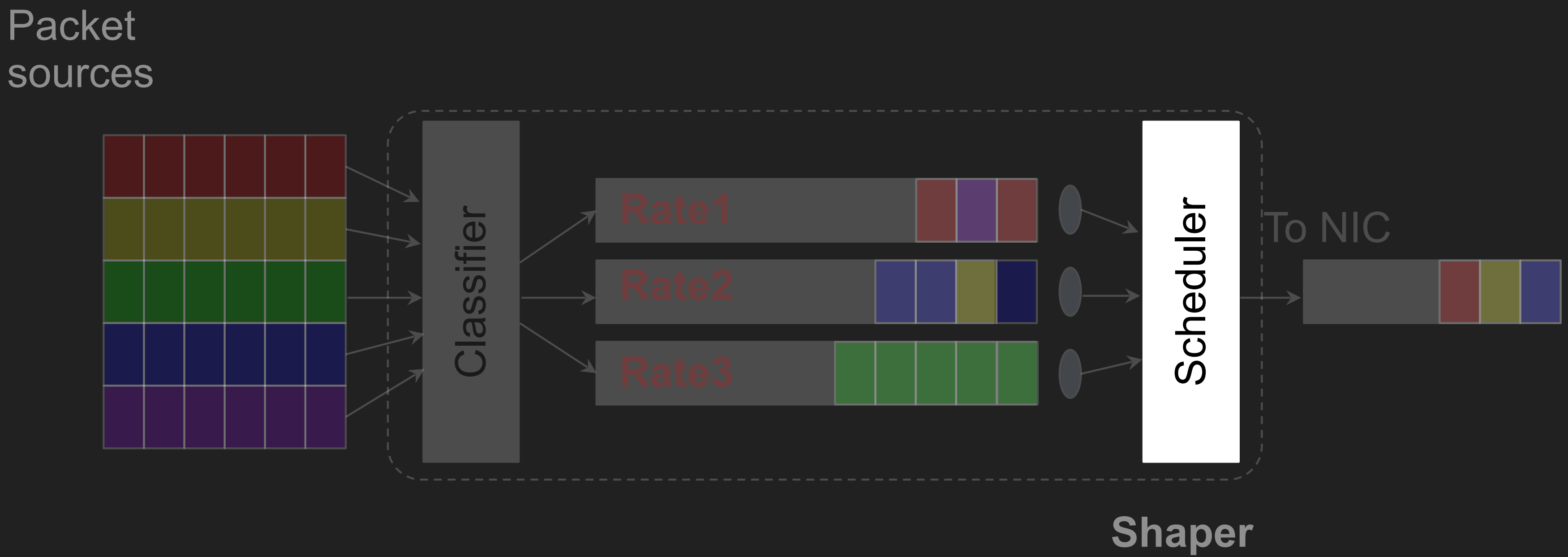

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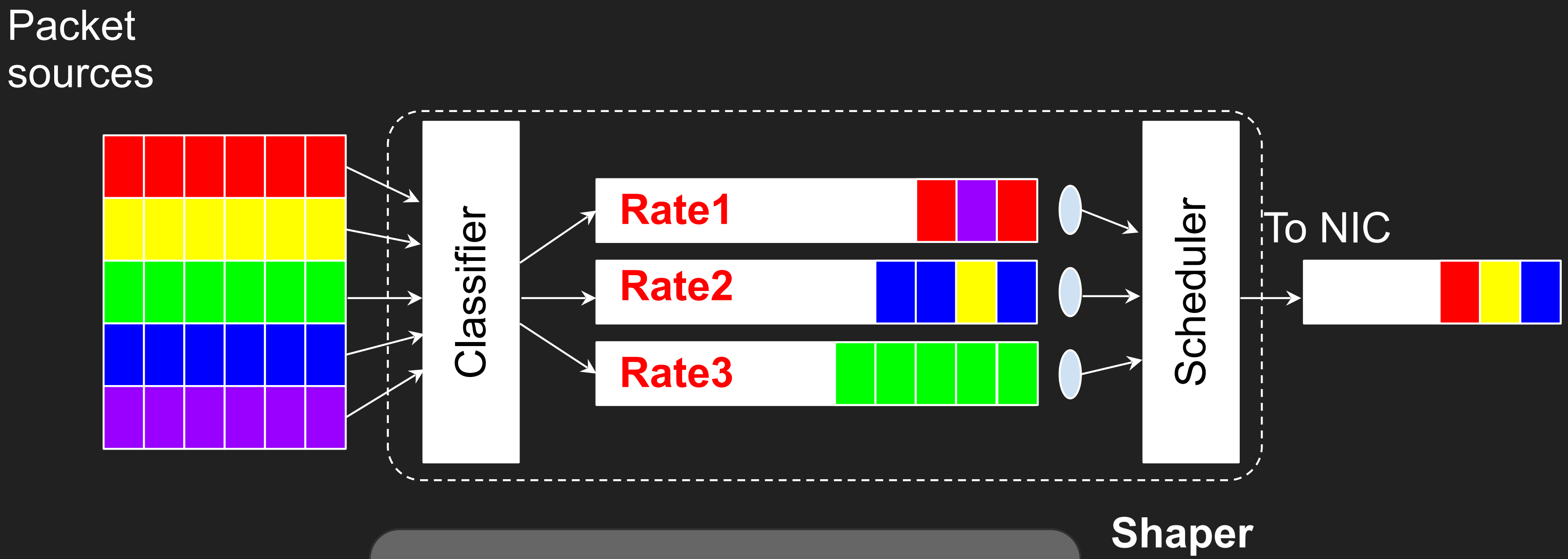
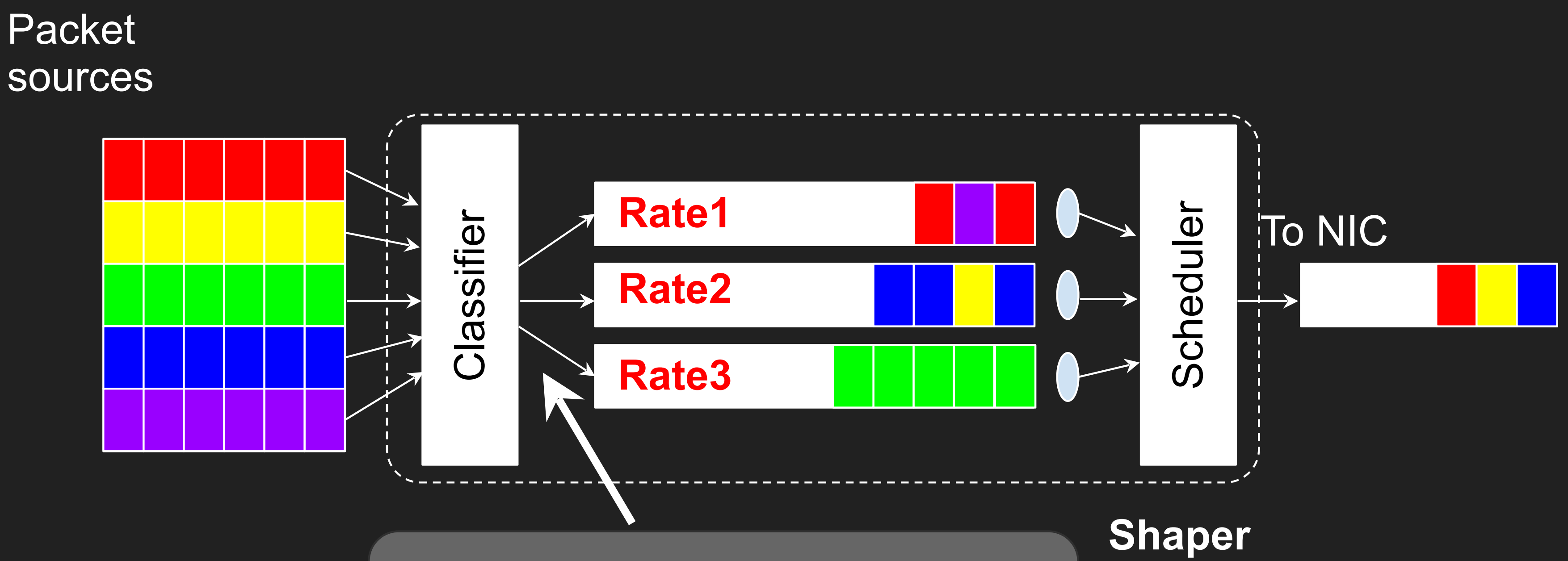


Overhead of managing a queue per configured rate

Traffic Shaping



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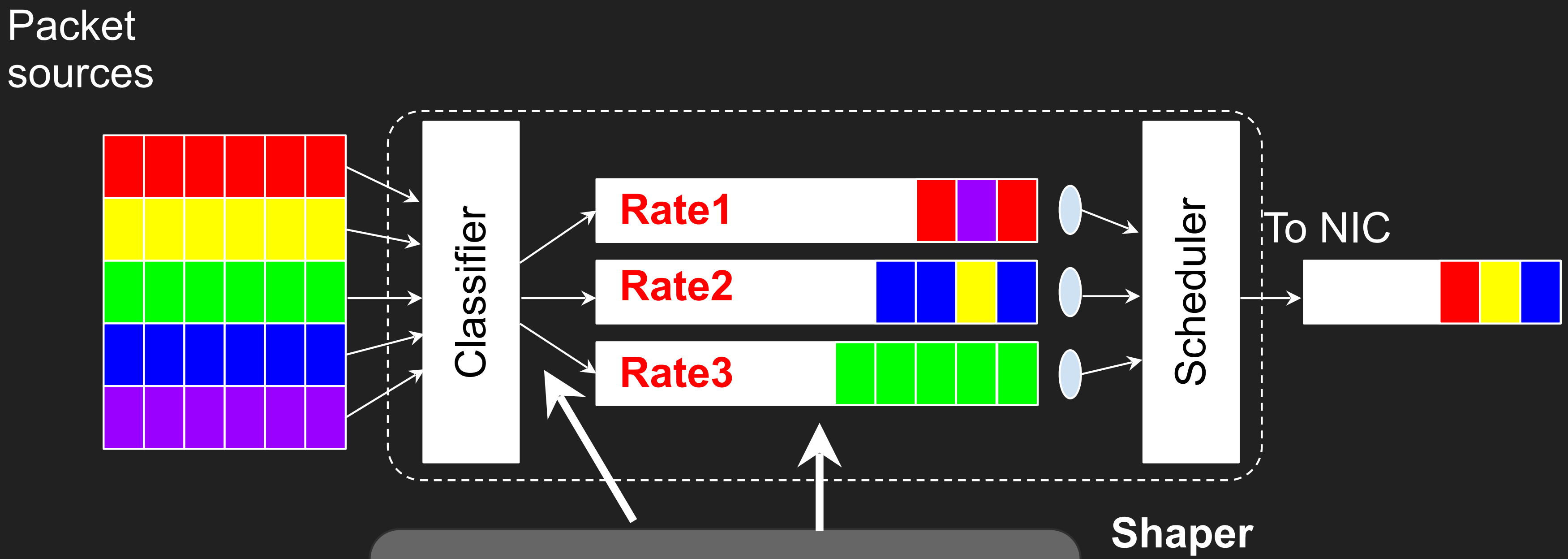

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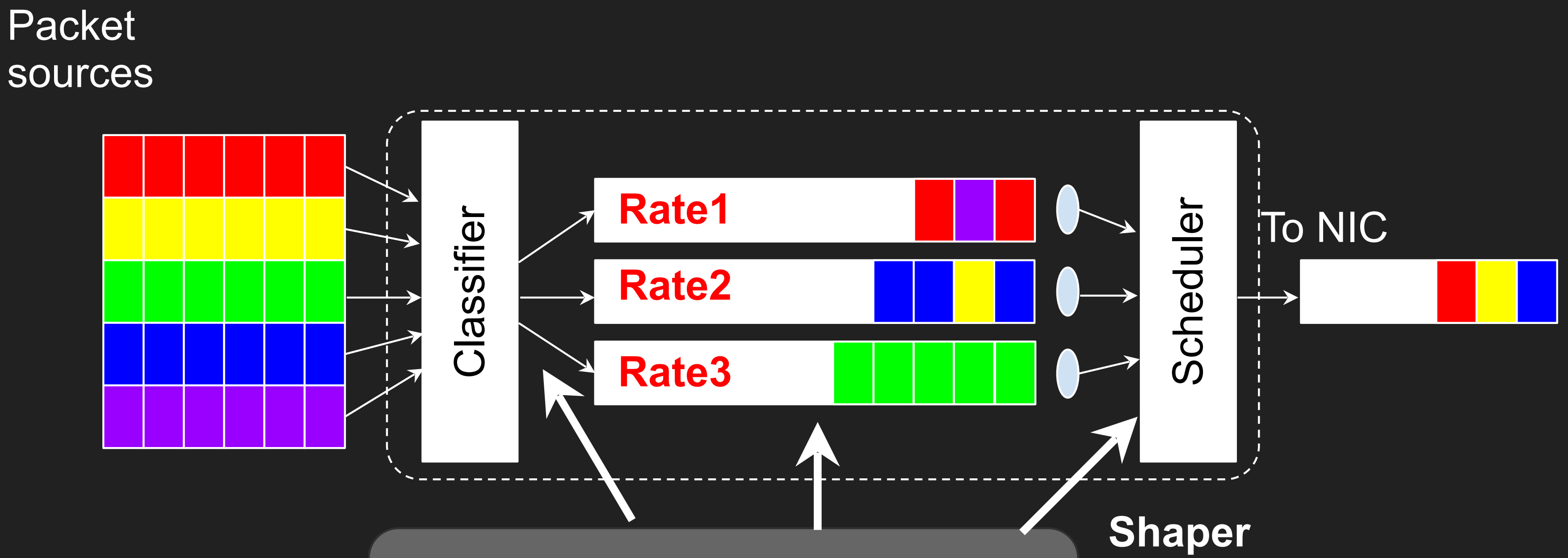
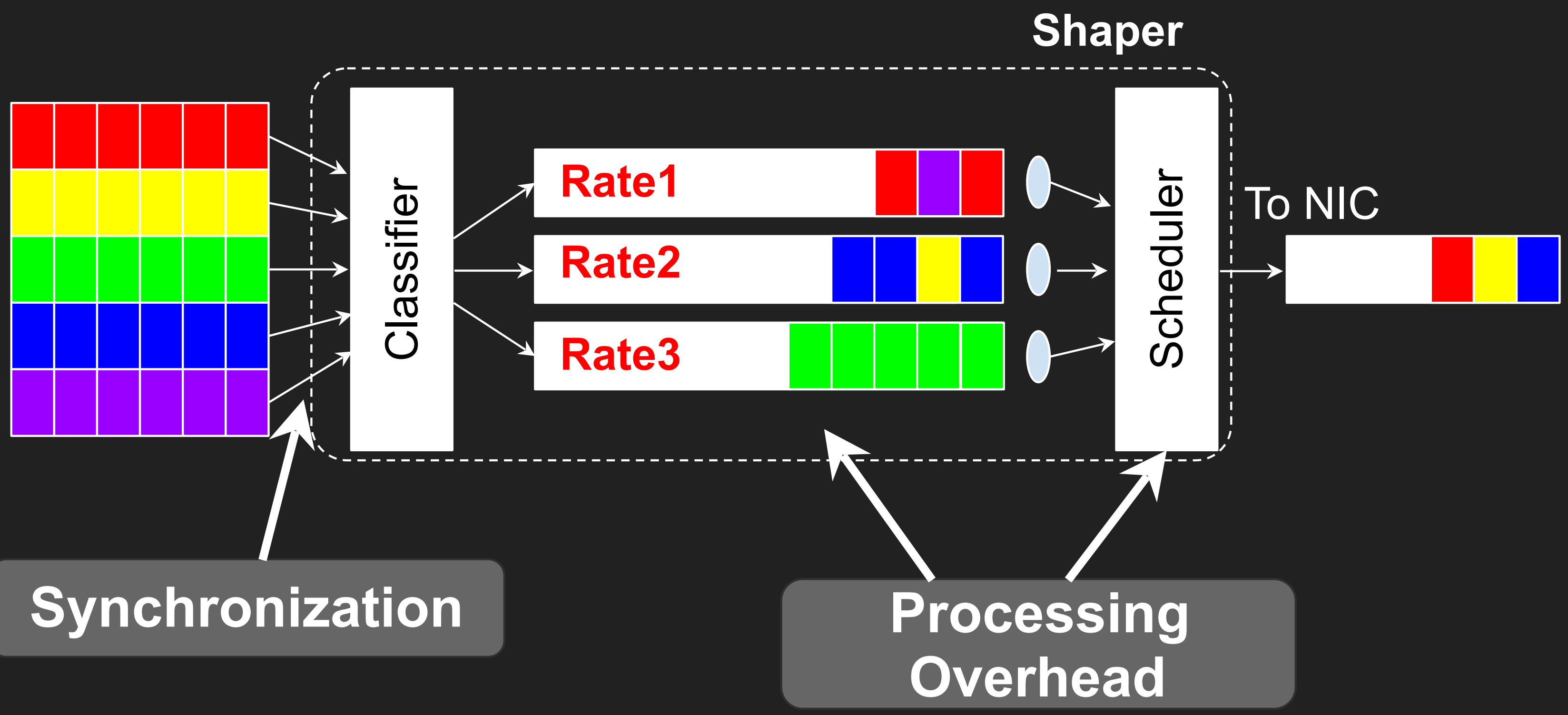


Overhead of managing a queue per configured rate

We need new traffic shapers that can handle tens of thousands of flows and rates

Main Idea💡
Replace the **many queues**
with **a single low-overhead queue**

Contributions



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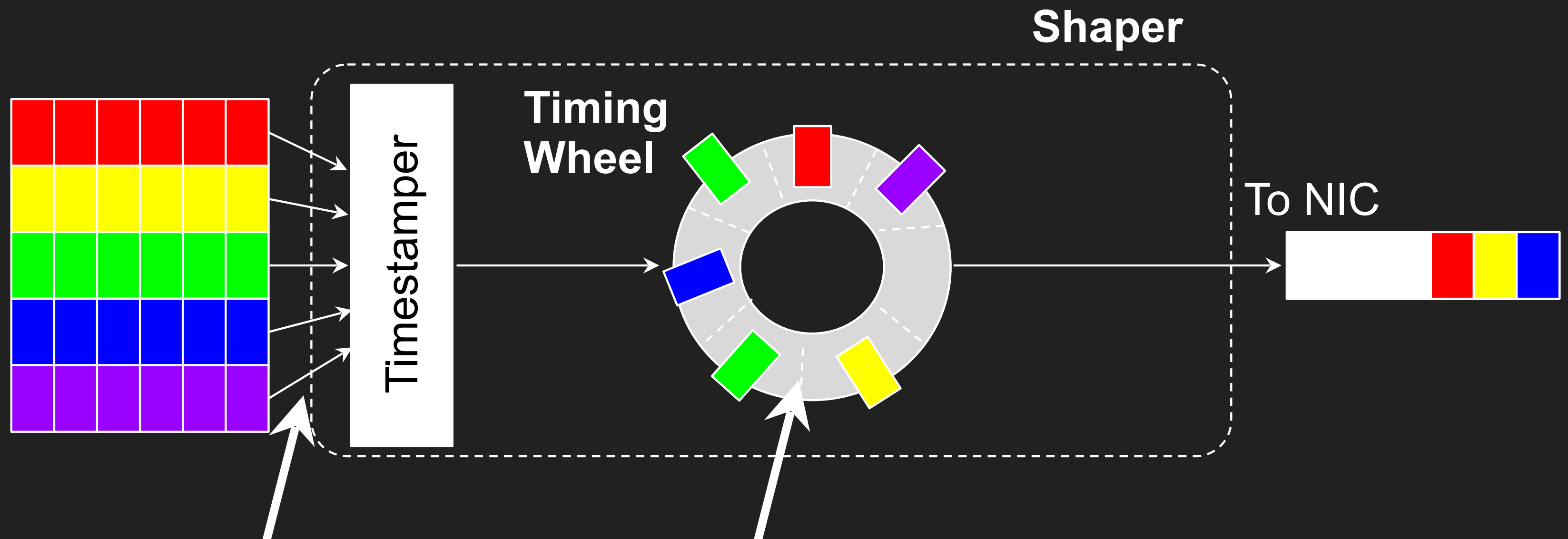
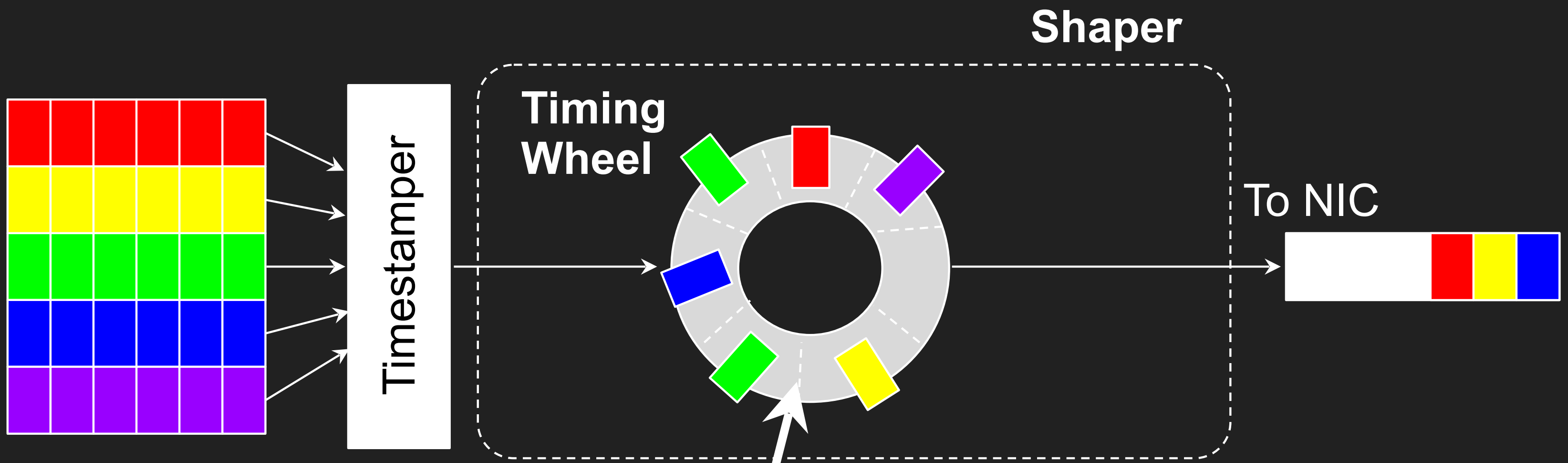


Synchronization

Single, O(1), Queue

Contributions



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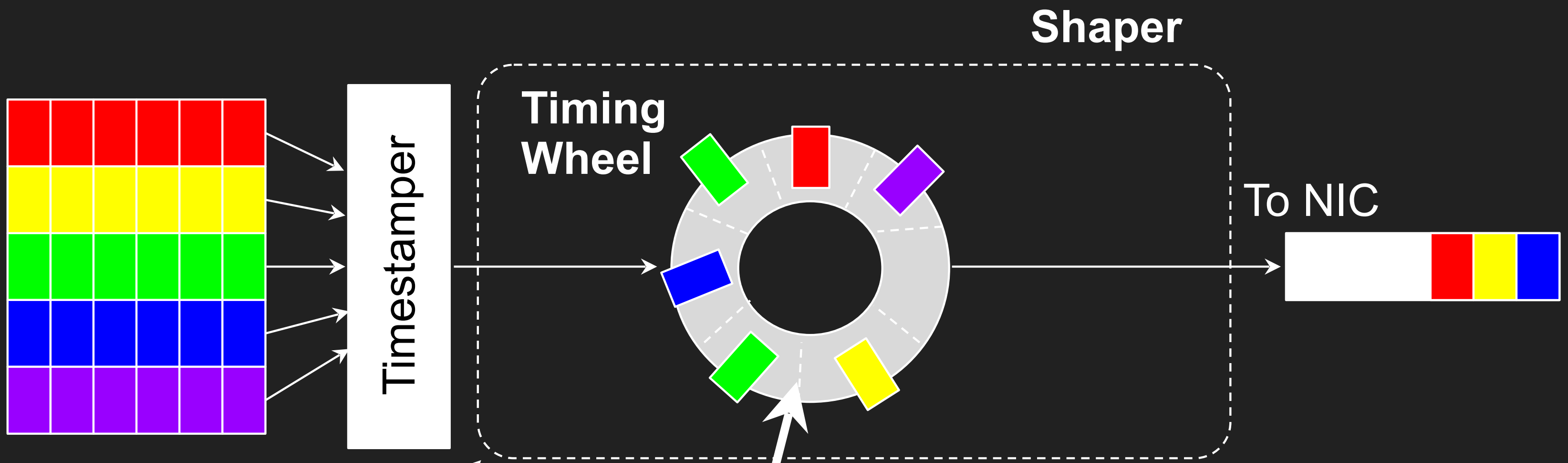
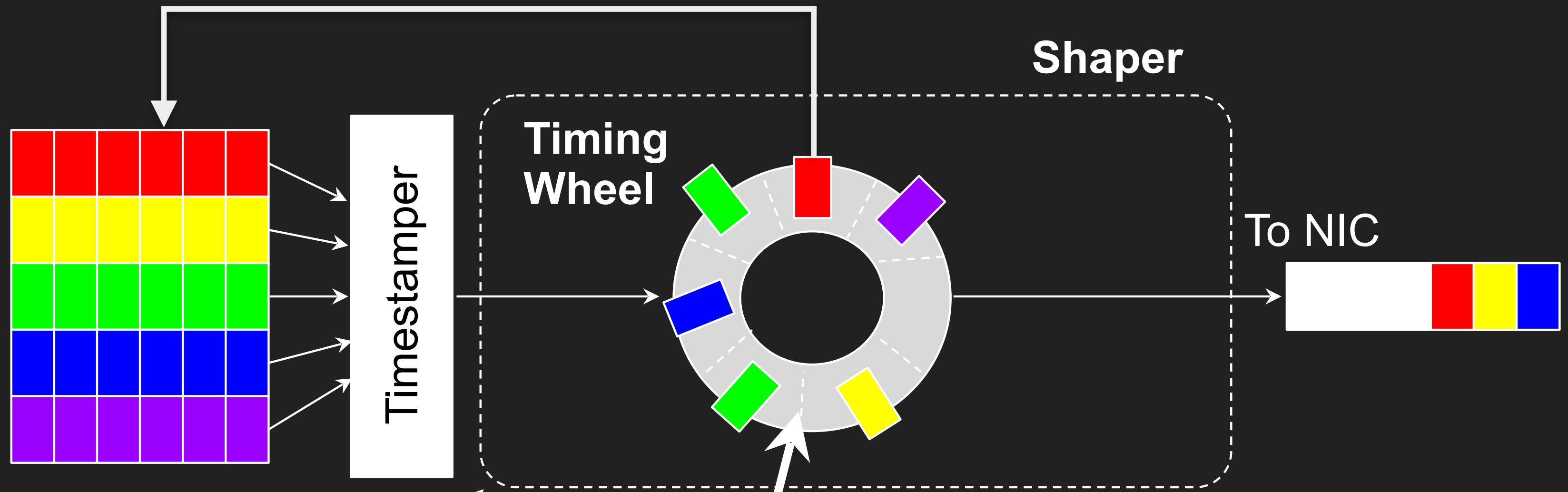


One Shaper per Core

Single, O(1), Queue

Contributions

Apply backpressure



One Shaper per Core

Single, O(1), Queue

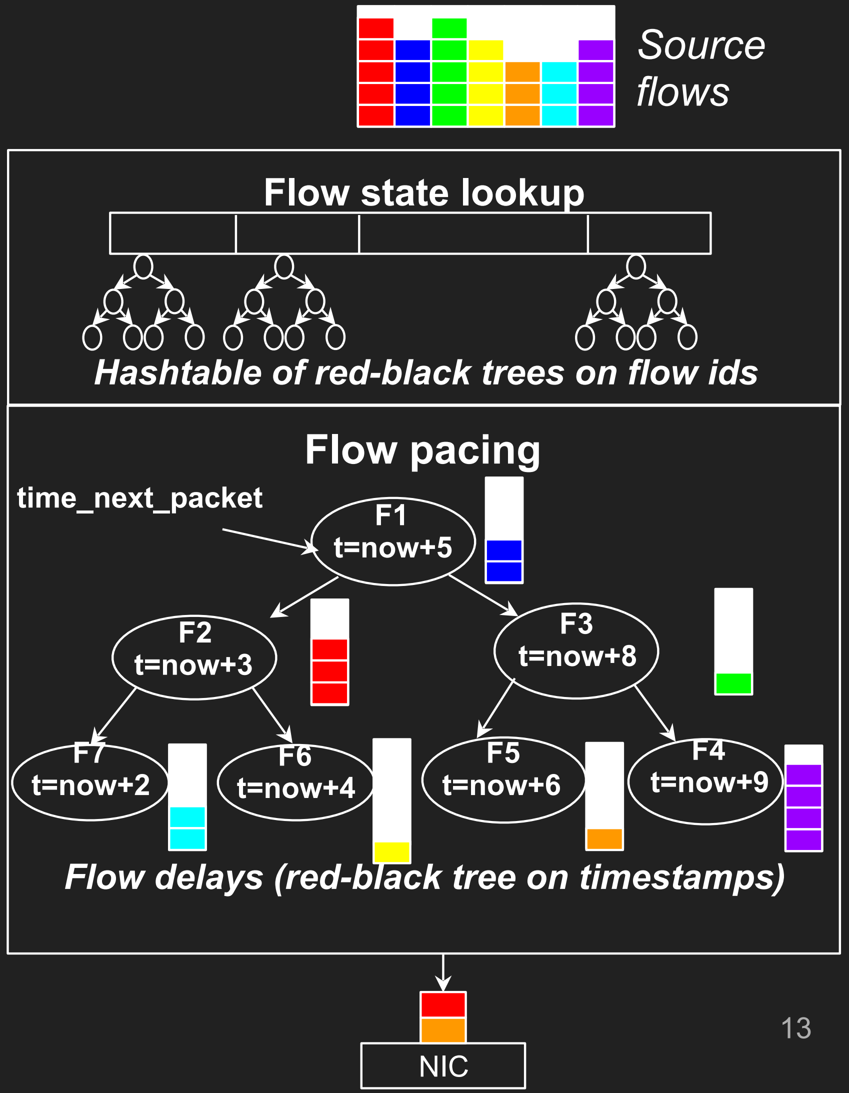
Outline

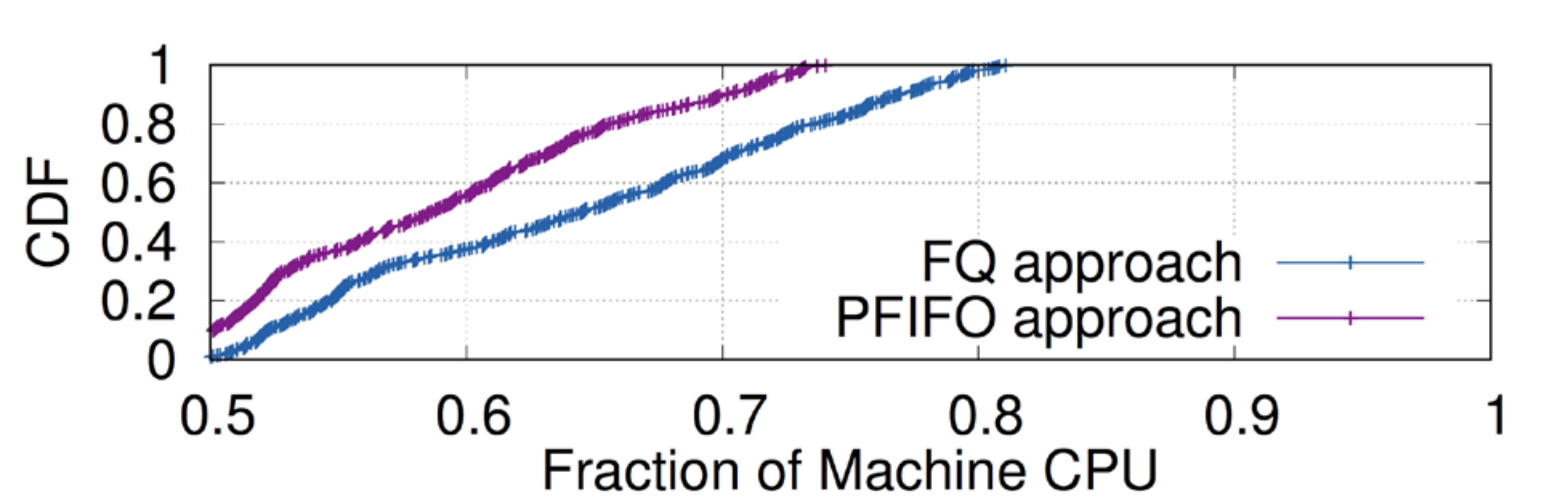
- Problems with Current Shapers
- Carousel Overview
- Single Queue Shaping
- Backpressure
- Evaluation

Problems with Current Shapers

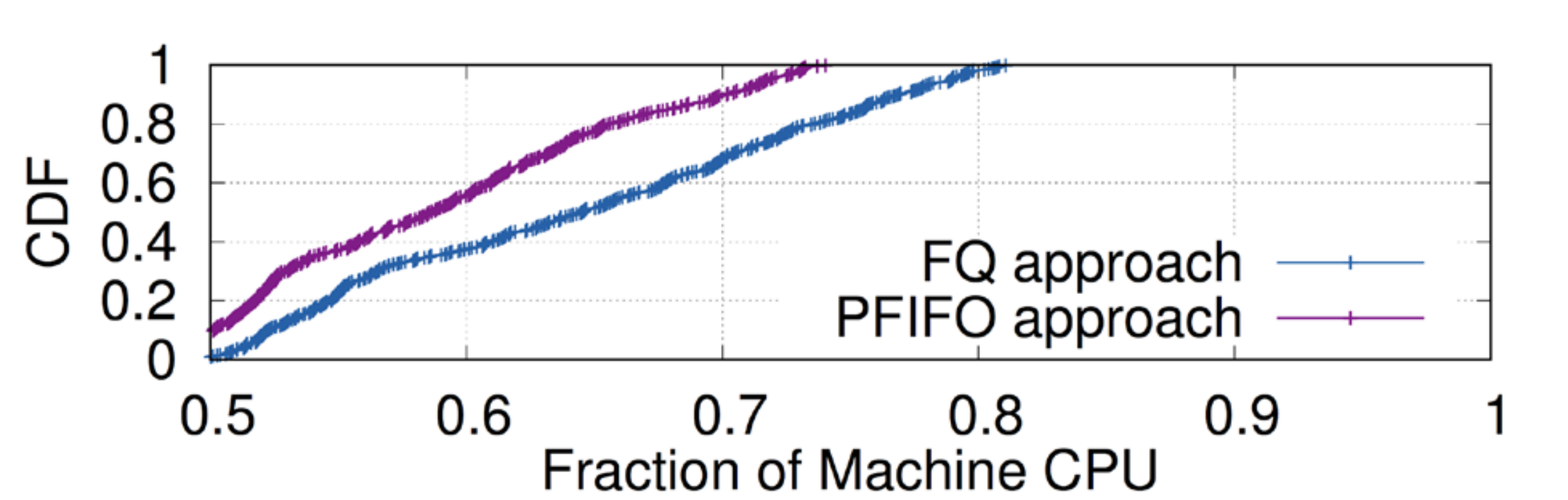
FQ/Pacing

- Implements per TCP flow pacing
- Requires a queue per flow
    - Flows are kept in order of their scheduled transmission time
    - Flows are dequeued in order
- O(log n) operations per packet to operate on a sorted list of flows





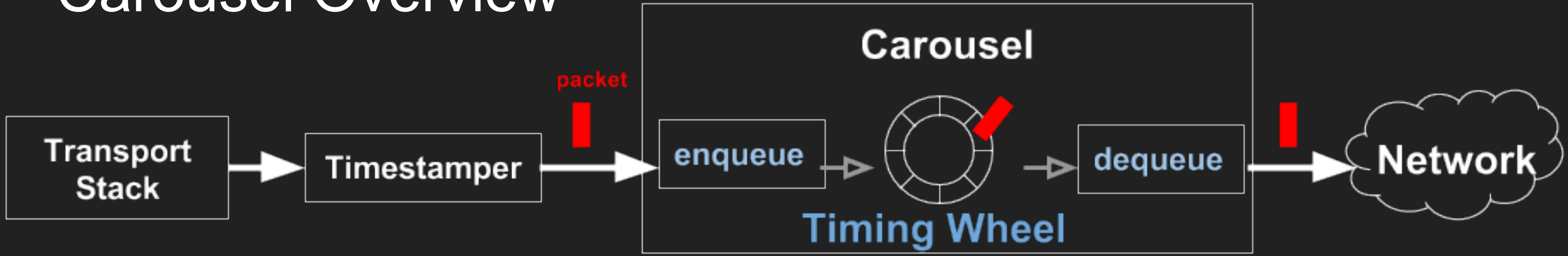
CPU utilization for FQ/pacing and a NOOP Qdisc for the same load



FQ/Pacing introduces 10% more CPU overhead

Carousel Overview

Carousel Overview



- Relies on a single queue for all packets from all flows
- Requires a high frequency timer or busy polling
- Pinned to a single core

Single Queue Shaping

Single Queue Shaping

- All packet are sorted by their transmission time in one data structure
- A single queue for all traffic will need to handle tens of thousands of packets
- **Challenge:**
  Enqueue and dequeue in a data structure of sorted elements at line rate

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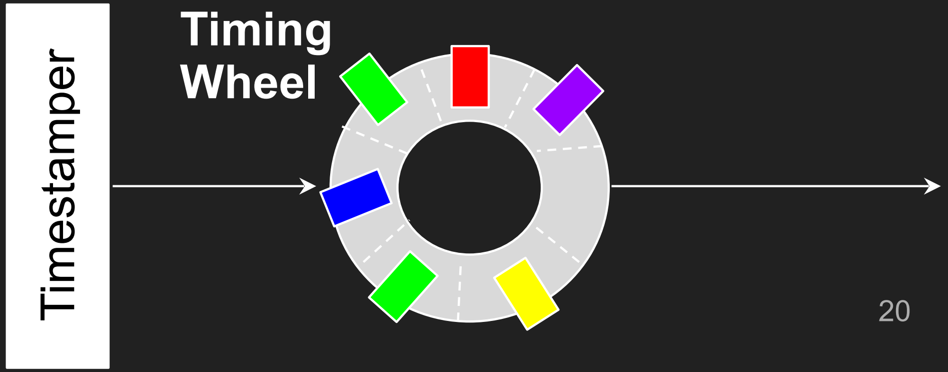
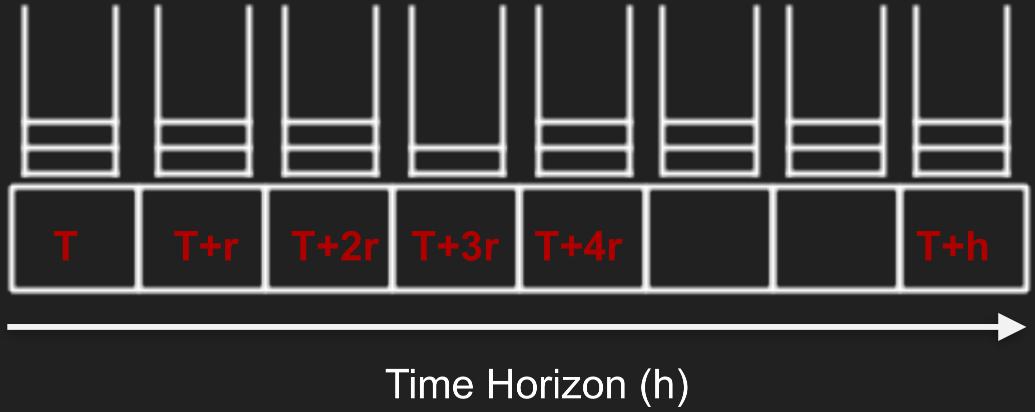


Timing Wheel [Varghese et al. SOSP ’87]

- Bucket sort approach to Calendar Queue covering a time horizon
  - Relies on having a minimum rates
- Implemented as an array of buckets each a linked list of packets
  - Each bucket represents a certain time range

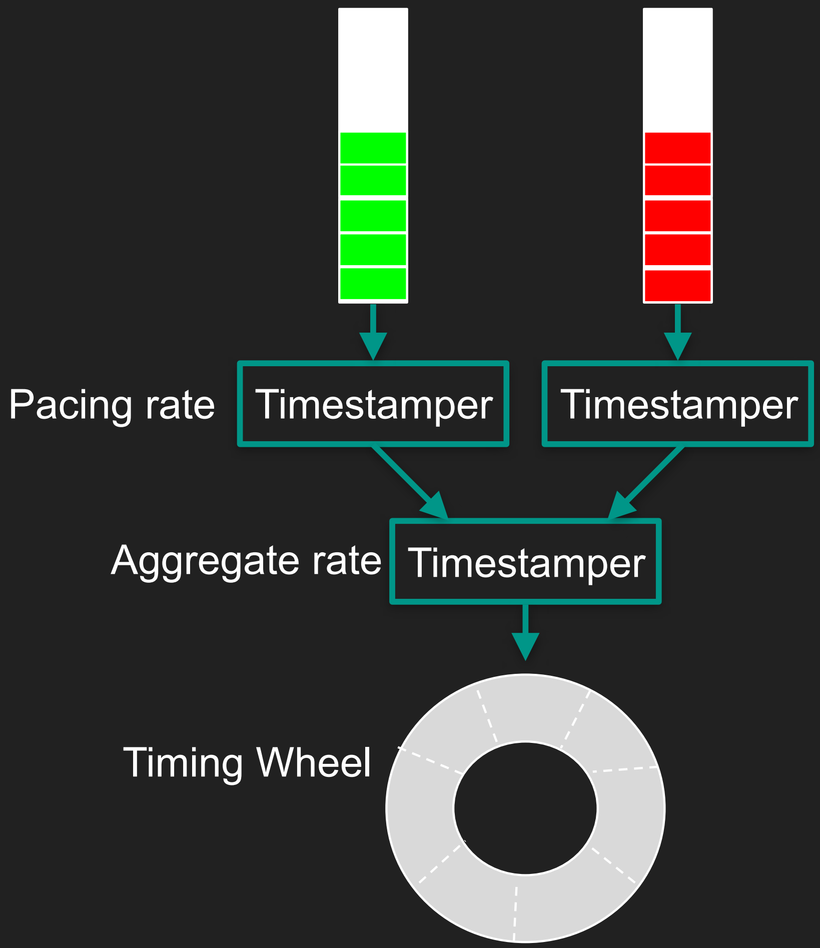


Timing Wheel Benchmark

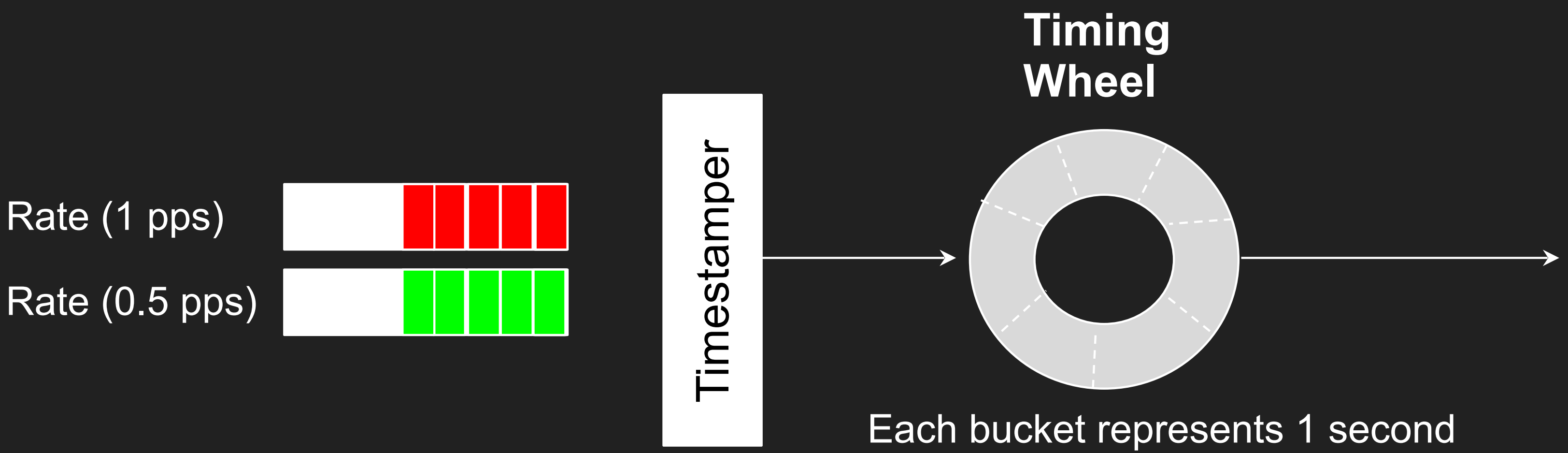
- Measured overhead per enqueue/dequeue pairs
- Overhead per element is between 21-22 nanoseconds
  - Fixed for 2000 to 2 million sorted elements
  - 21 nanoseconds per packet = 500 Gbps (for 1500 byte packets)

Timestampers

- Packets are timestamped by policy enforcers in their transmission path
  - TCP timestamps a packet based on its pacing rate
  - Bandwidth enforcer timestamps a packet based on its policy-based aggregate rate
- Carousel picks the largest timestamp
- NextTimestamp = LastTimestamp + $\frac{\text{SizeOfPacket}}{\text{ConfiguredRate}}$



Example of Shaping using Carousel



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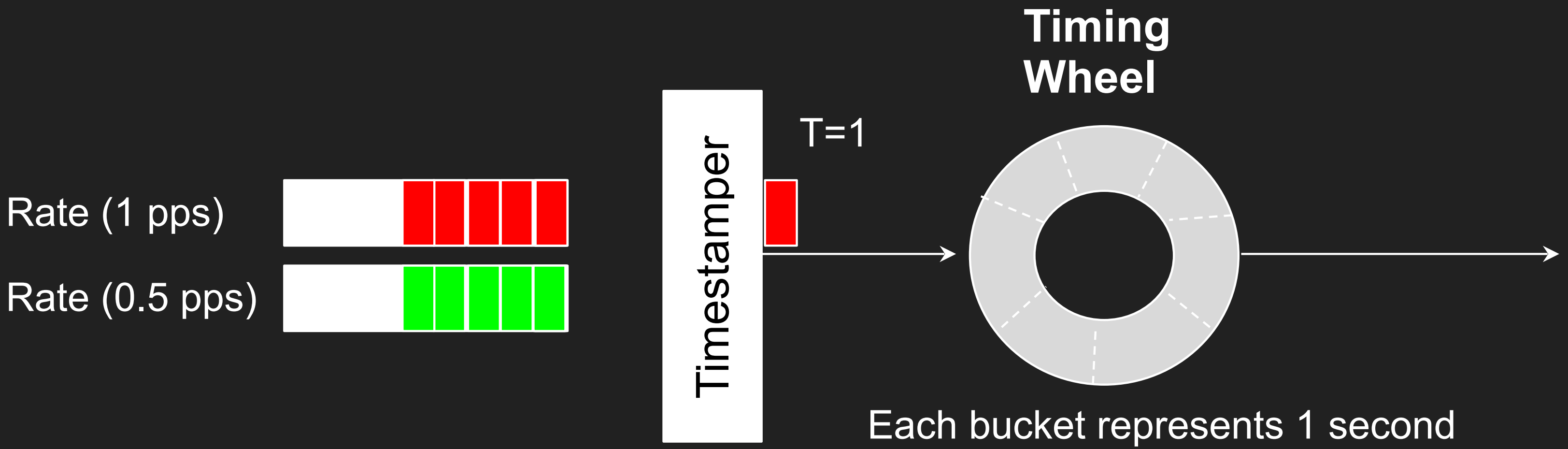

A time step **0**

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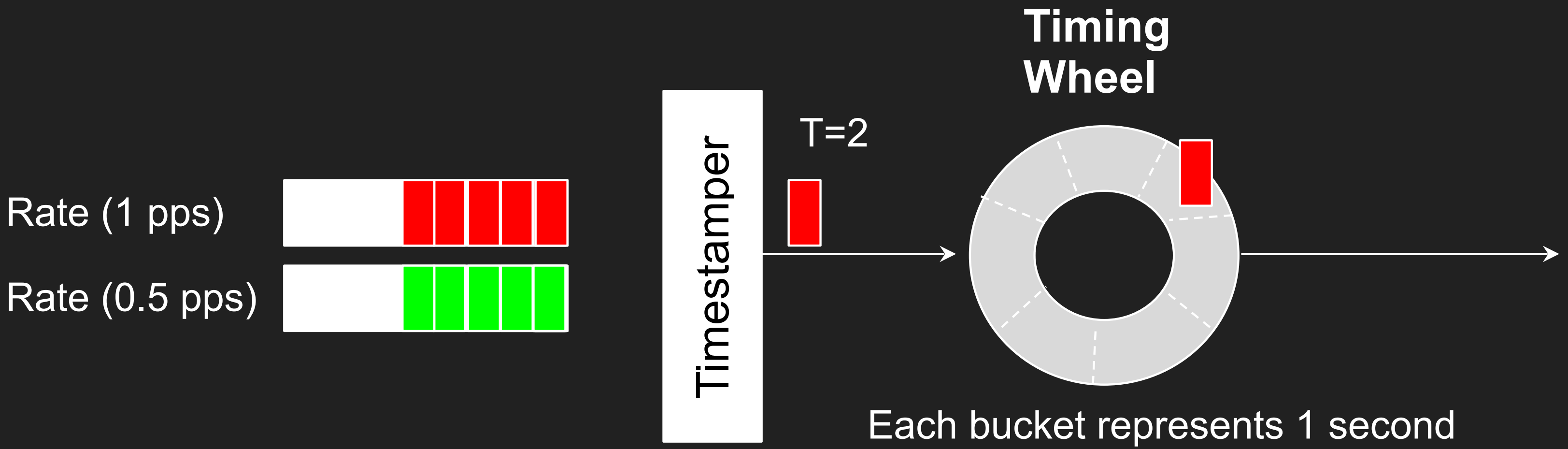

Each bucket represents 1 second

A time step **0**

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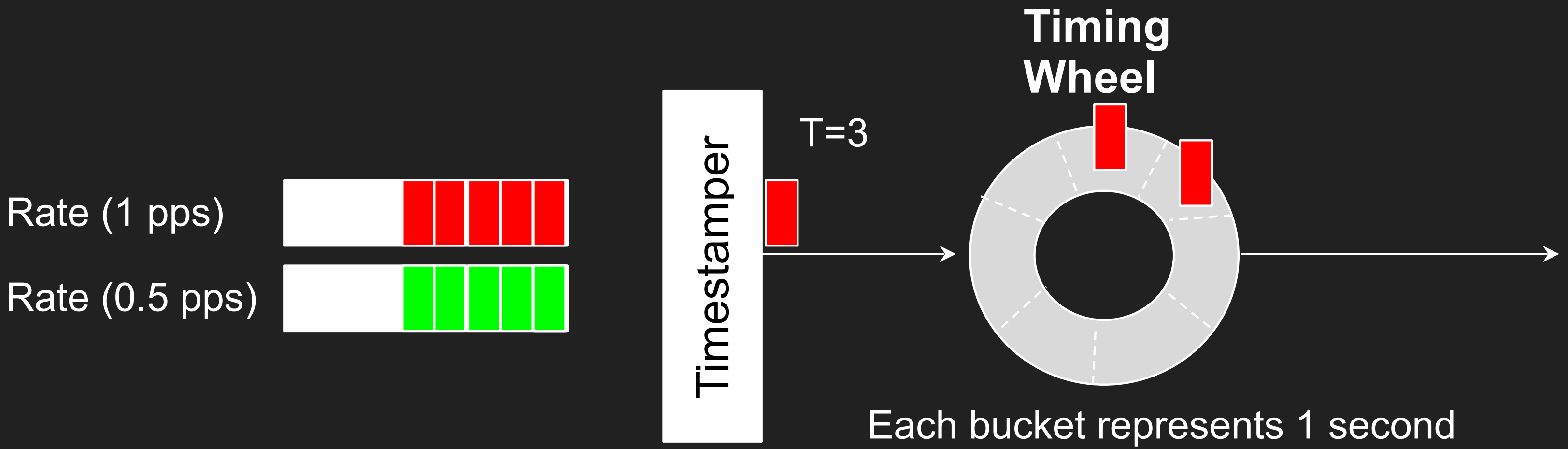

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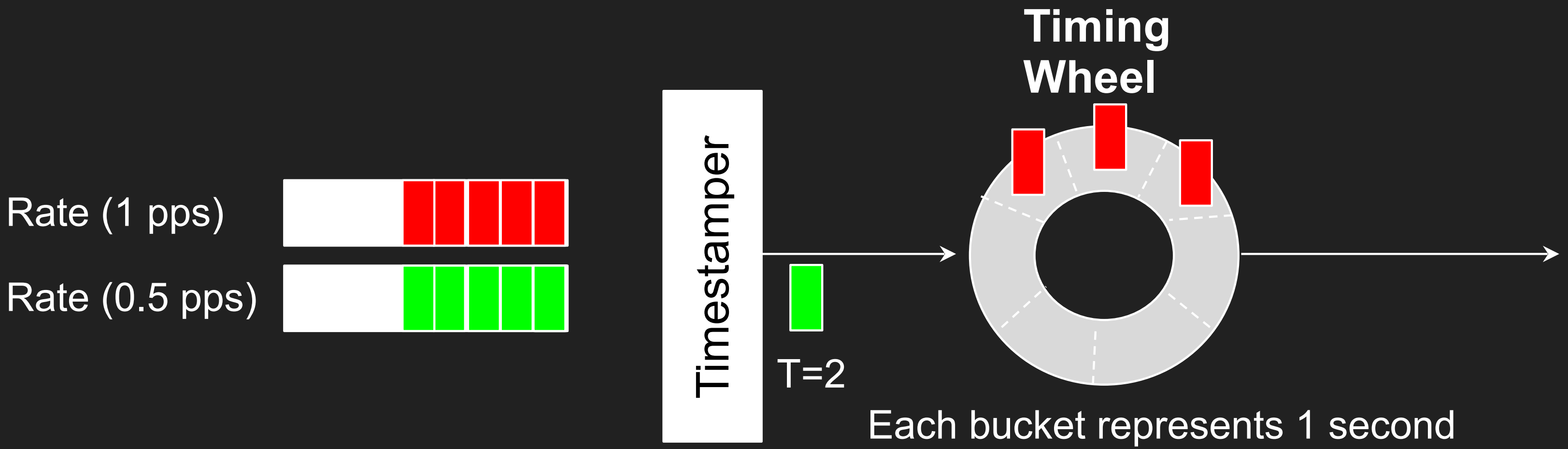

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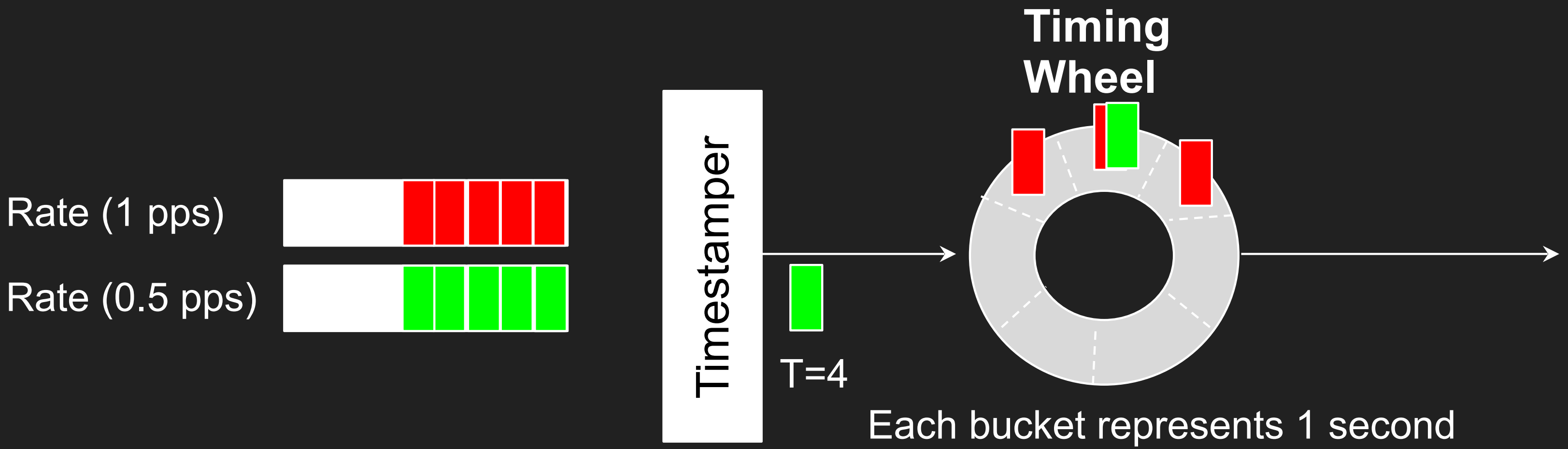

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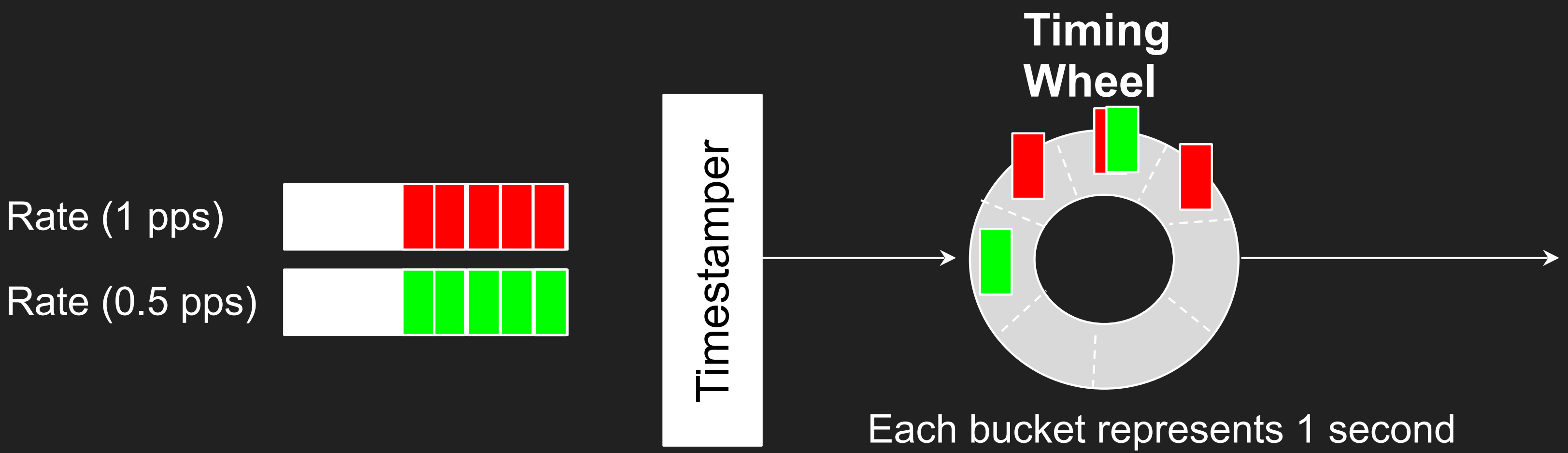

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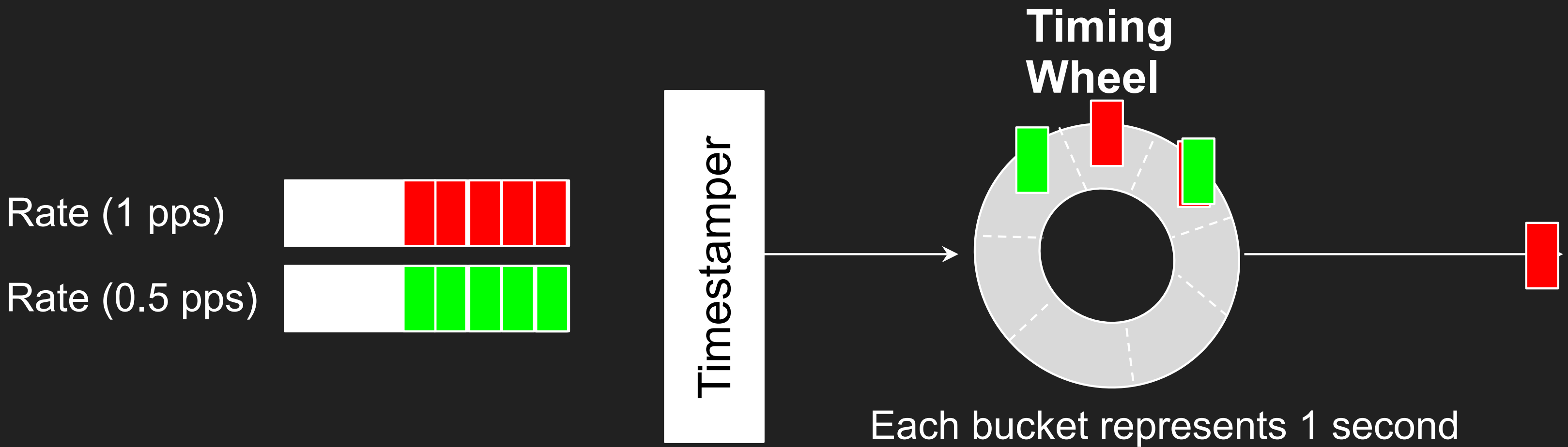
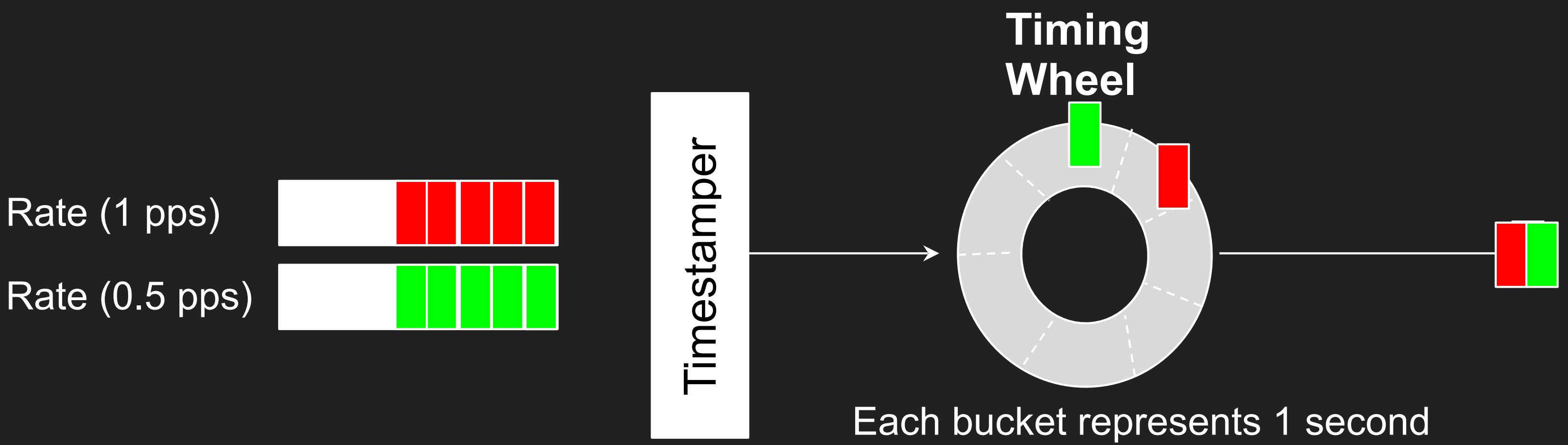


Each bucket represents 1 second

A time step **1**

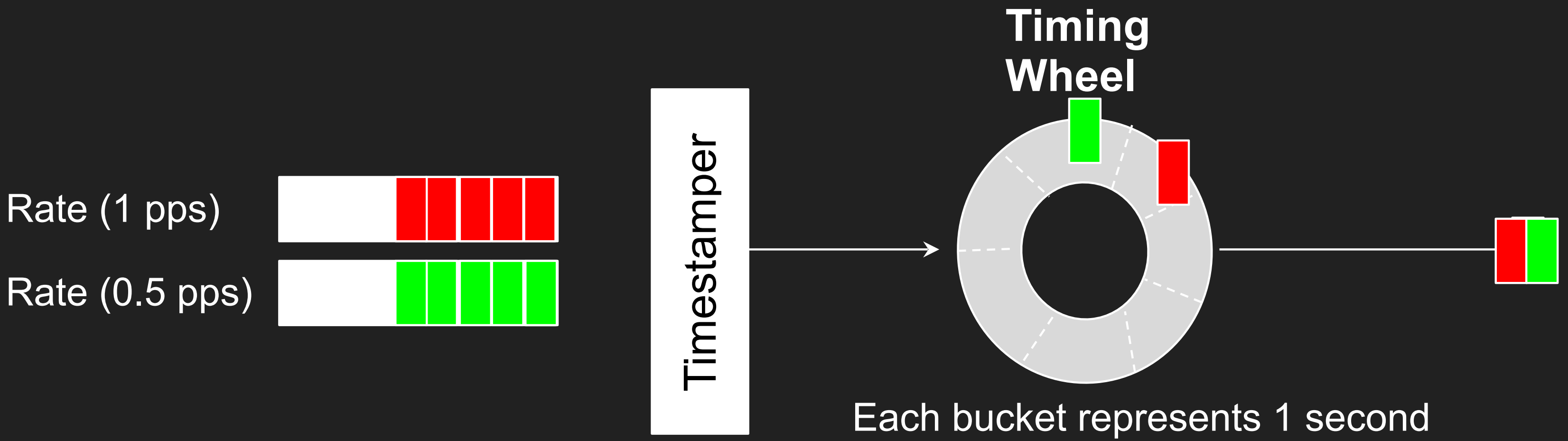
Example of Shaping using Carousel



Each bucket represents 1 second

A time step **2**

Example of Shaping using Carousel



Rate (1 pps)

Rate (0.5 pps)

Timestamper

Timing Wheel

Each bucket represents 1 second

Backpressure with Deferred Completion

The Value of Backpressure

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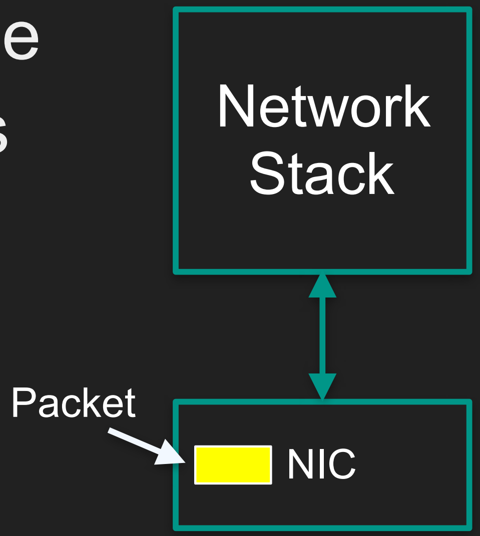
- Without backpressure shaper queues get full with small number of flows causing
  - Unnecessary drops (when the queue is full the queue tail drops)
  - Head of Line Blocking
- Backpressure allows shapers to control sender rate and avoid overwhelming the shaper

The Completion Signal

- Completions are signals from the NIC to the network stack to inform it that a packet has been transmitted



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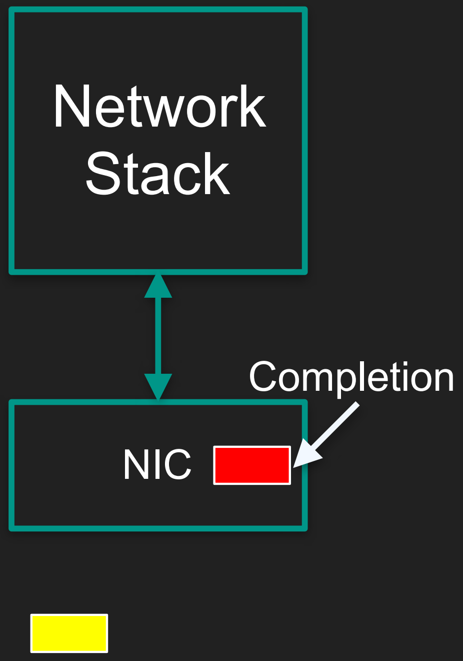

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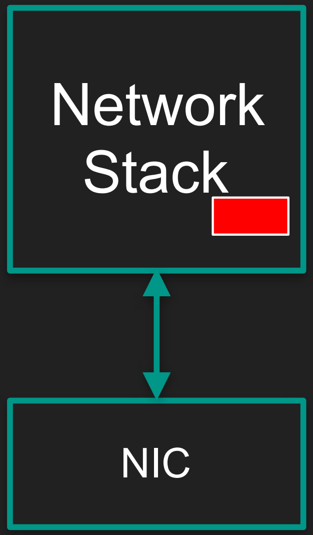

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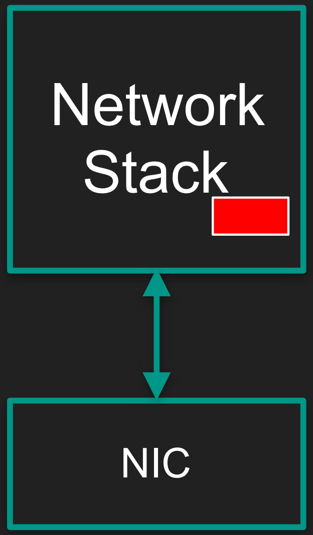

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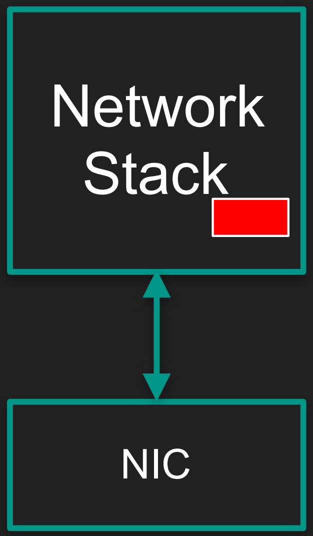

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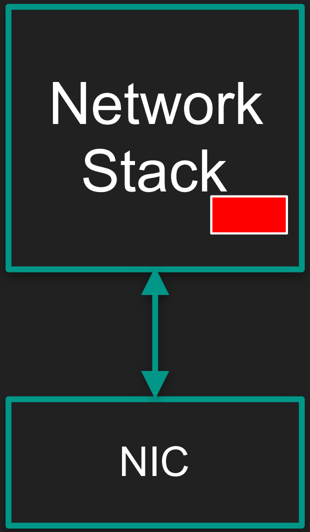
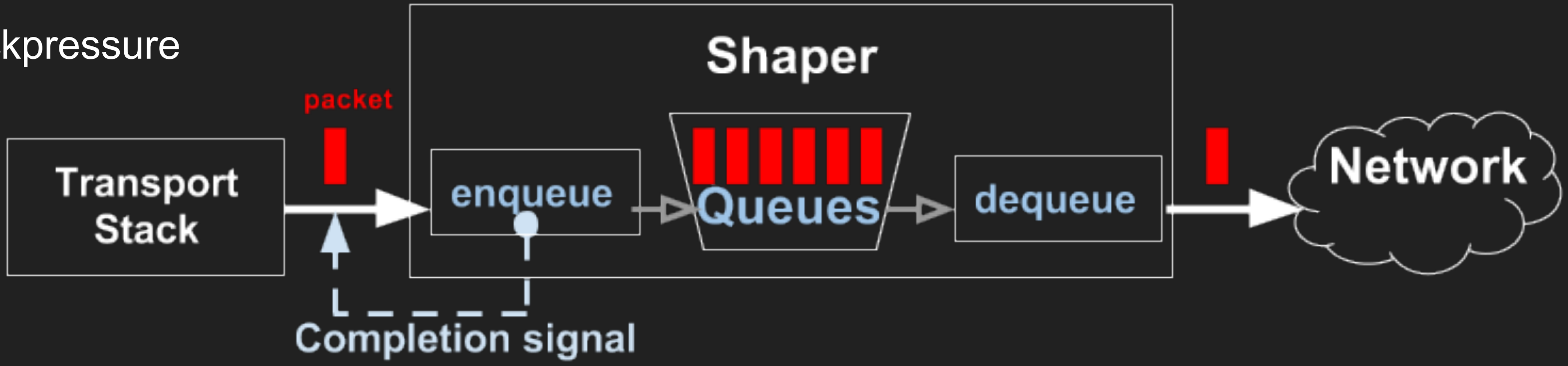
- Completions should be delivered out of order and completely controlled by Shapers



Backpressure with Deferred Completion

Without Backpressure



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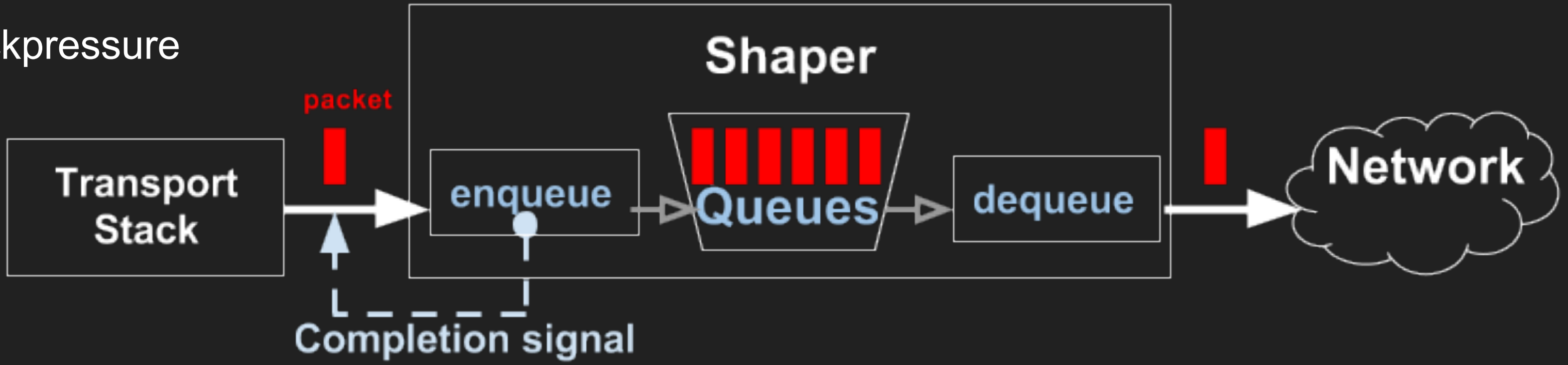

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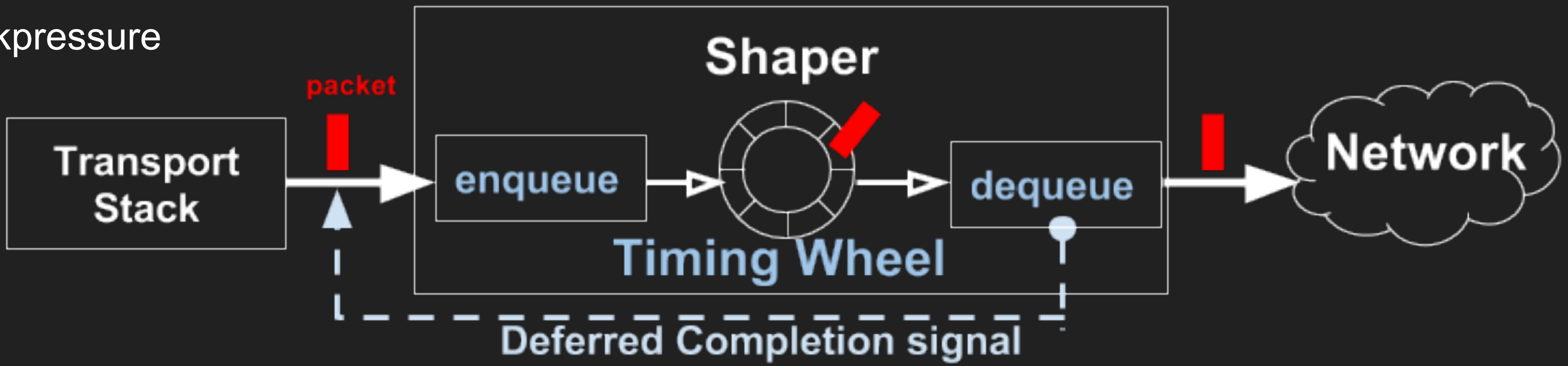

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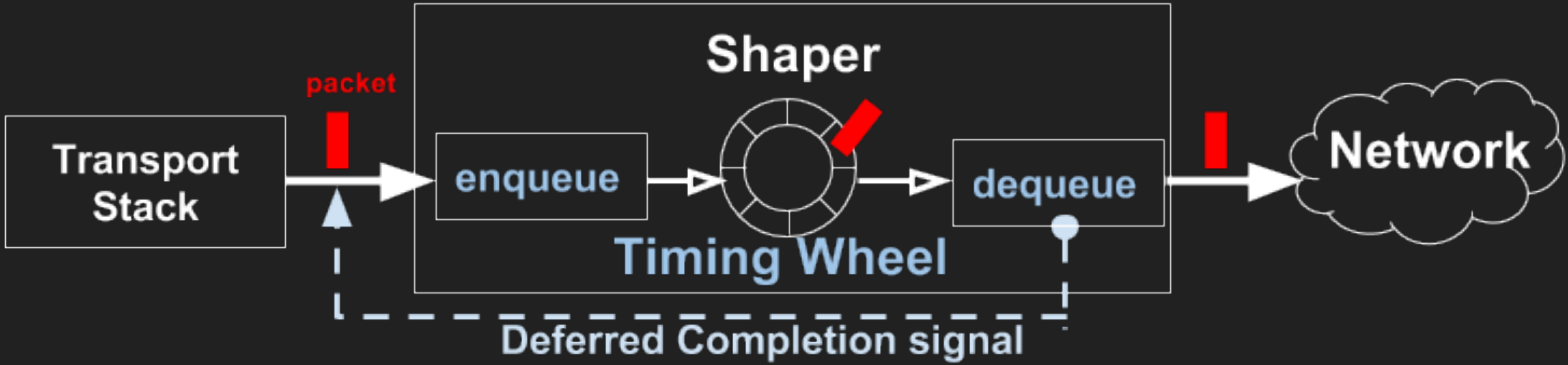

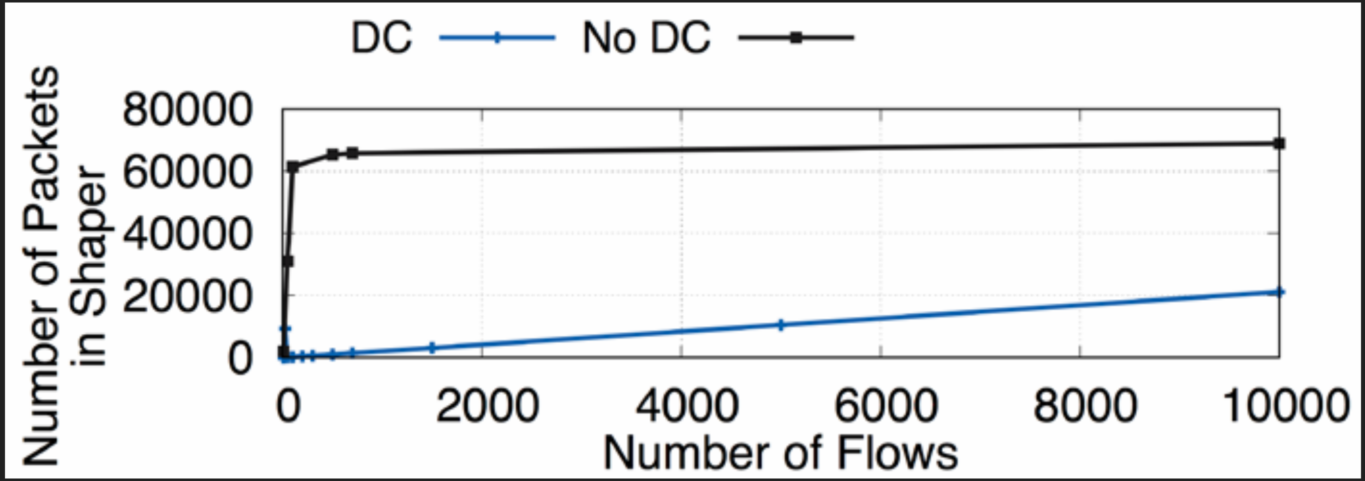

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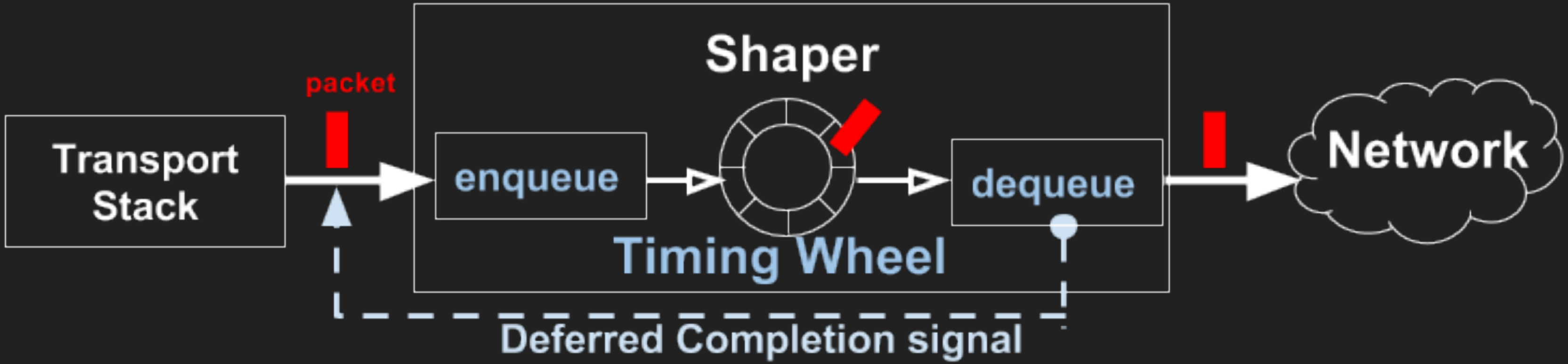

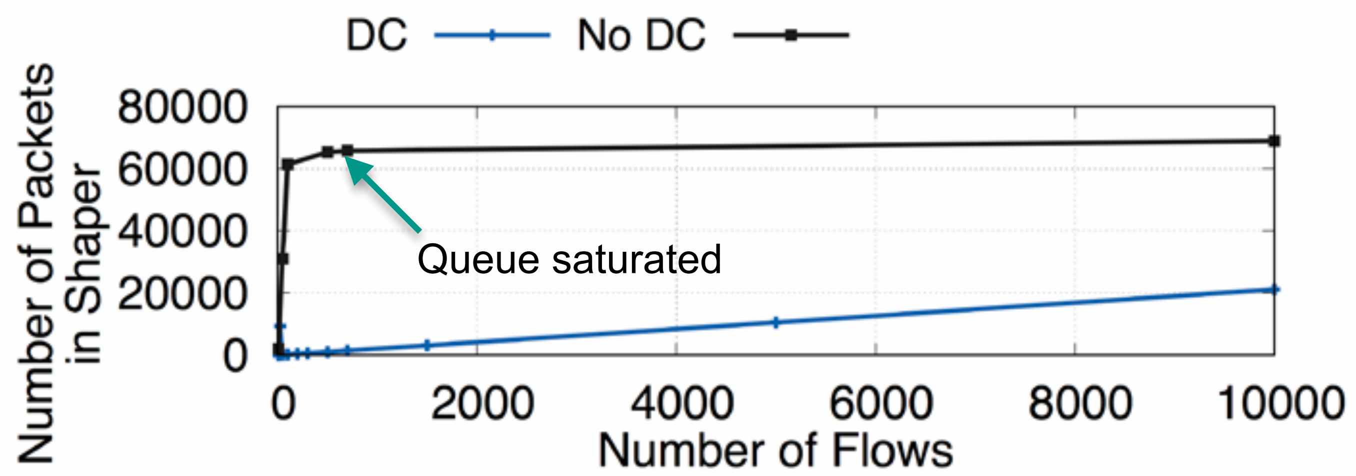

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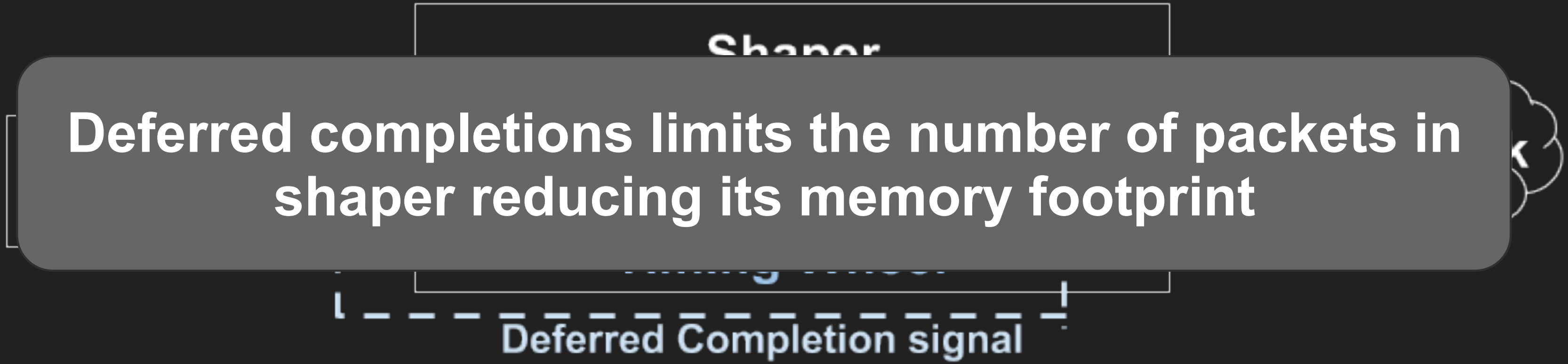
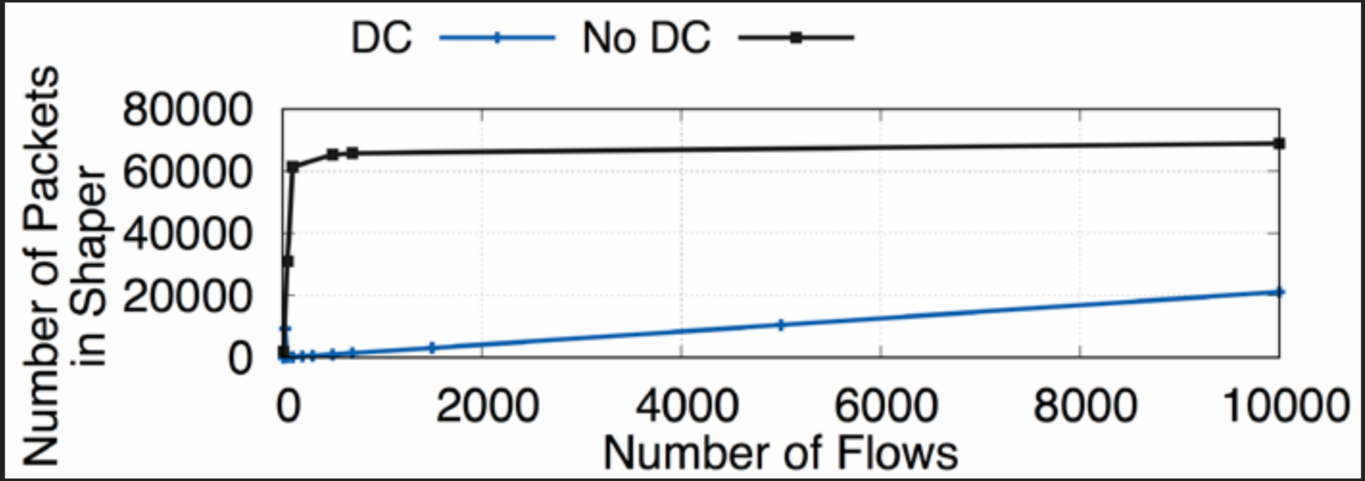


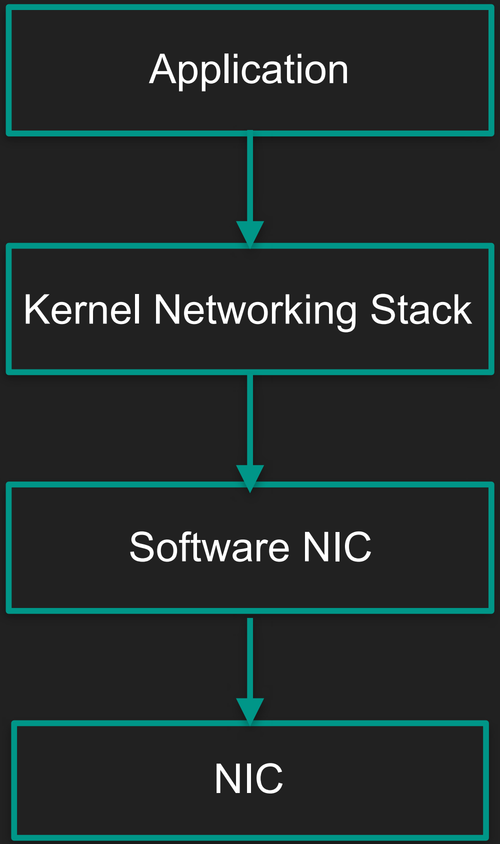
Deferred completions limits the number of packets in shaper reducing its memory footprint



Evaluation

Evaluation Setup

- Carousel deployed within a Software NIC



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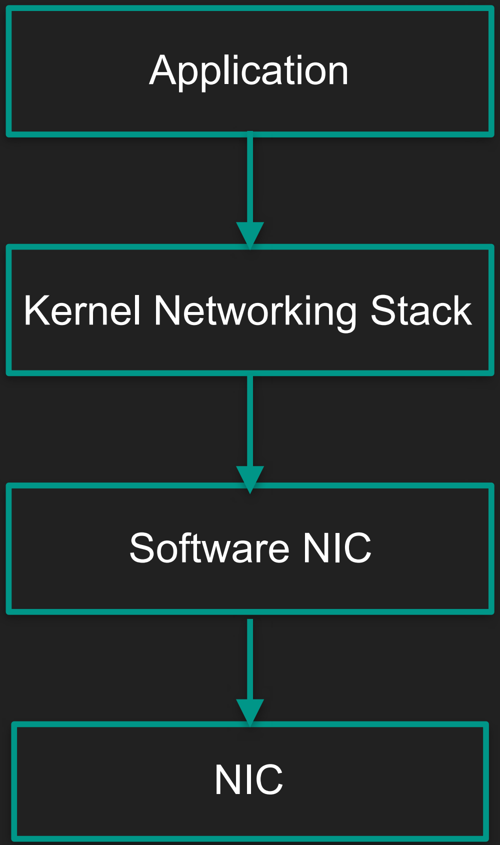

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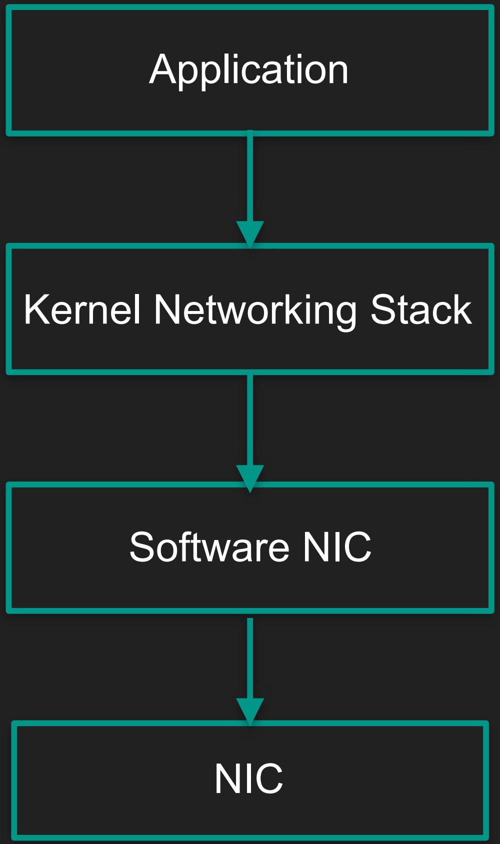
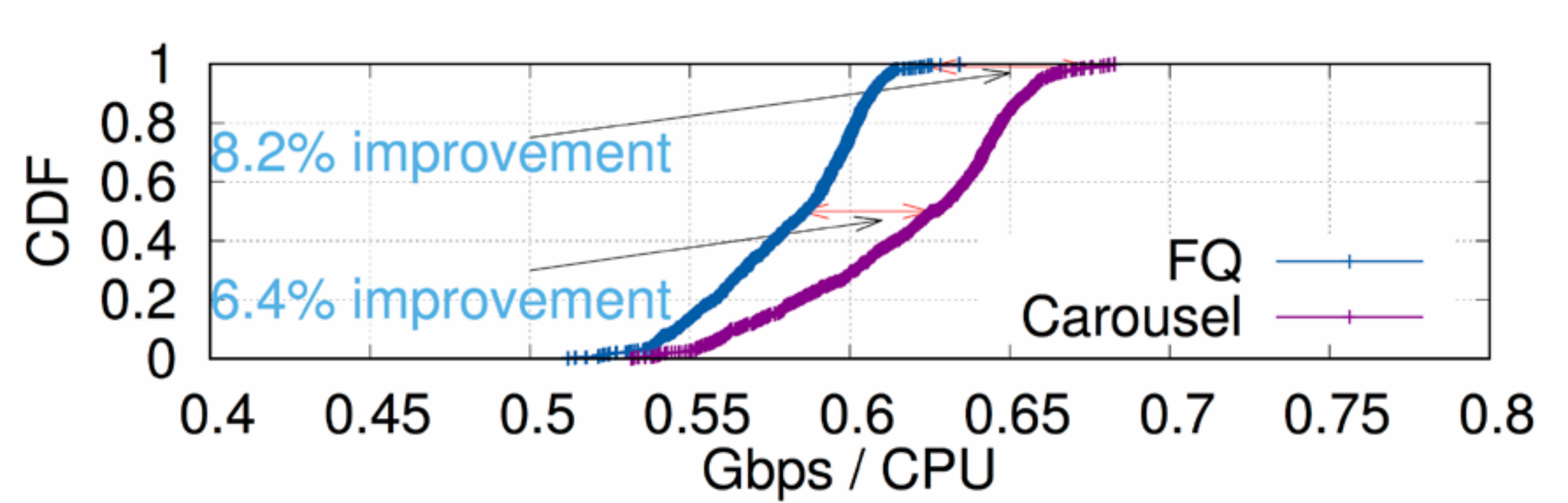
- Evaluation on Youtube servers comparing Carousel and FQ/Pacing
- Each server handles up to 50k sessions concurrently



Evaluation Metric

- Measures Gbps served per CPU utilization
  - Metric used is Gbps/CPU (higher is better)
  - Compare machines with similar CPU utilization
  - Measurements performed during peak 12-hours per day
- Evaluation is performed for:
  - Overall CPU utilization
  - Software NIC utilization

Overall CPU Utilization



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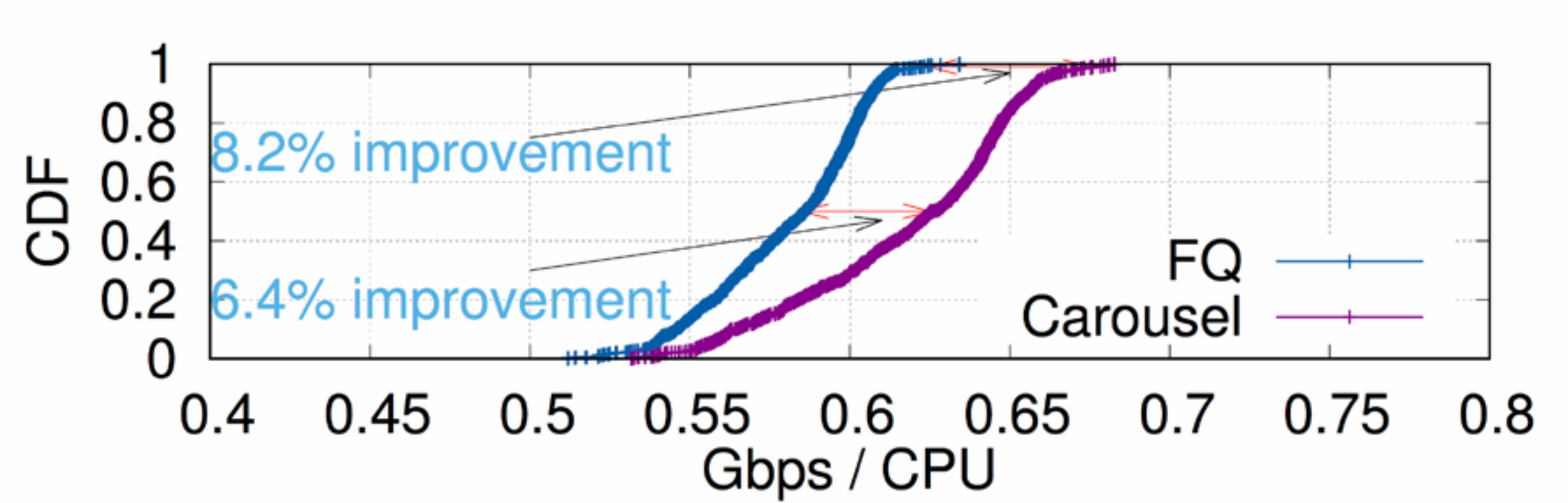
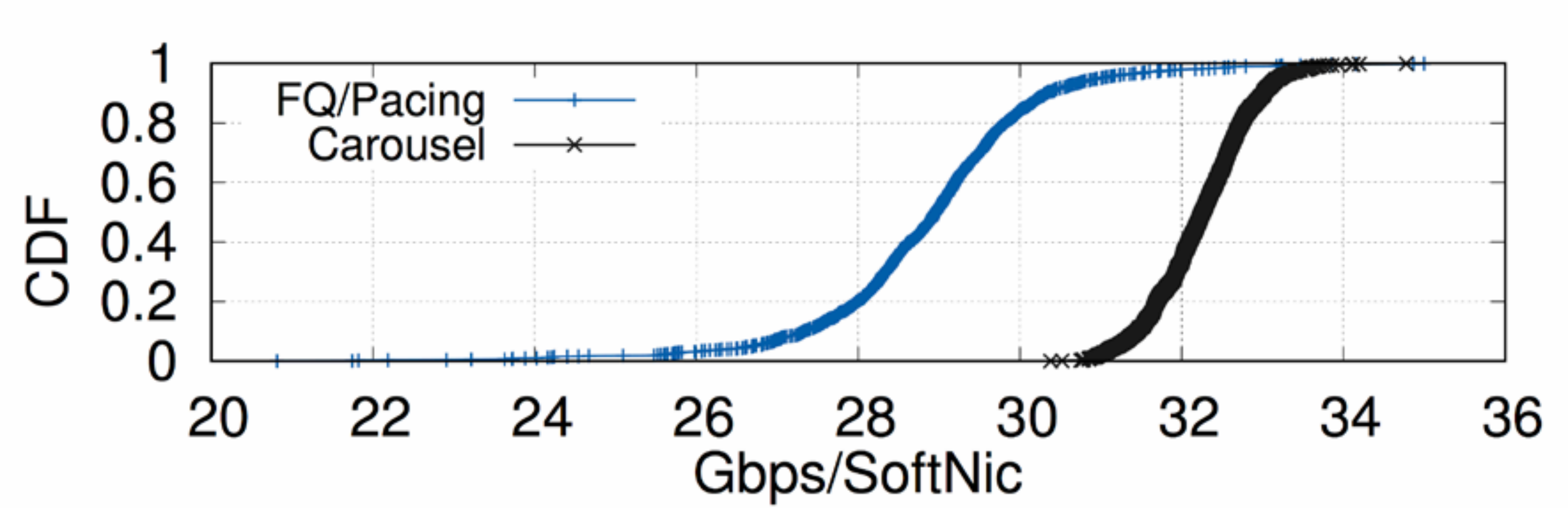
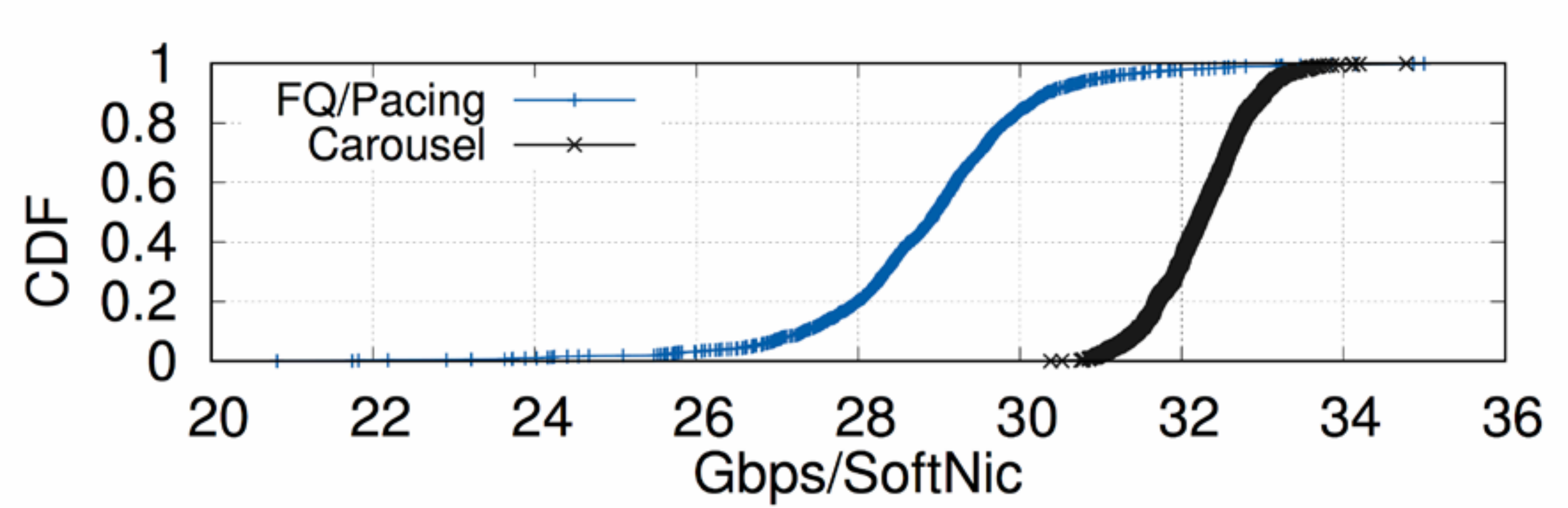


Carousel saves up to 8.2% of overall CPU utilization (5.9 cores on a 72 core machine)

SoftNIC Utilization

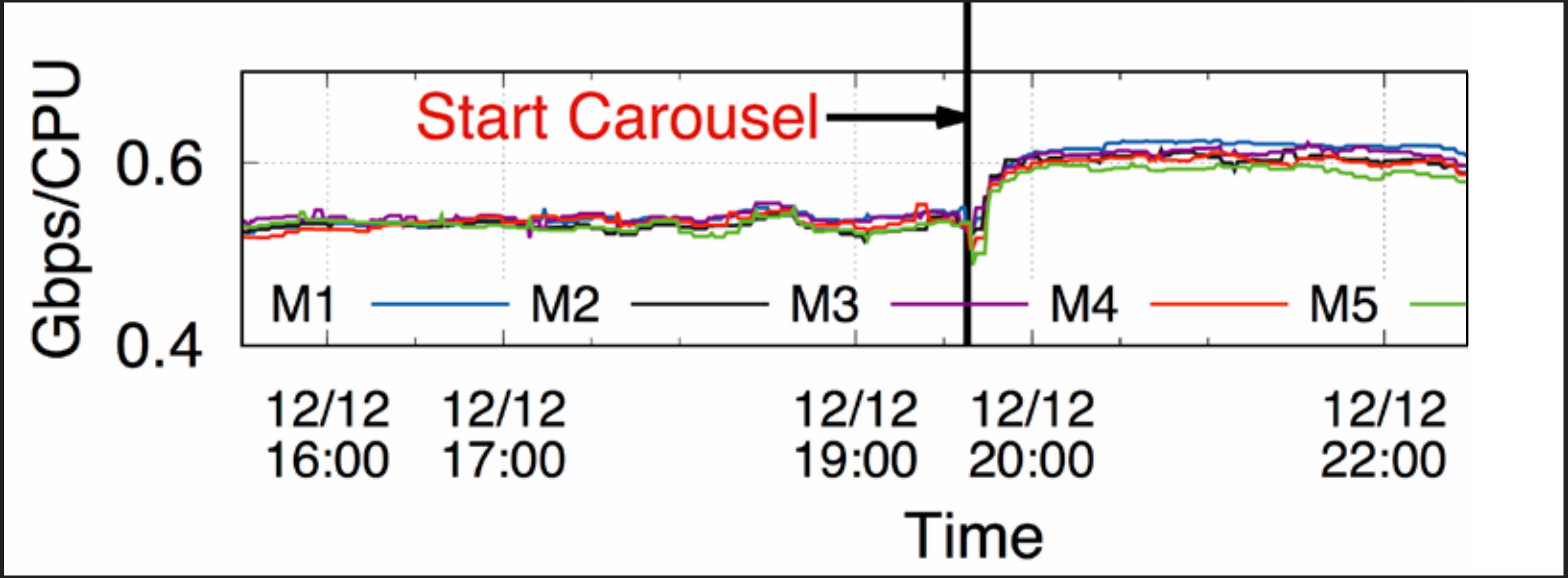


SoftNIC Utilization



Carousel improves even Software NIC utilization by 12% by increasing size of batches of packets enqueue in the Software NIC

Evaluation Summary



Performance improvement when Carousel starts on 5 different machines

Conclusion

- Carousel allows networks operators for the first time to shape tens of thousands of flows individually
- Carousel advantages make a strong case for providing single-queue shaping and backpressure in kernel, userspace stacks, hypervisors, and hardware

Questions?