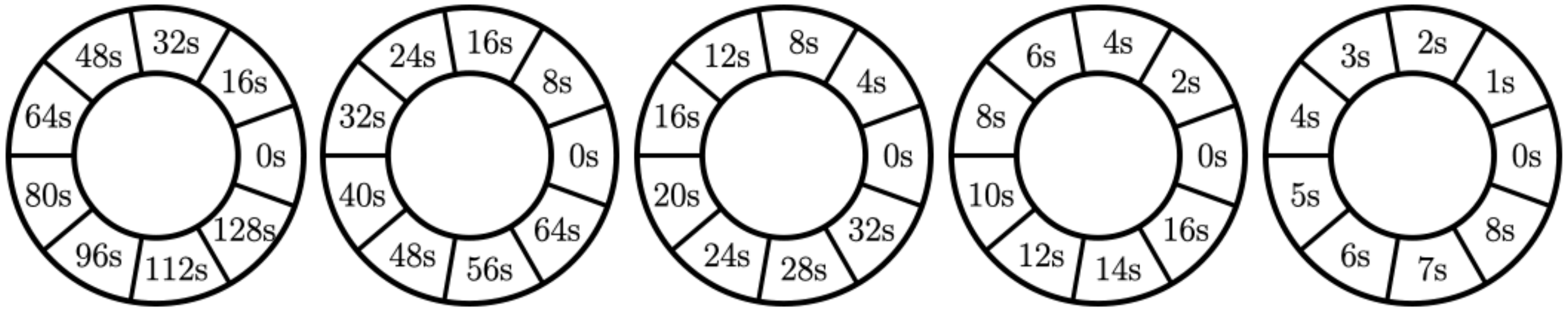
IEEE INFOCOM



Burst can be Harmless: Achieving Line-rate Software Traffic Shaping by *Inter-flow Batching*

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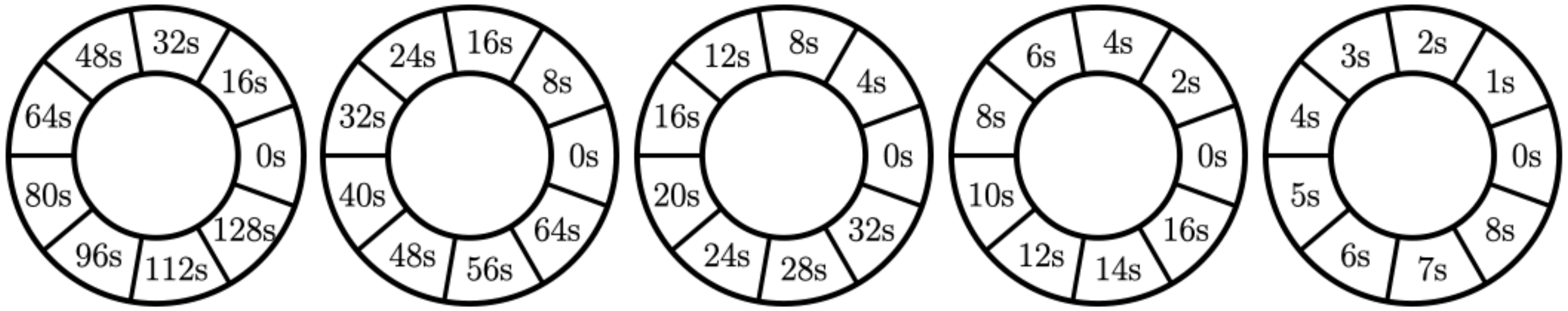

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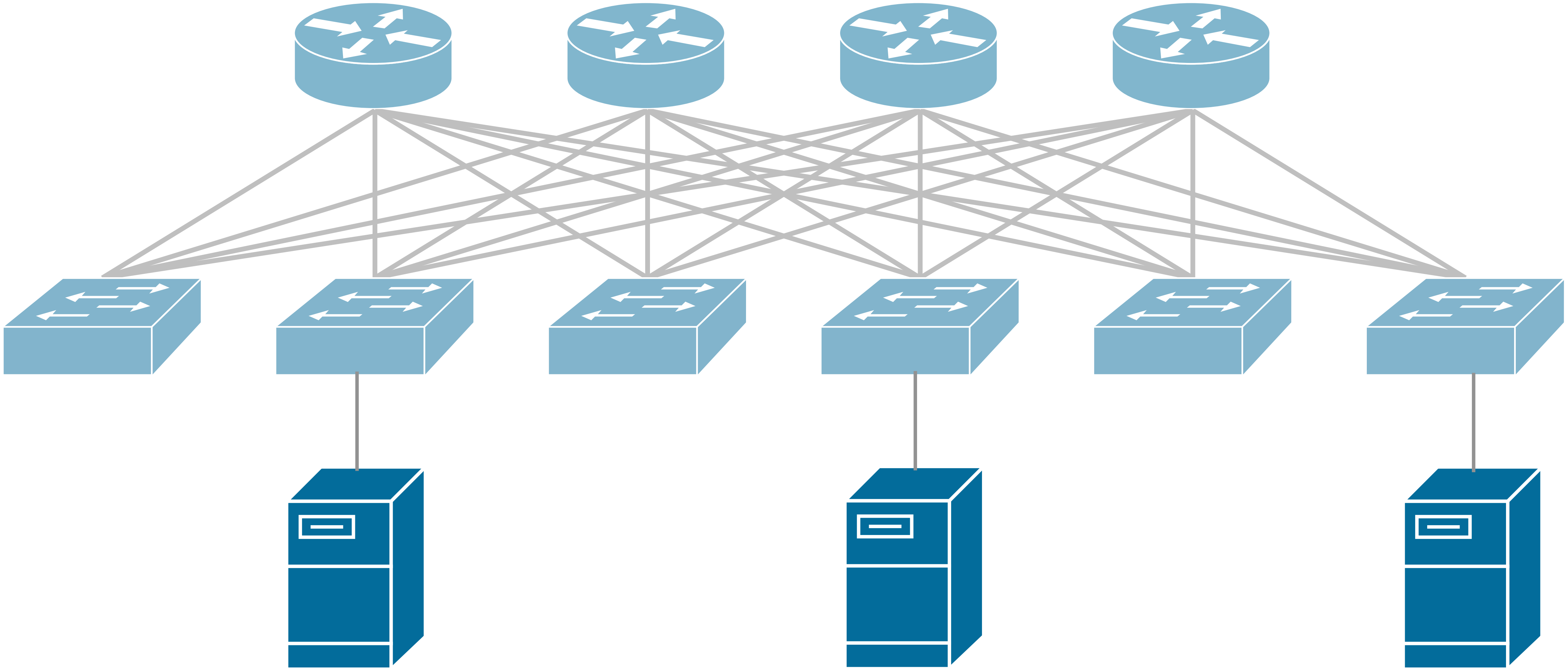
Traffic Shaping / Rate Limiting at End Hosts



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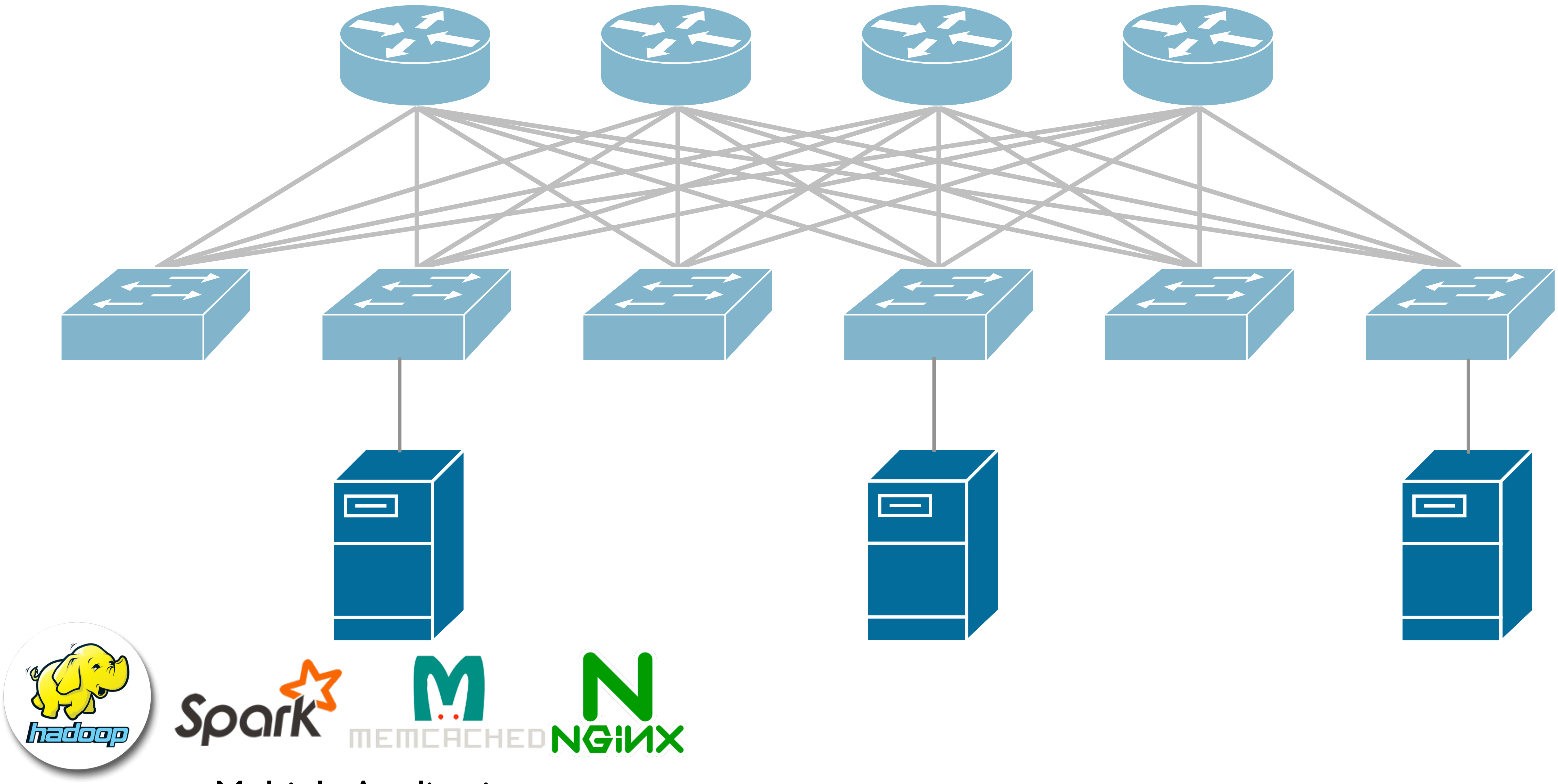
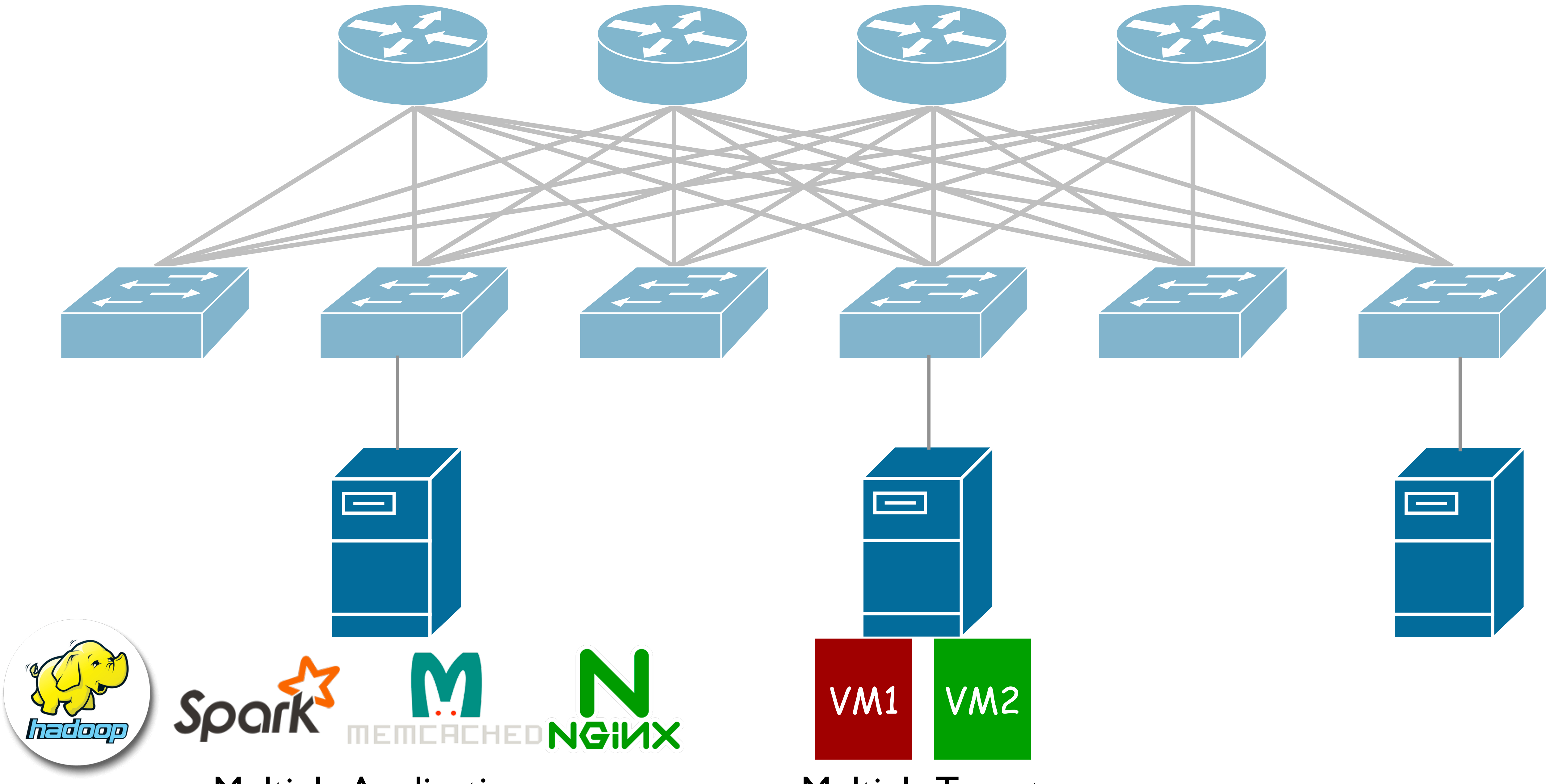


Multiple Applications

Traffic Shaping / Rate Limiting at End Hosts



Multiple Applications

Multiple Tenants

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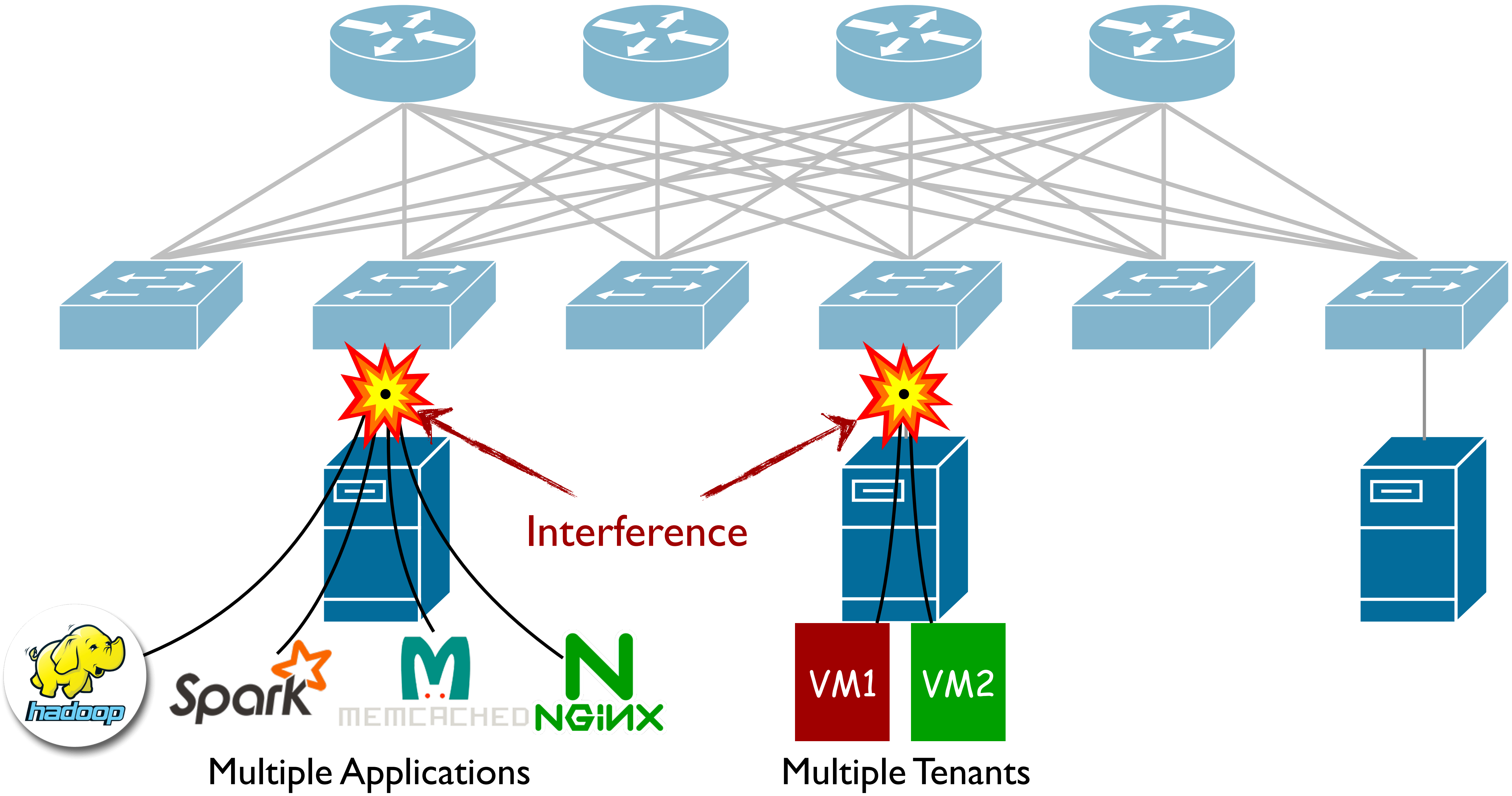

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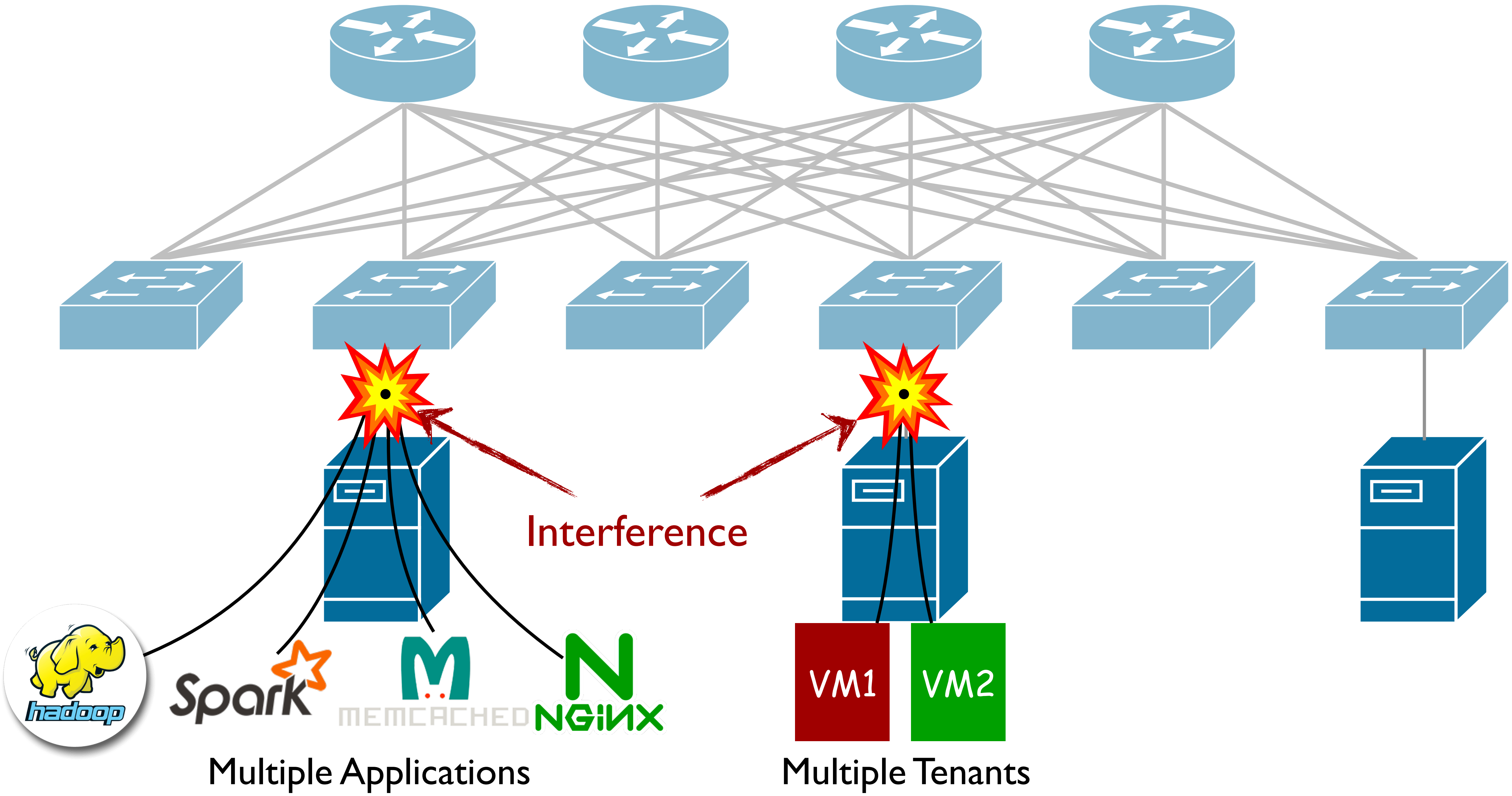


Interference

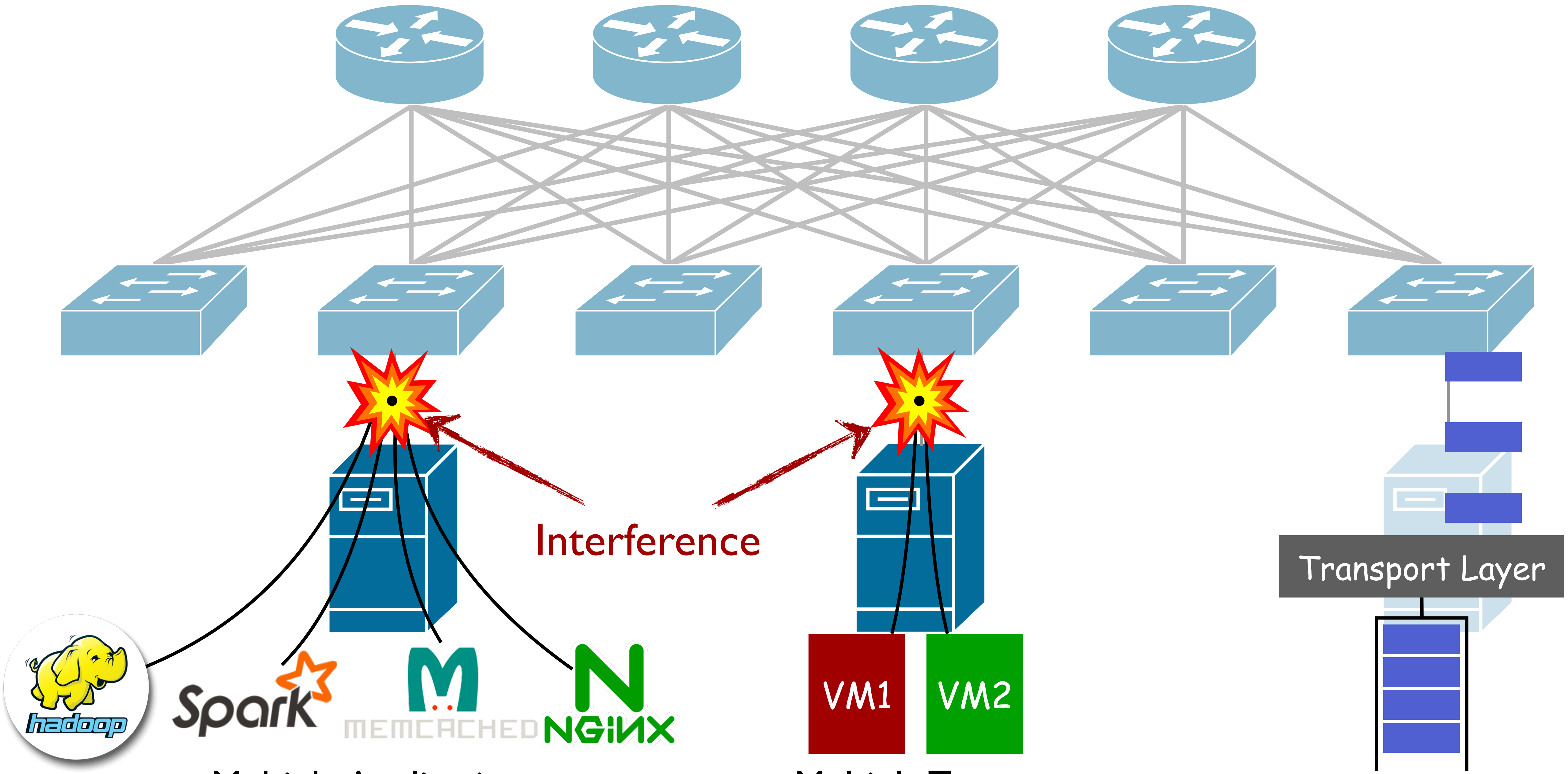
Multiple Applications

Multiple Tenants

❶ Performance Isolation

- Throttle traffic rate

Traffic Shaping / Rate Limiting at End Hosts



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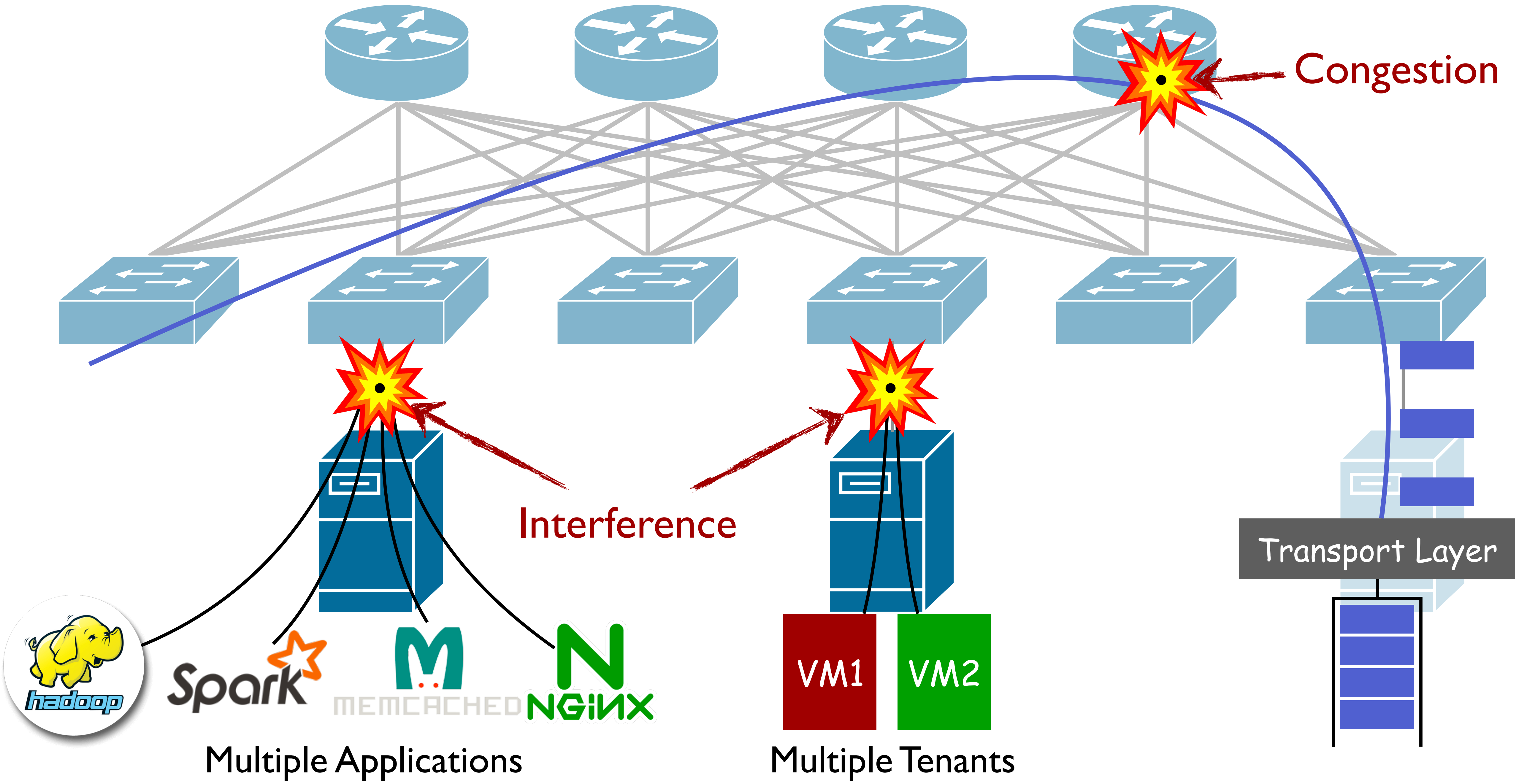

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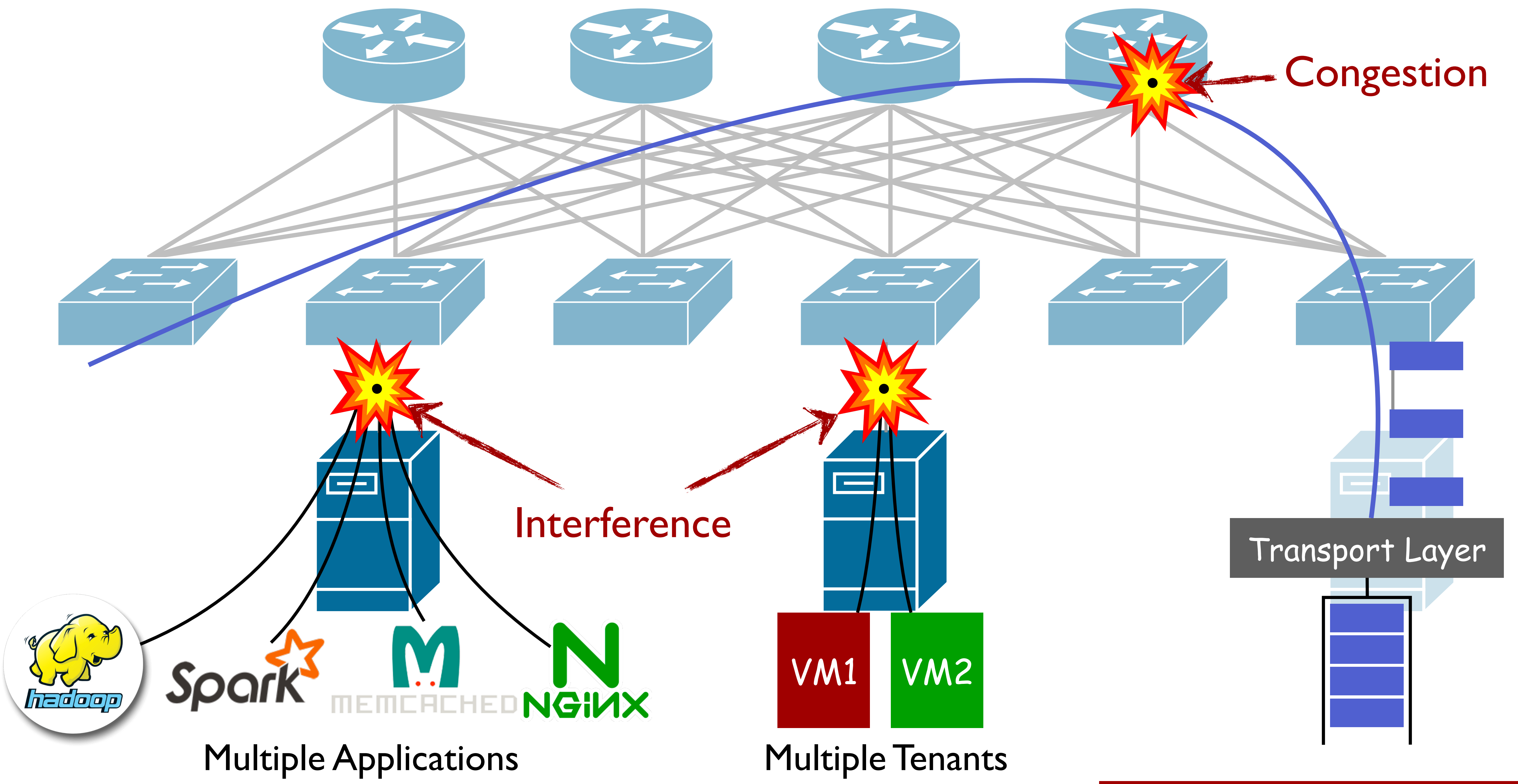


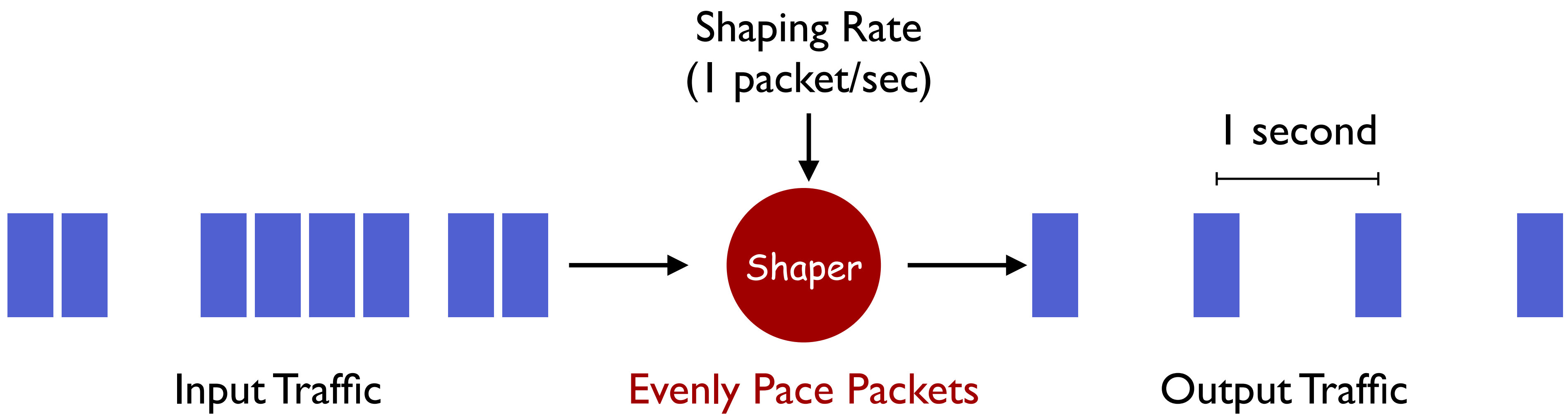
❶ Performance Isolation

- Throttle traffic rate

❷ Congestion Control

- Adjust sending rate
- Eliminate traffic bursts

Software Traffic Shaping



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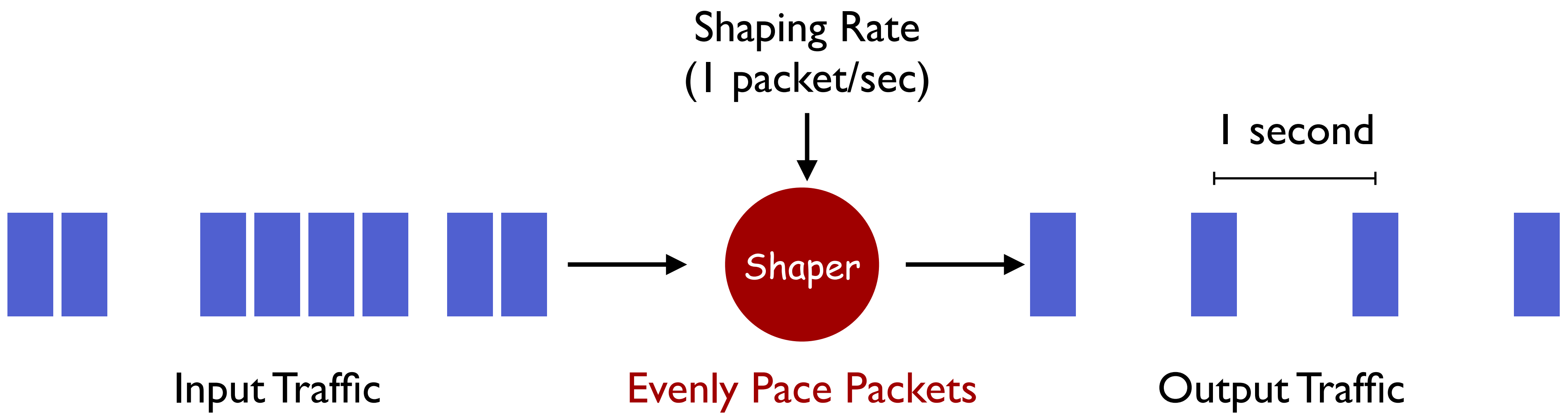
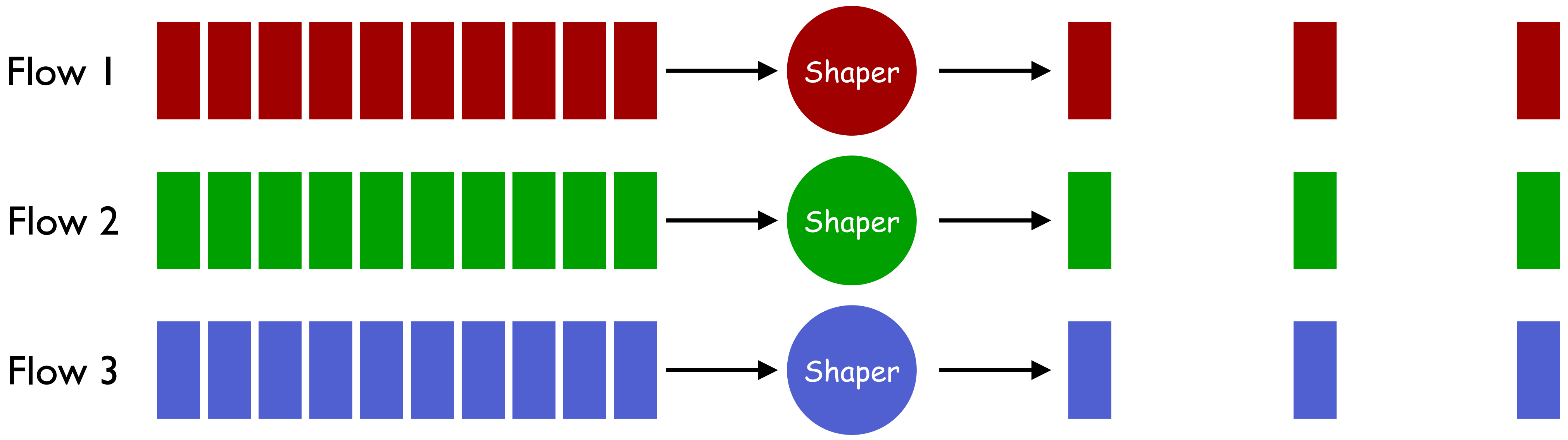
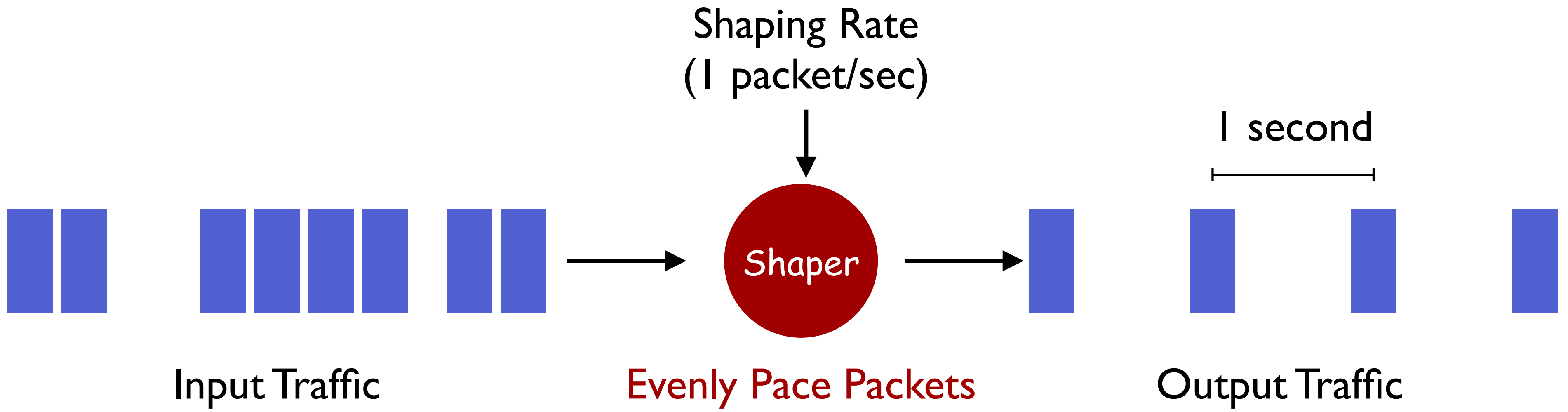


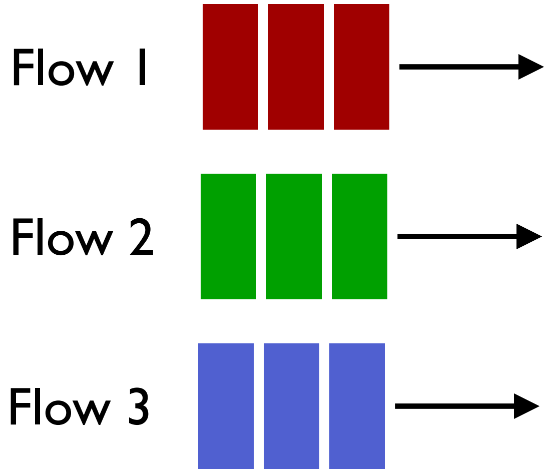


Traditional Traffic Shaper (e.g., tbf, htb)

- Each flow has a separate shaper
- High overhead with massive flows

Software Traffic Shaping

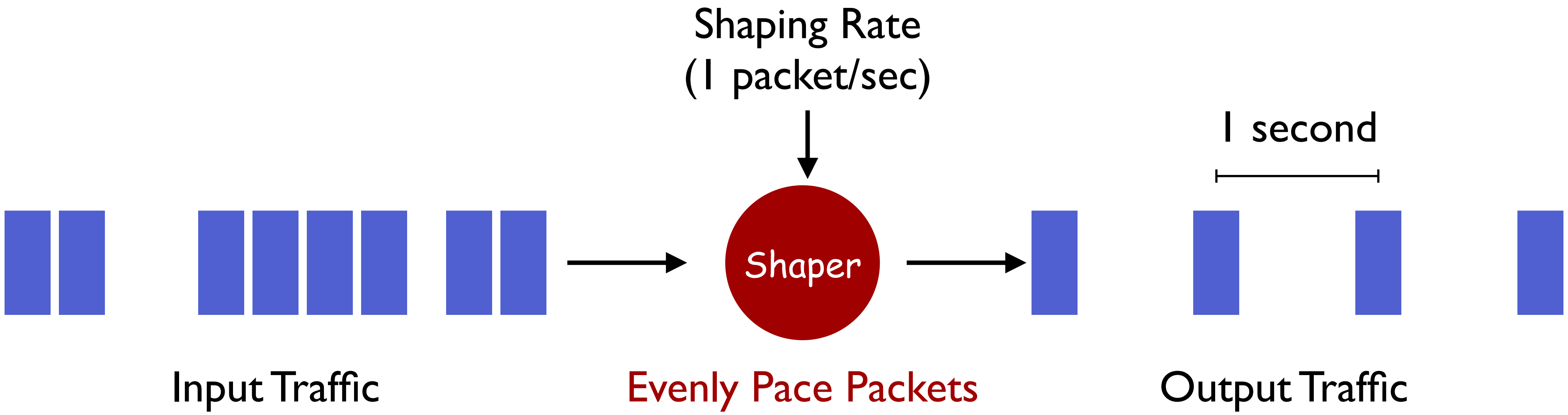


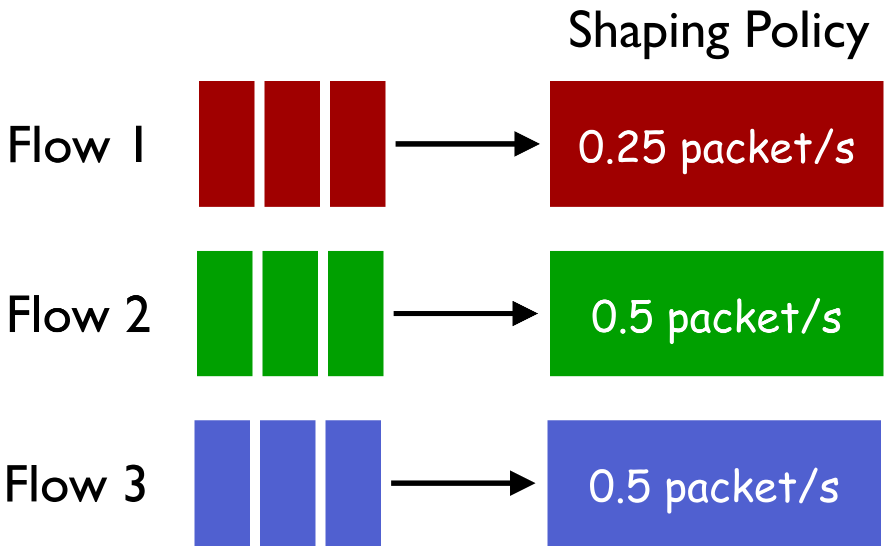


State-of-the-Art Traffic Shaper (Carousel[SIGCOMM'17], Eiffel[NSDI'19])

- Decouple the shaping policy and shaping enforcement
- Shape all flows with a single queue

Software Traffic Shaping





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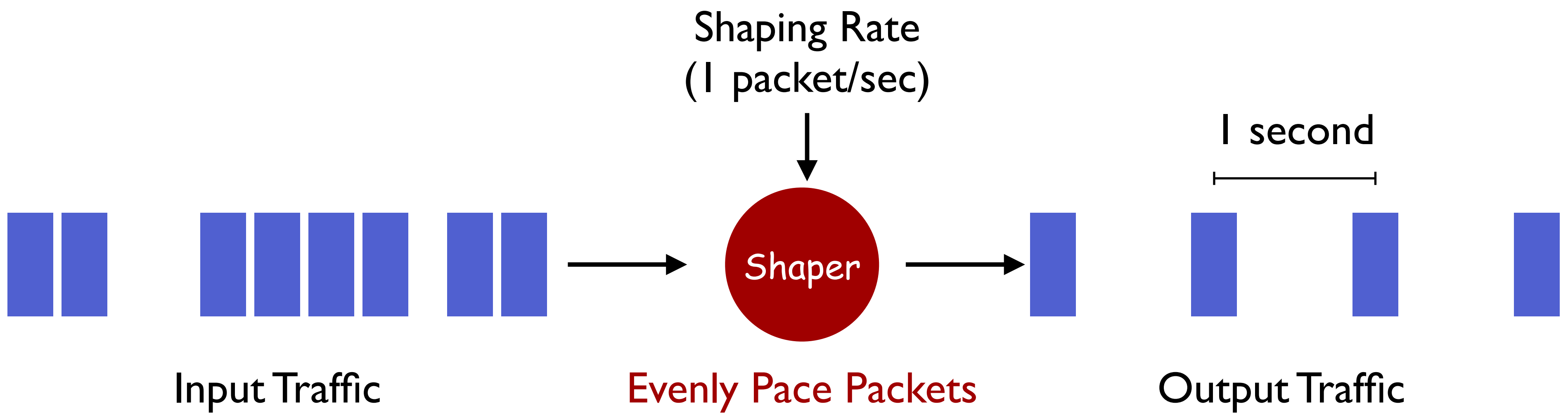

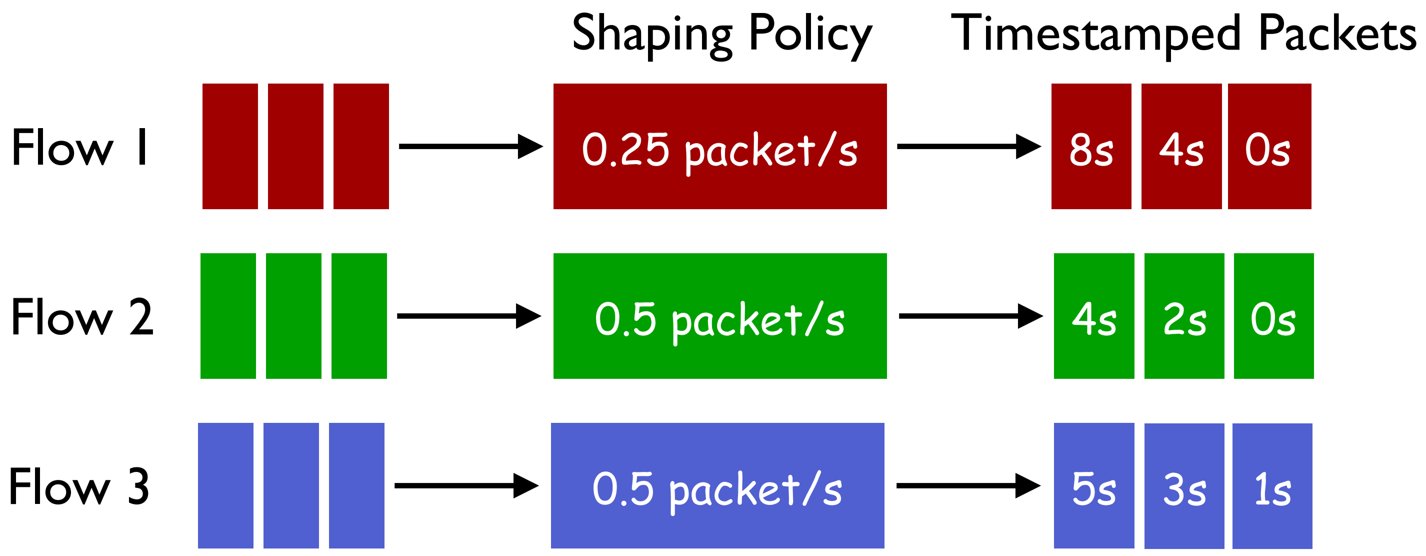

❶
Timestaming packets

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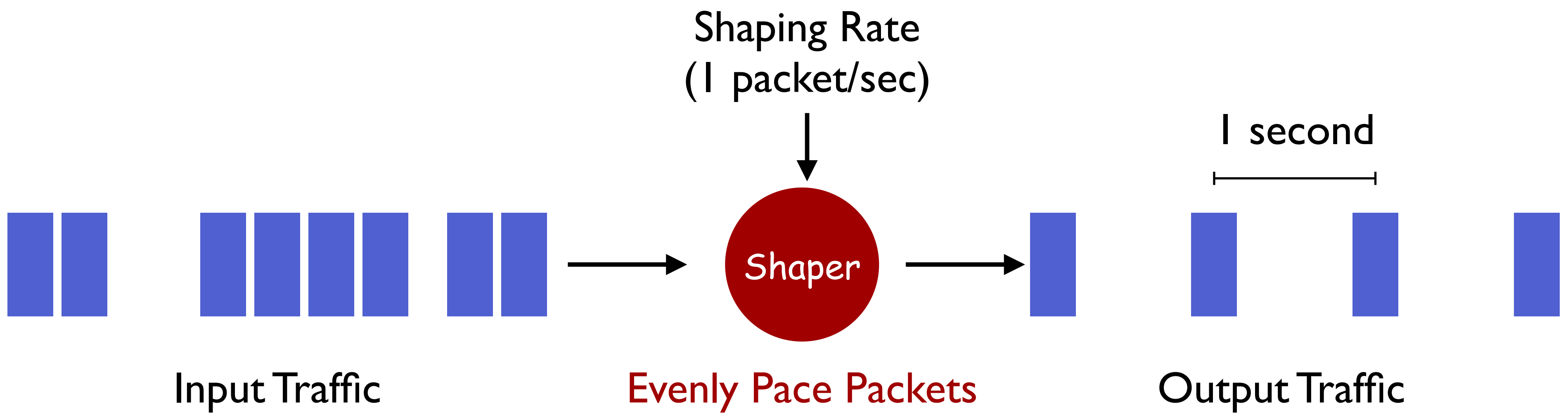


Shaping Rate
(1 packet/sec)

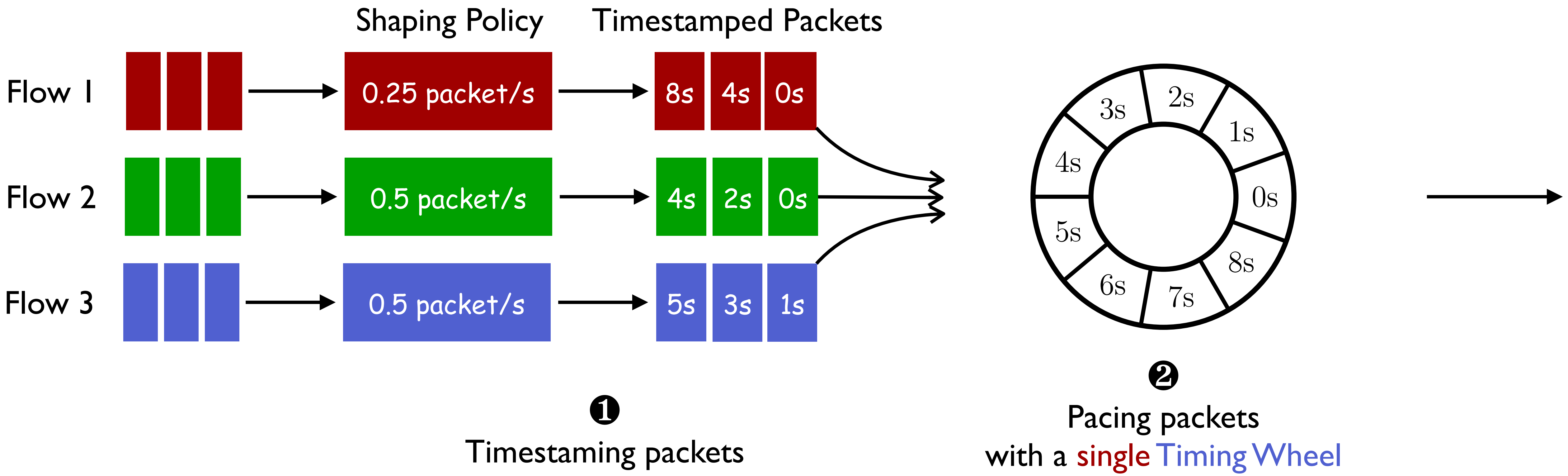
1 second

Shaper

Input Traffic

Evenly Pace Packets

Output Traffic



Shaping Policy

Timestamped Packets

Flow 1

0.25 packet/s

8s 4s 0s

Flow 2

0.5 packet/s

4s 2s 0s

Flow 3

0.5 packet/s

5s 3s 1s

3s 2s 1s 4s 0s 5s 8s 6s 7s

❶
Timestaming packets

❷
Pacing packets
with a single Timing Wheel

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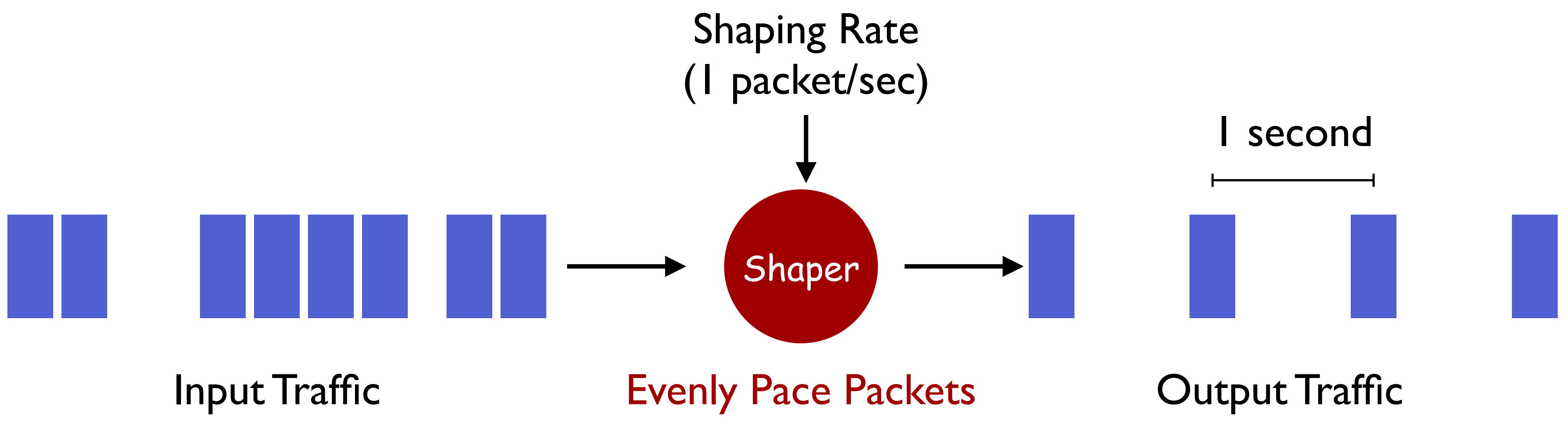

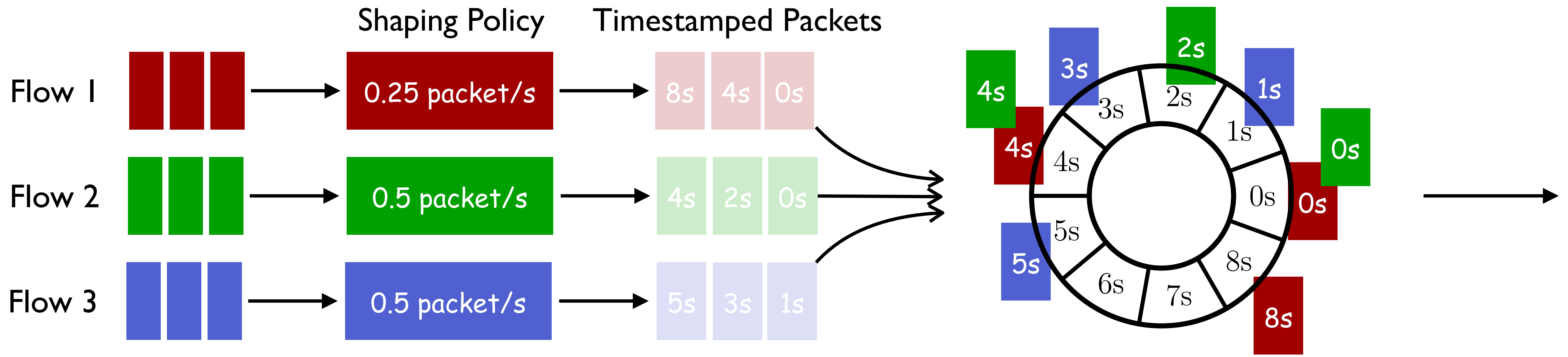

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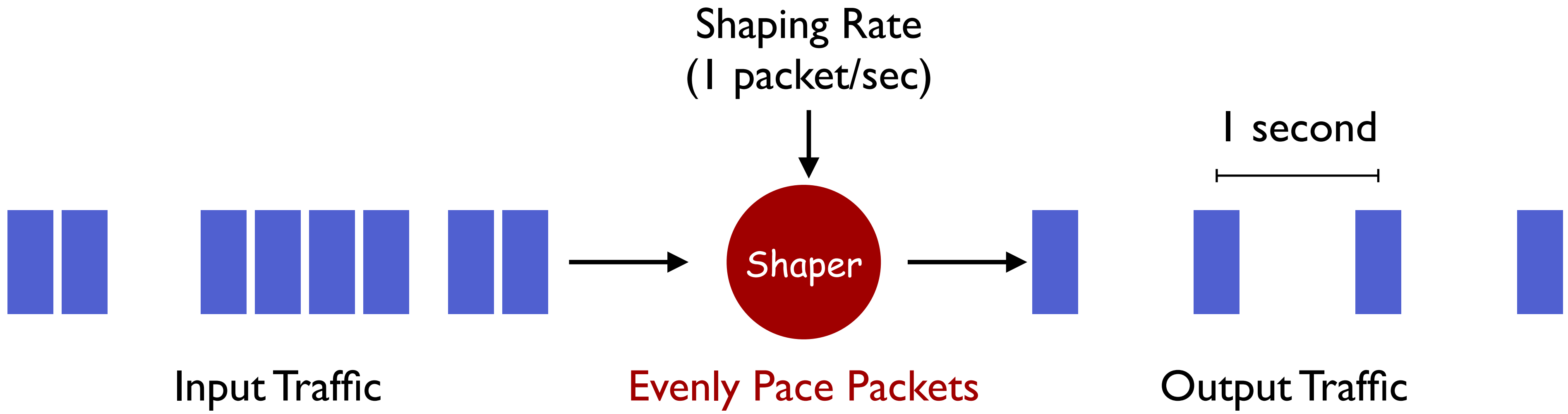
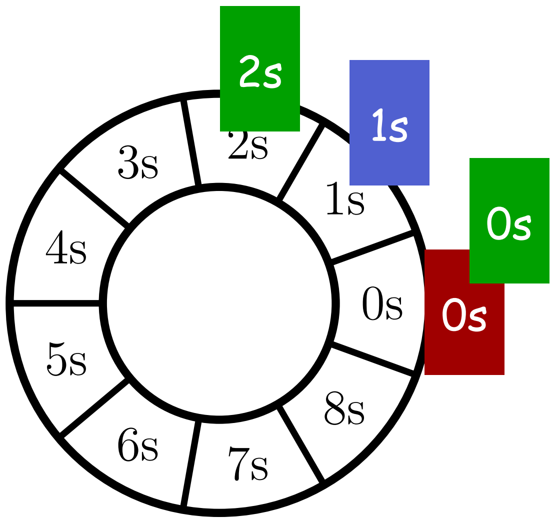
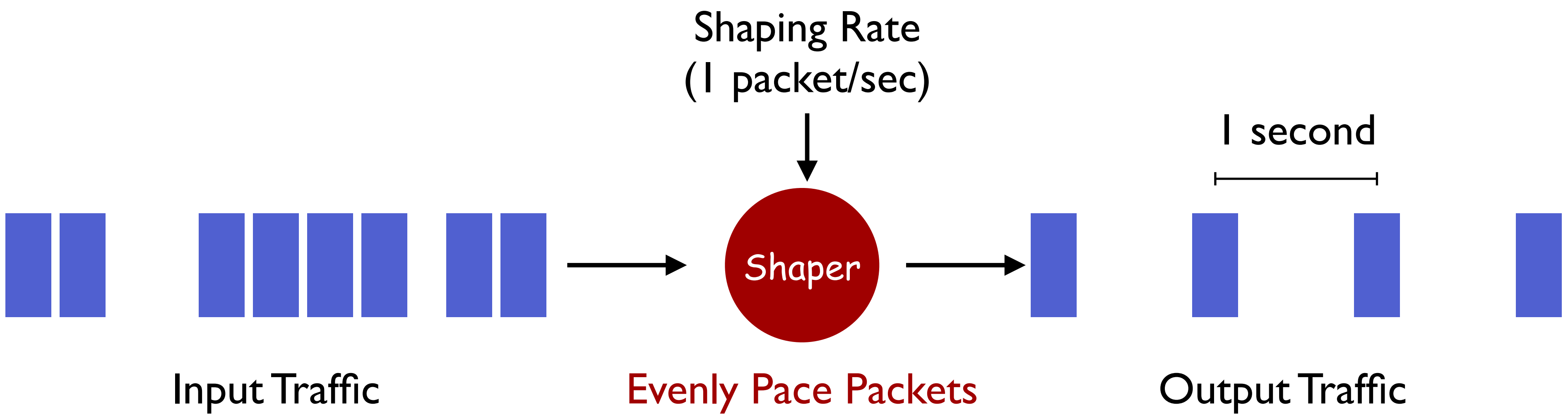




Current time = 0s

Pacing packets with Timing Wheel

Software Traffic Shaping



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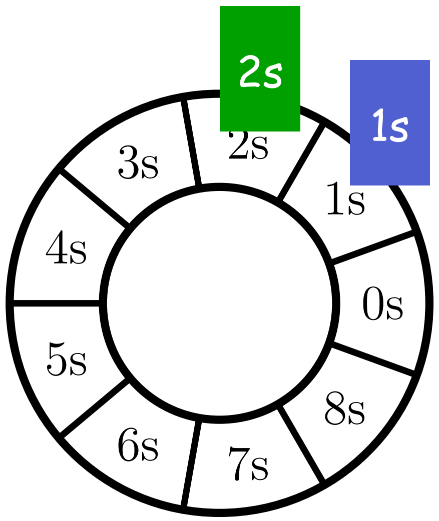
Evenly Pace Packets

Output Traffic



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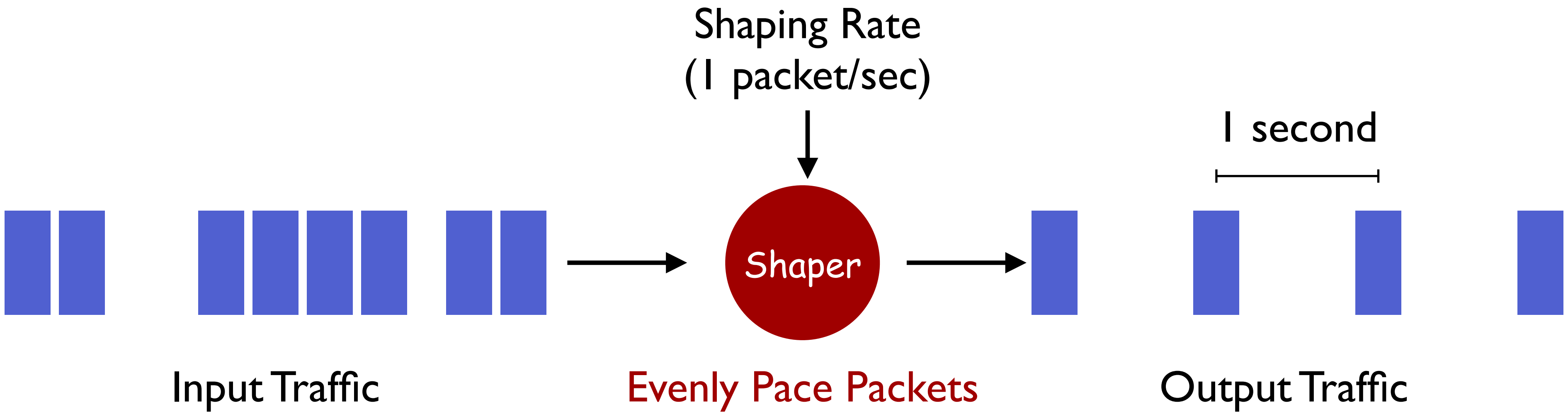
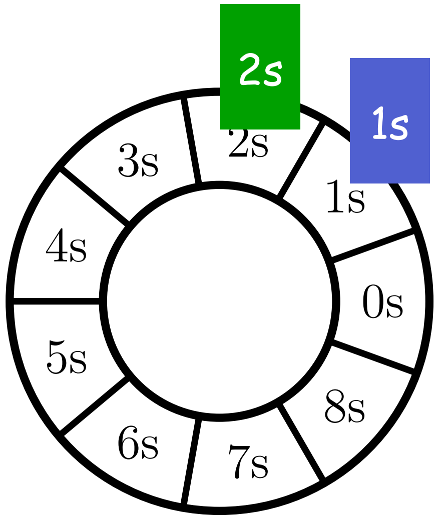
Pacing packets with Timing Wheel

Software Traffic Shaping





Current time = 1s

Pacing packets with Timing Wheel

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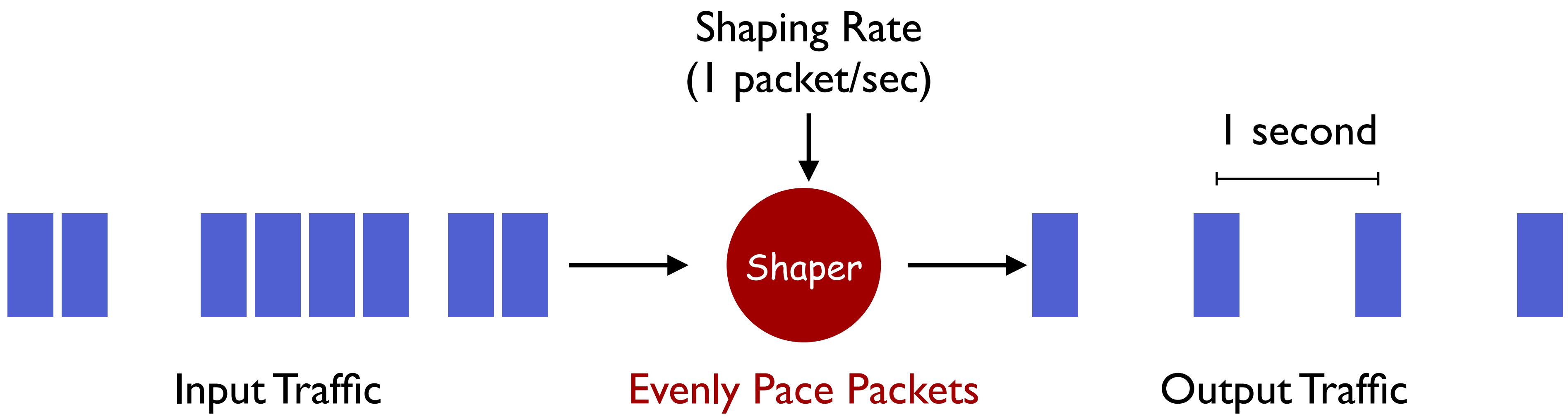

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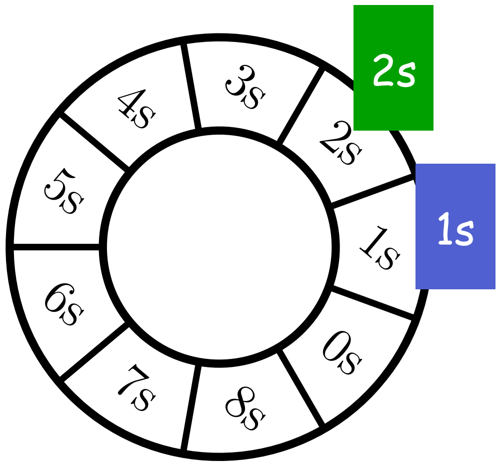

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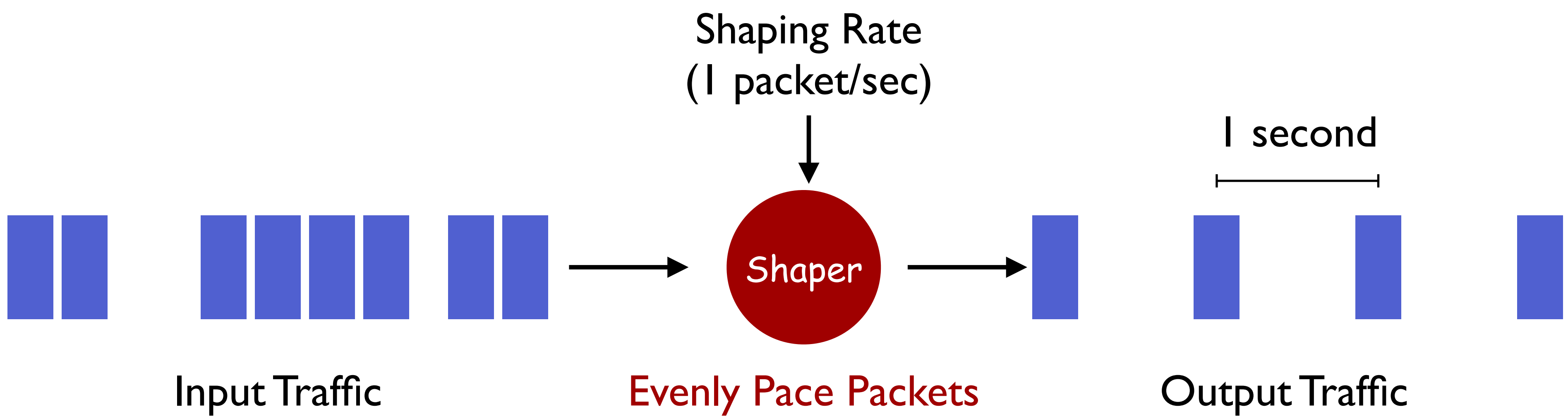

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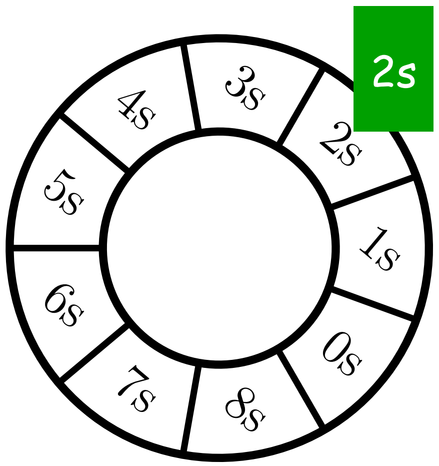

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Pacing packets with Timing Wheel

Overhead of Software Traffic Shaping

- State-of-the-art Shaper: Timestamping + Timing Wheel
  - ✓ Minimal queue maintenance overhead (i.e., One queue)
  - ✓ Minimal enqueue/dequeue overhead (i.e., O(1))
  - ✗ Still unsatisfactory
    - Incur high overhead
    - Unable to achieve accurate shaping in 100Gbps network

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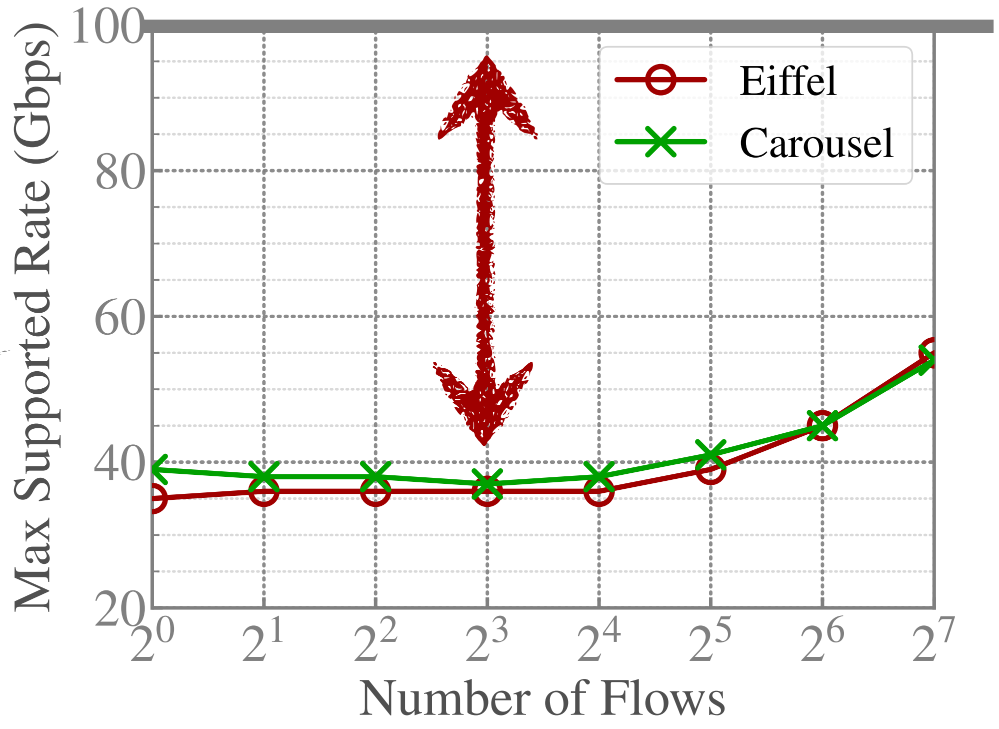

Network Capacity

maximum shaping rate with which a shaping scheme is able to achieve high shaping accuracy (i.e., shaping error < 1%).

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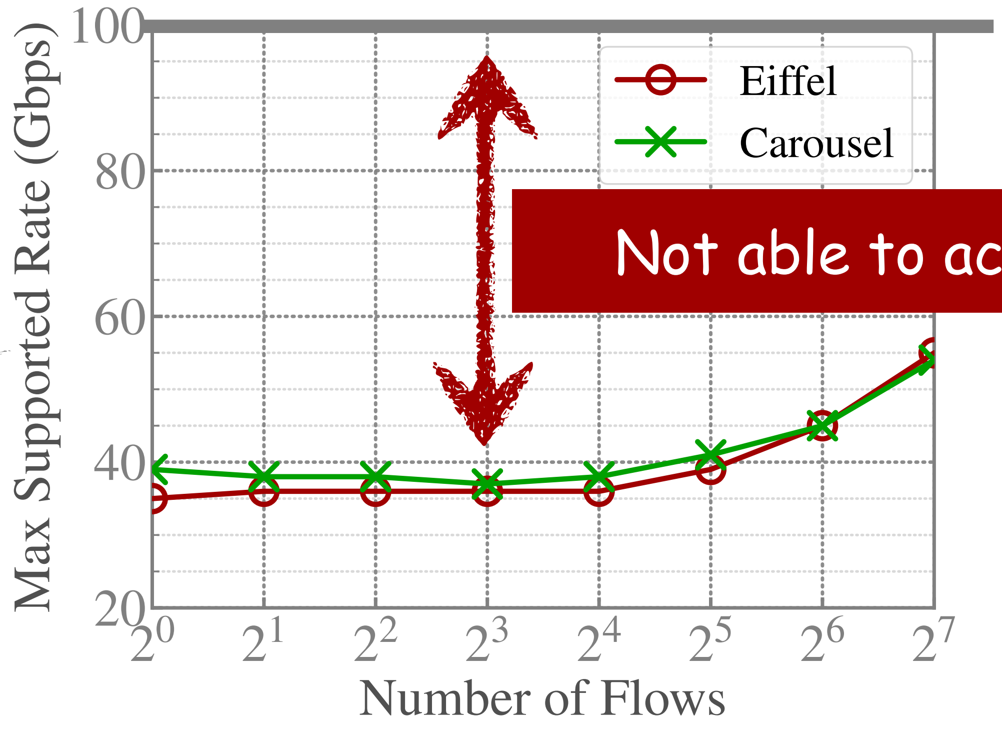

Network Capacity

Not able to achieve high shaping speed

maximum shaping rate with which a shaping scheme is able to achieve high shaping accuracy (i.e., shaping error < 1%).

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Is it?

internal overhead

Our observation:

It is the external overhead that hinders shaping from achieving higher speed

Overhead of Software Traffic Shaping

- What is external overhead?
    - Massive Software Interrupts
        - Wait for some time to send another packet
    - Per-packet PCIe operations

Overhead of Software Traffic Shaping

- What is external overhead?
  - Massive software Interrupts
    - Wait for some time to send another packet
  - Per-packet PCIe operations
    - 40Gbps rate for 1500B packets → PCIe write every 300ns
    - A separate PCIe write can take up to 900ns[1]

[1] B. Stephens, A. Akella, and M. Swift, "Loom: Flexible and Efficient NIC Packet Scheduling," in USENIX NSDI, 2019.

Overhead of Software Traffic Shaping

- What is external overhead?
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- How to reduce external overhead?
  - Batching to amortize per-packet overhead

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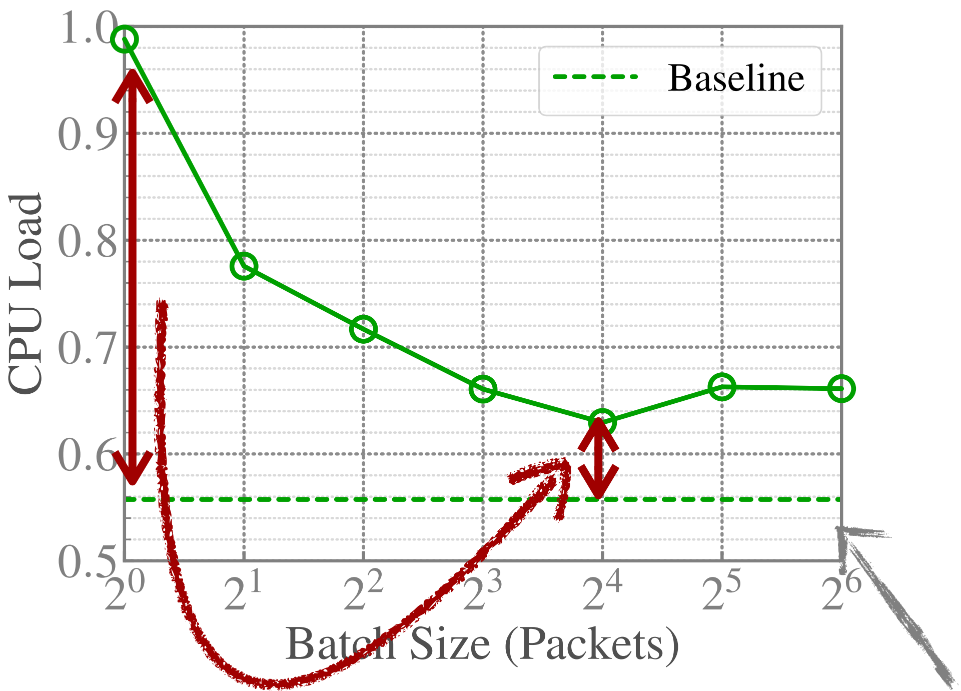

erhead of network stack

Reduce the CPU overhead by 5.9×

Kernel

Overhead of Software Traffic Shaping

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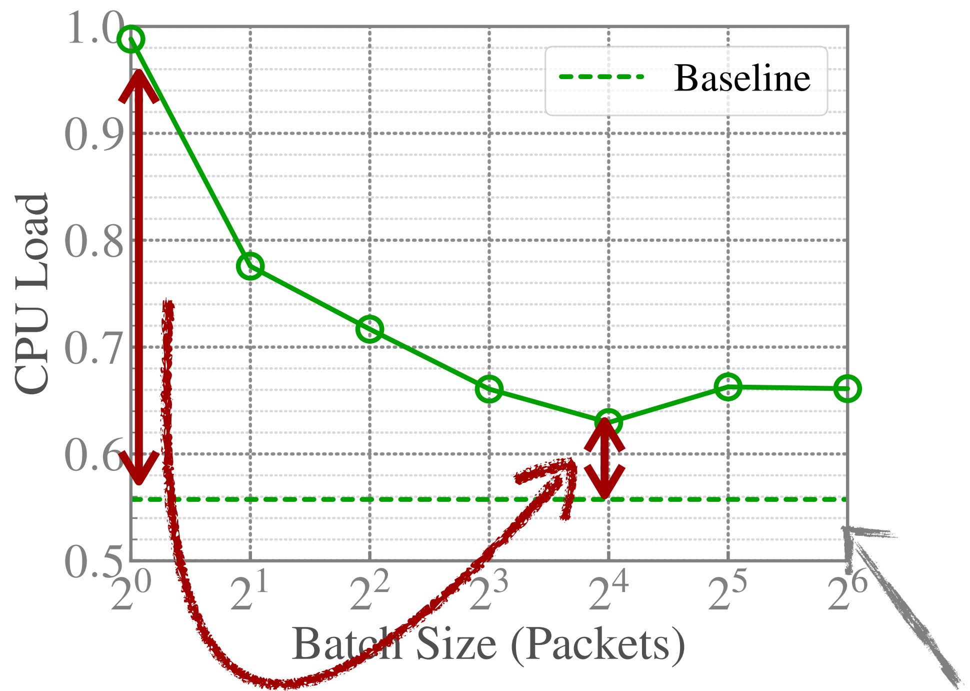

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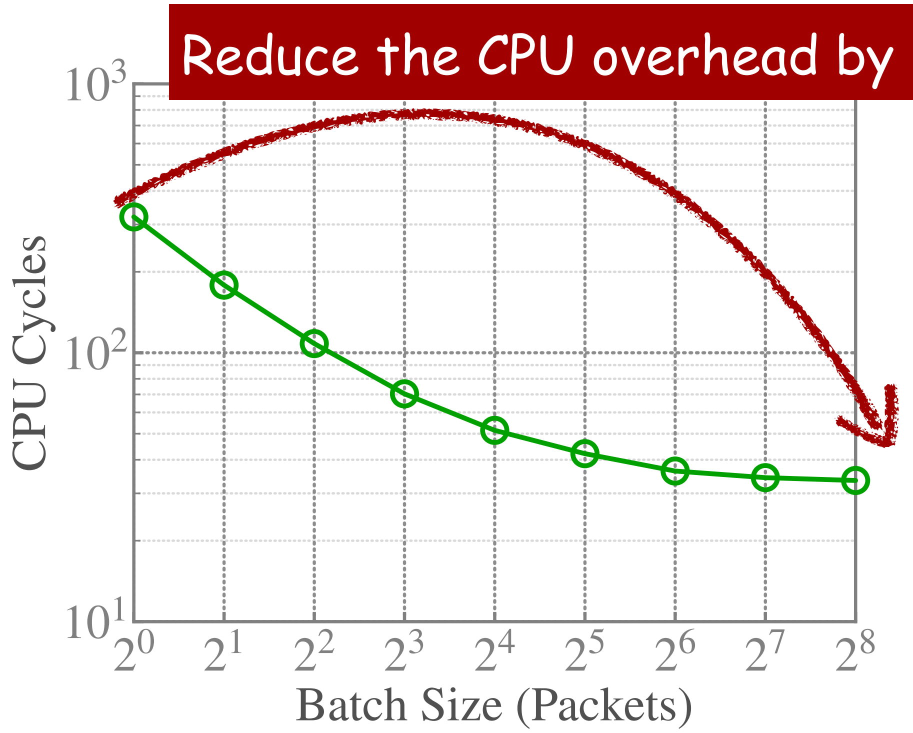
Kernel

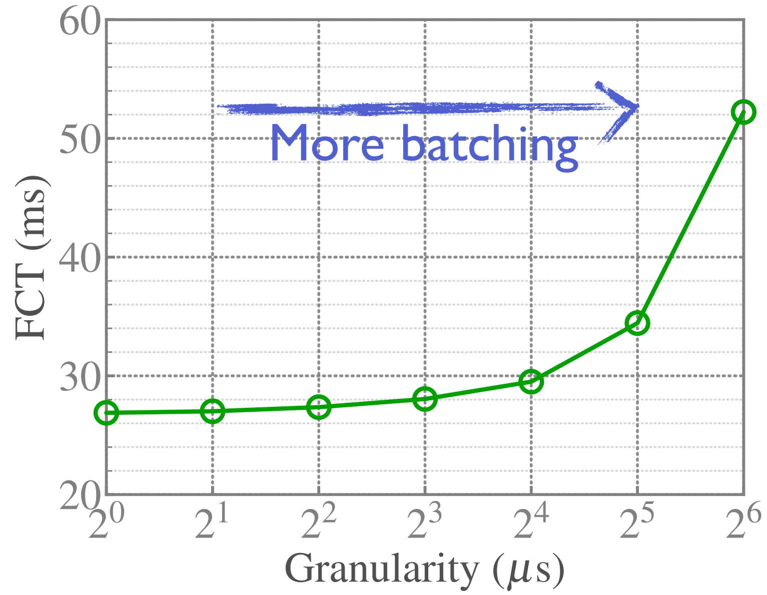
Reduce the CPU overhead by 9.5×



DPDK (w/o interrupt)

Overhead of Software Traffic Shaping

- What is external overhead?
- How to reduce external overhead?
  - Batching to amortize per-packet overhead
- Why not using batching?
  - Batching results in traffic bursts
  - Traffic bursts can degrade transmission performance



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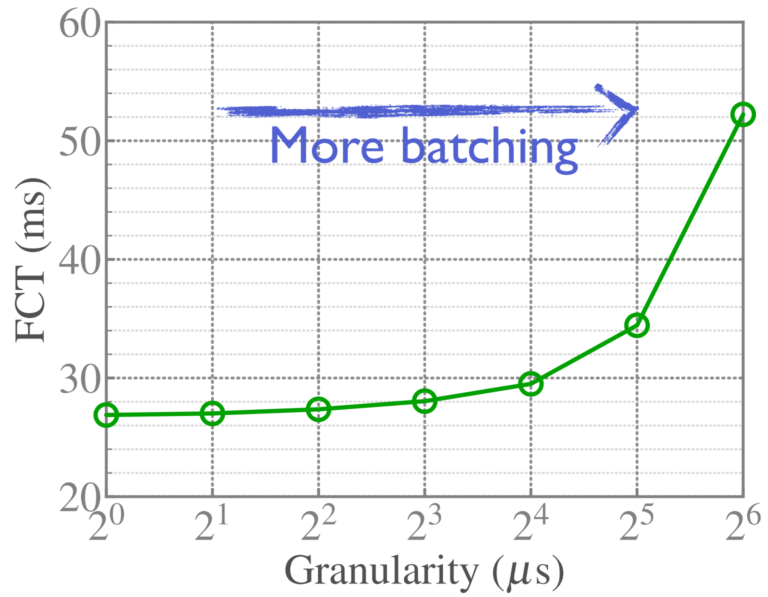
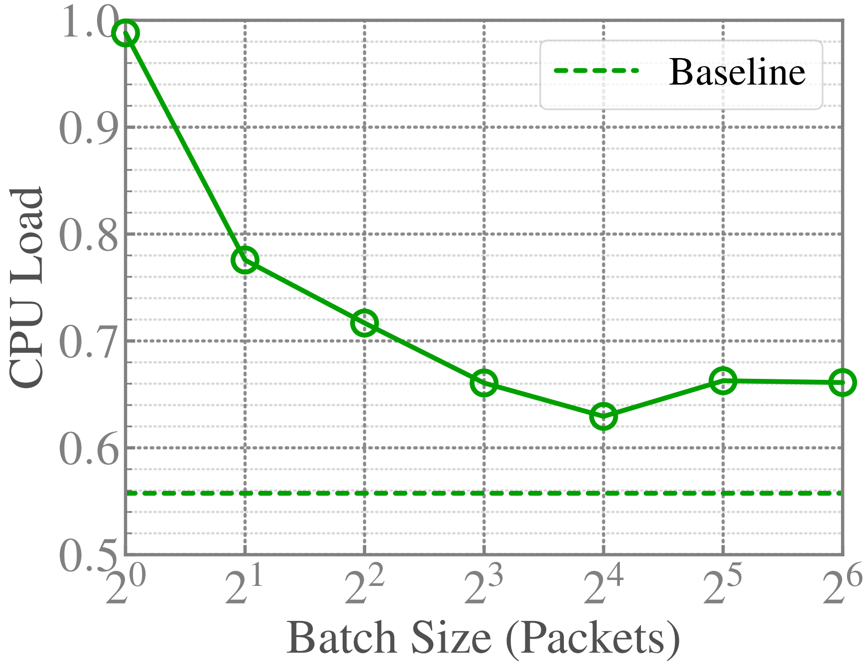


Batching can extend the FCT by ~2×

Dilemma of batching



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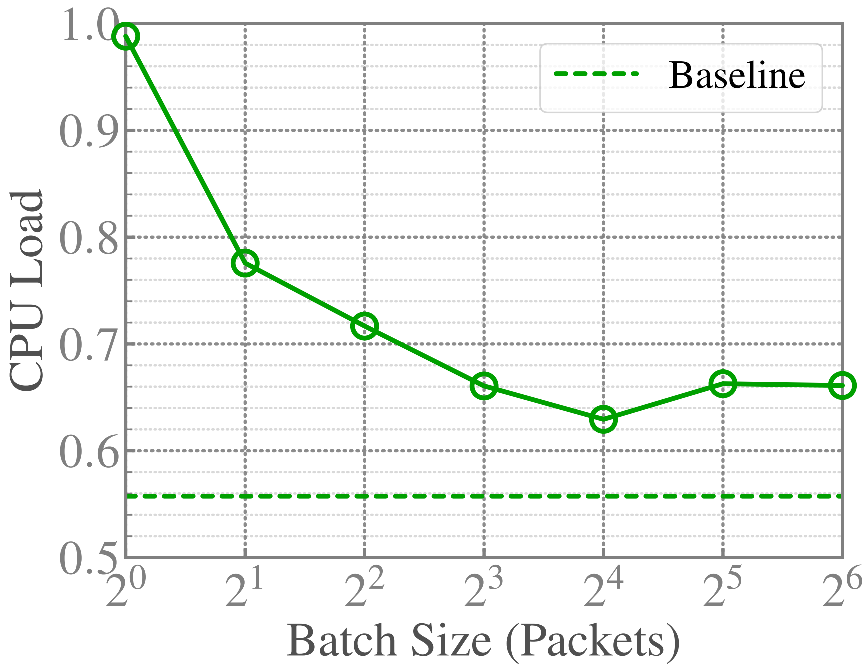

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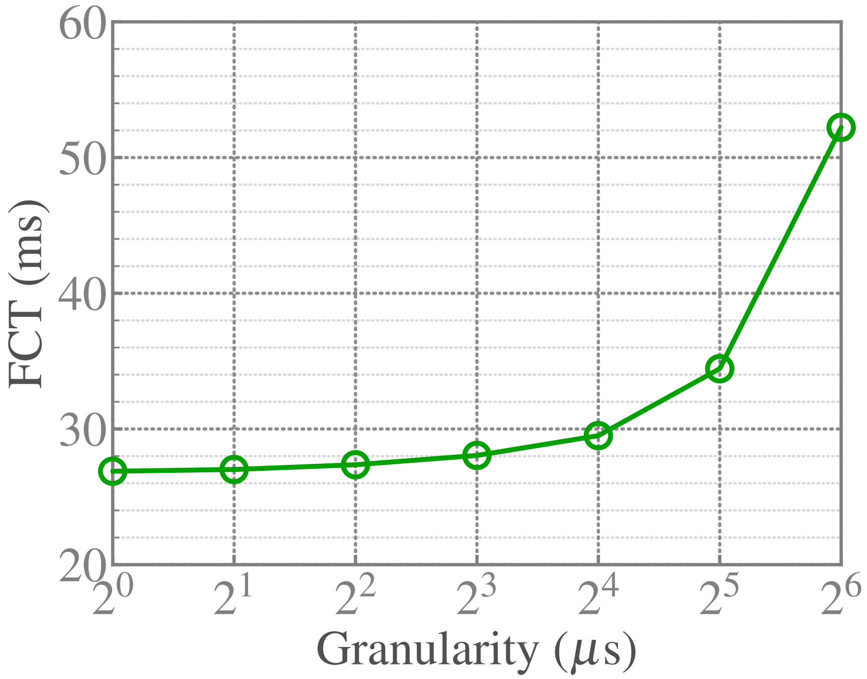

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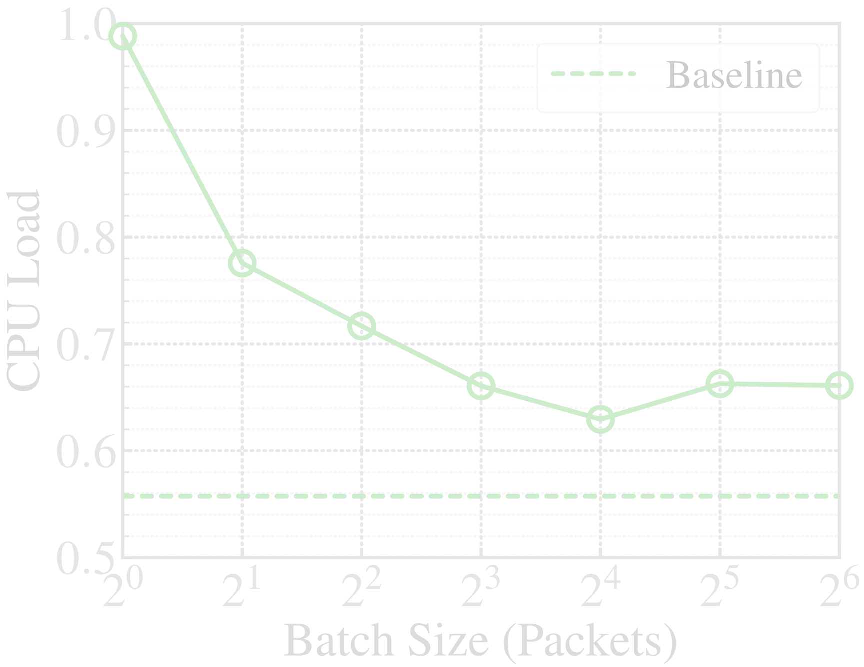

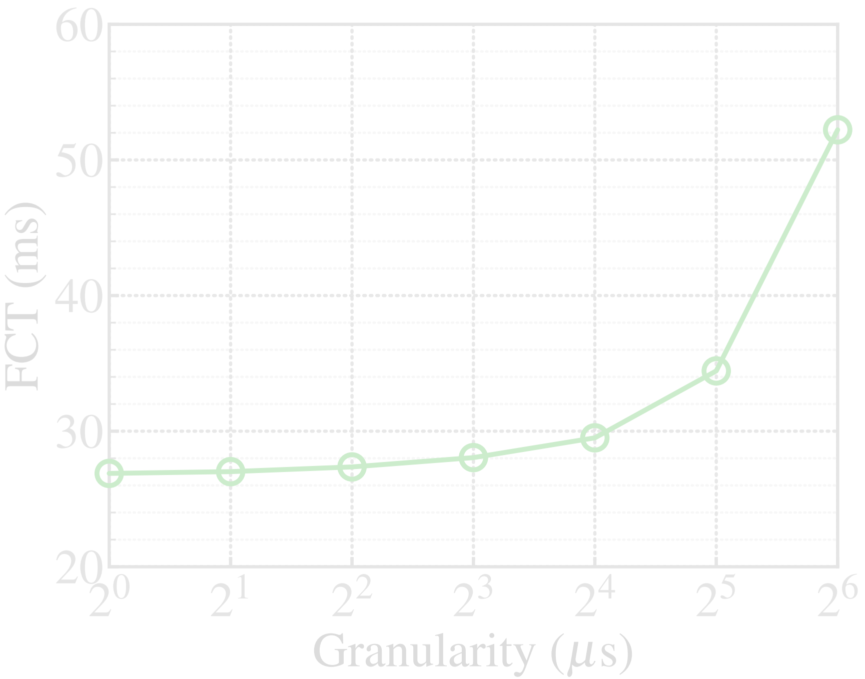

Can we achieve the best of both worlds?

Dilemma of batching

Our Insight

- Intra-flow burst is to blame
  - Bursts constituted by packets of the same flow

- Inter-flow burst can be *demultiplexed* before congestion point

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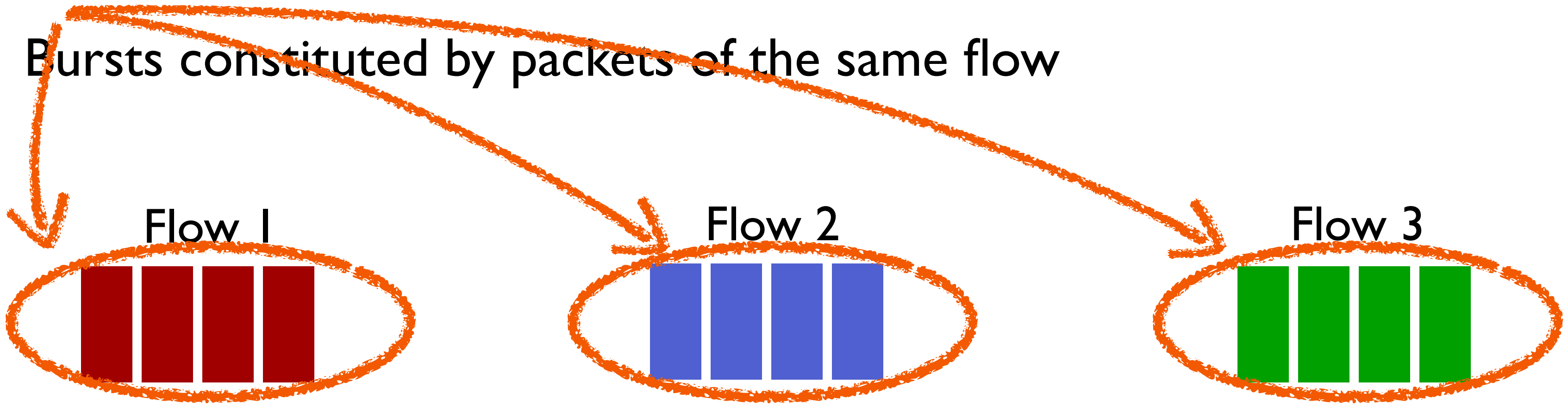

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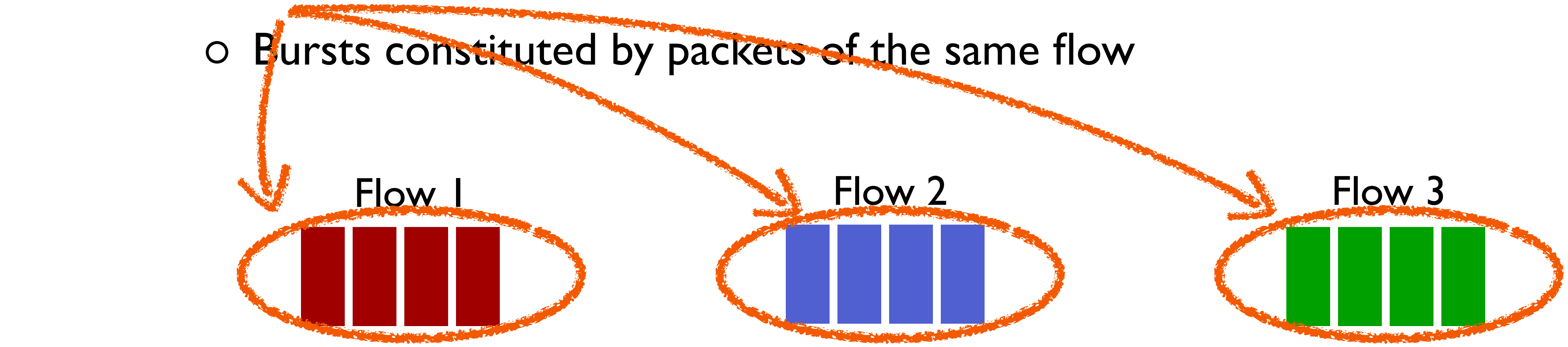

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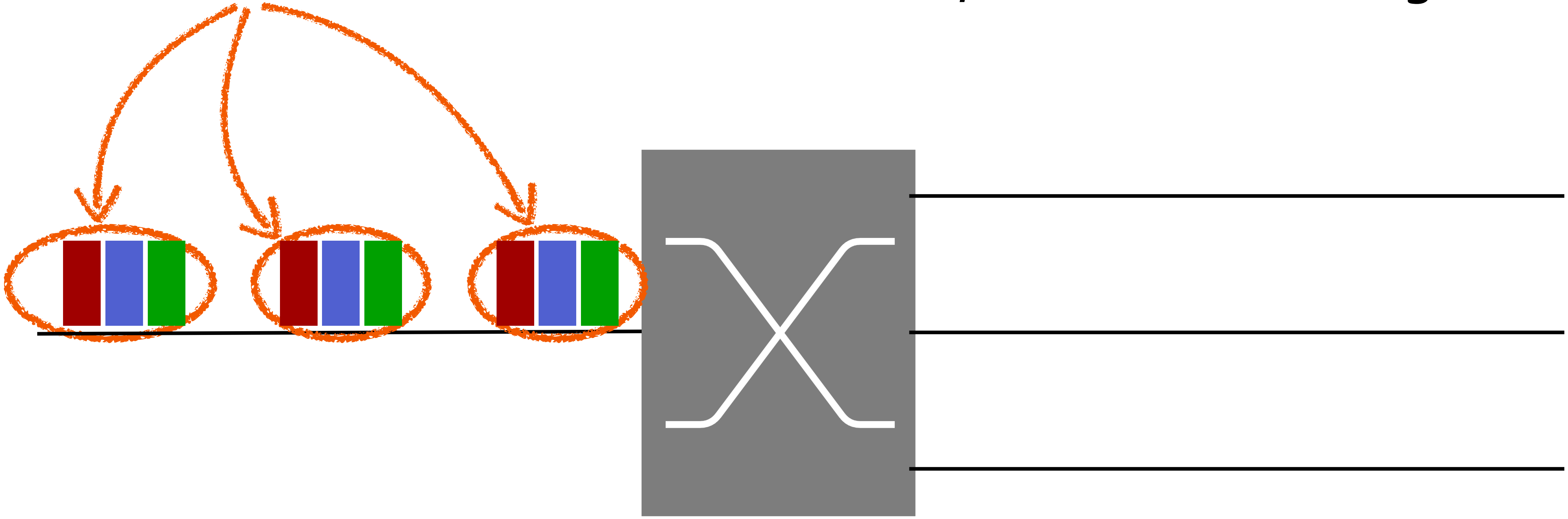

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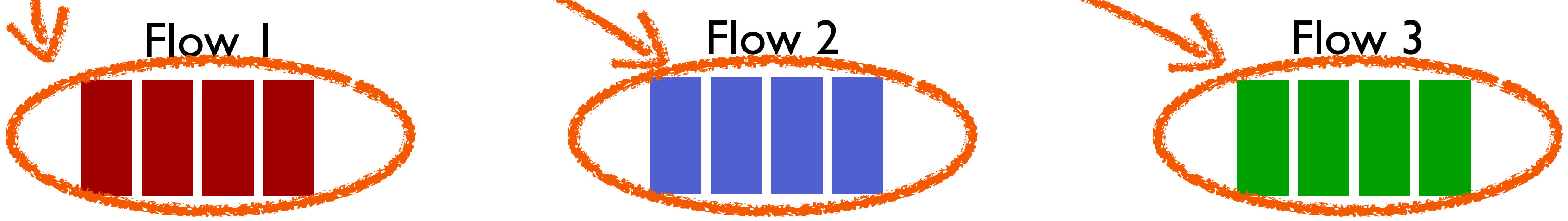

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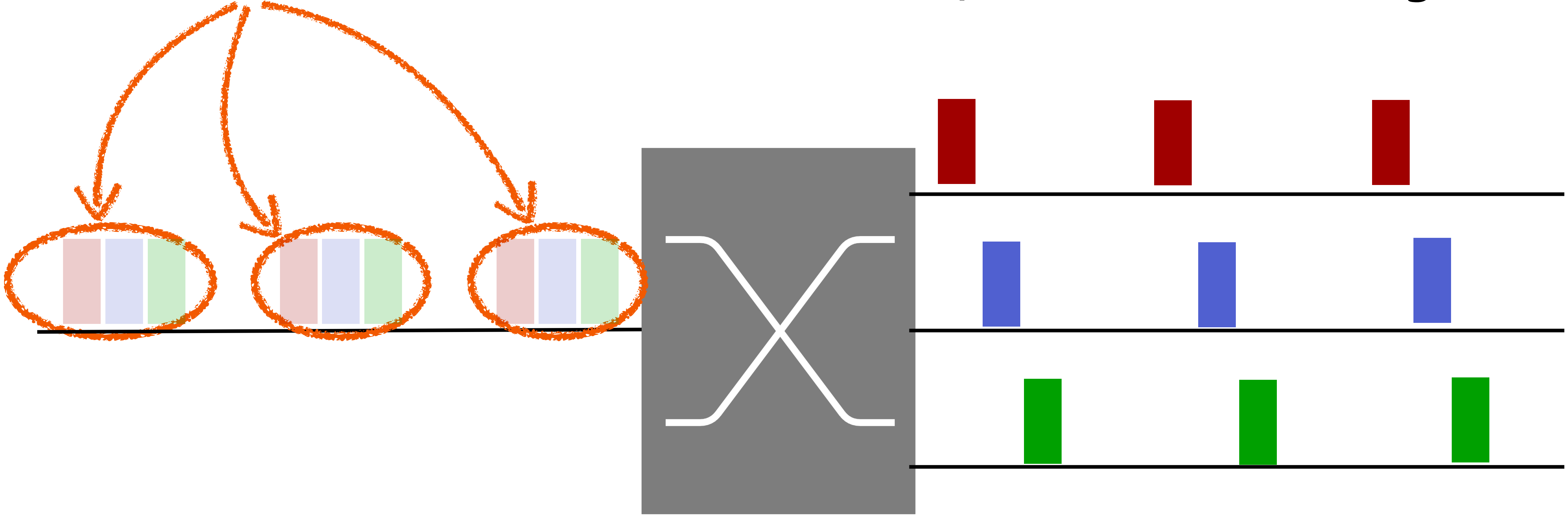


Our Insight

- Inter-flow burst can be *demultiplexed* before congestion point
  - Different flows from a host tend to have different routes
    - Most traffic is inner-rack
      - 75.7% of Hadoop traffic is destined to servers in the the same rack[SIGCOMM'17 Facebook]
      - 80% of cloud data center traffic stays within a rack[IMC'10 Microsoft]
    - Inter-rack traffic: ECMP
  - Most congestion occurs at the last hops[SIGCOMM'15 Google, IMC'17 Facebook]

Summary of Observations

- Batching is essential to achieve fast software traffic shaping on high-speed networks

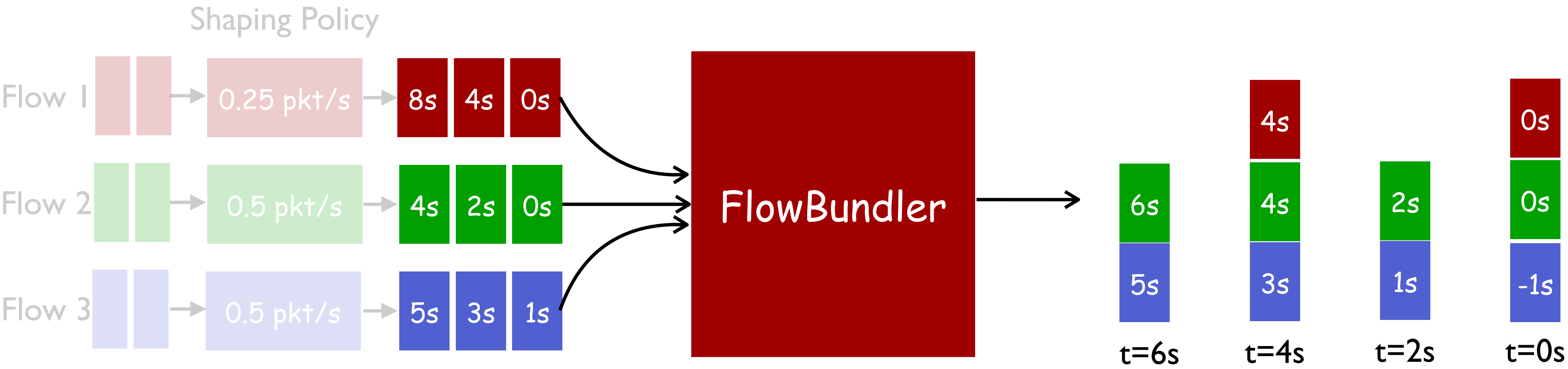
+

- Traffic shaping *only* needs to eliminate intra-flow bursts

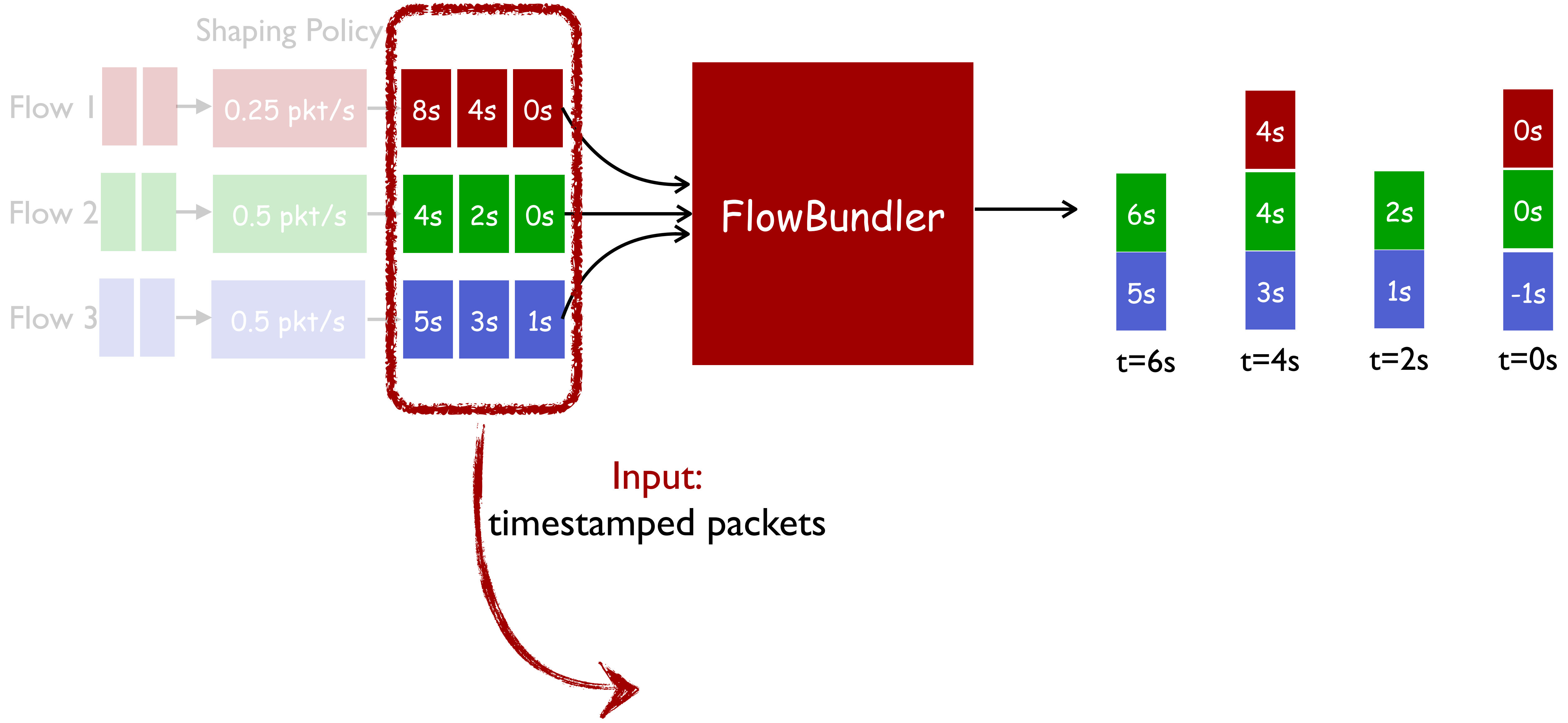
↓

- Traffic shaping can utilize inter-flow batching to reduce CPU overhead

Our Approach: FlowBundler

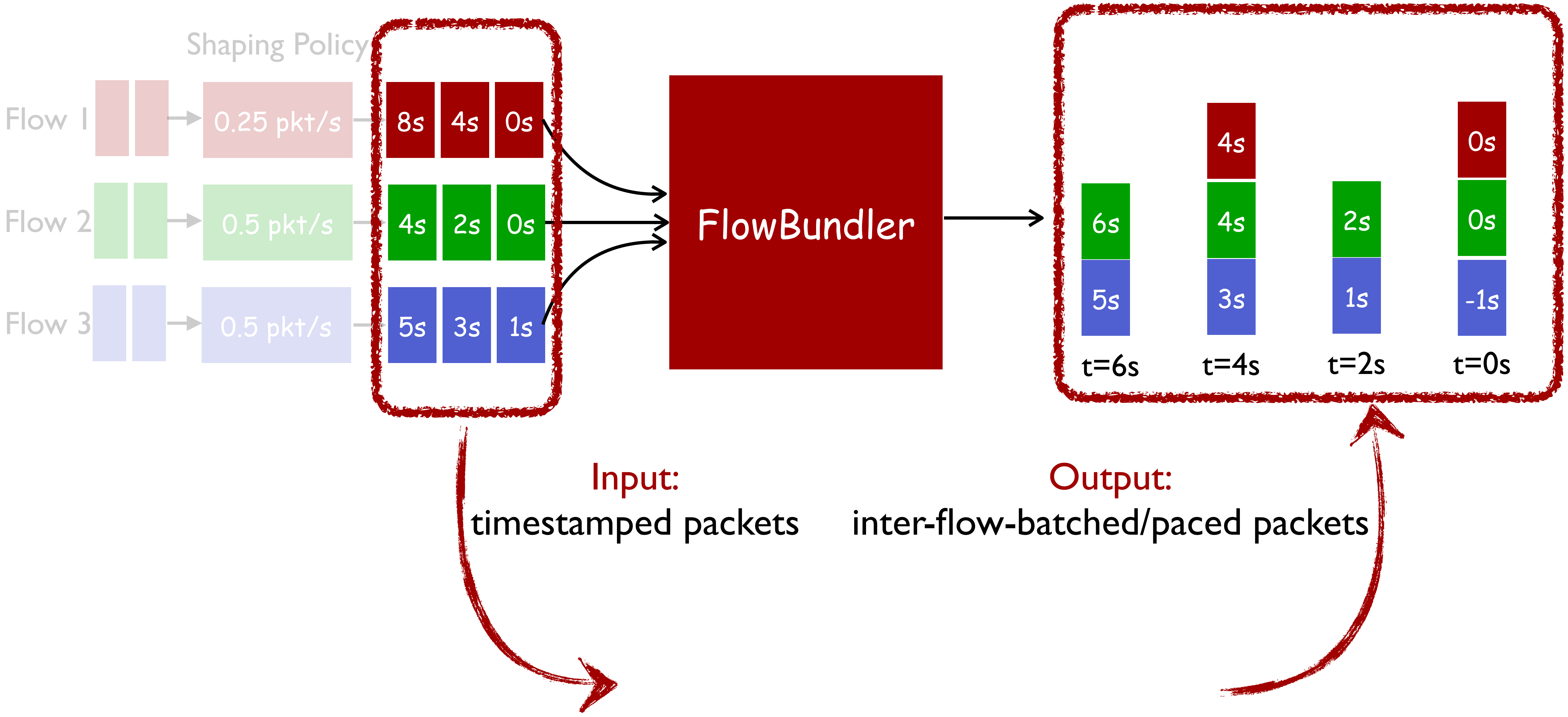


Our Approach: FlowBundler



Input:
timestamped packets

Our Approach: FlowBundler



Input:
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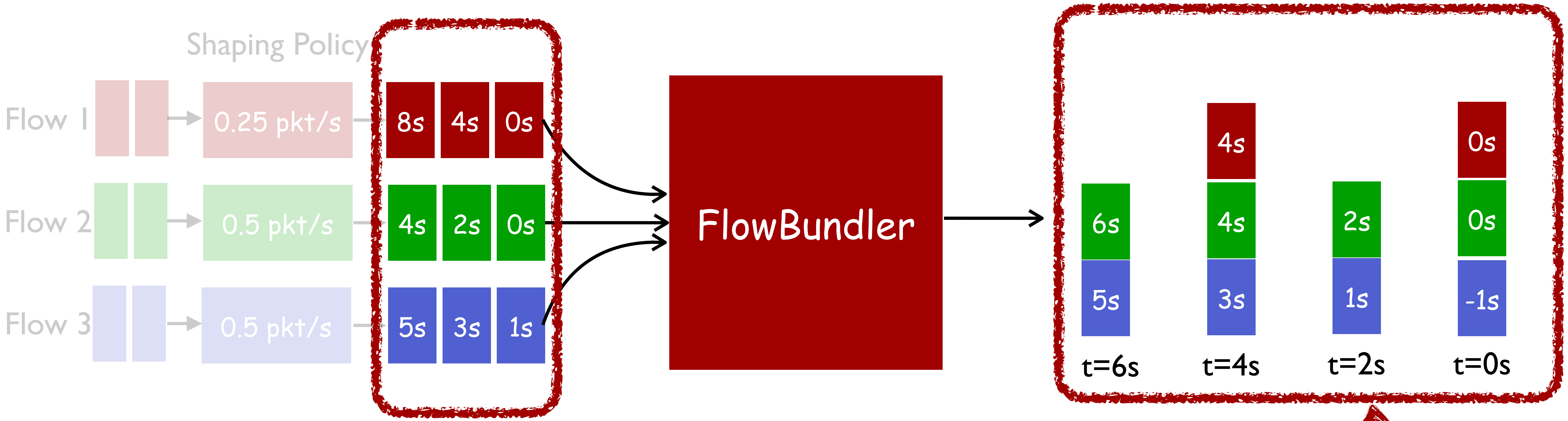
Output:
inter-flow-batched/paced packets

Our Approach: FlowBundler



Input:
timestamped packets

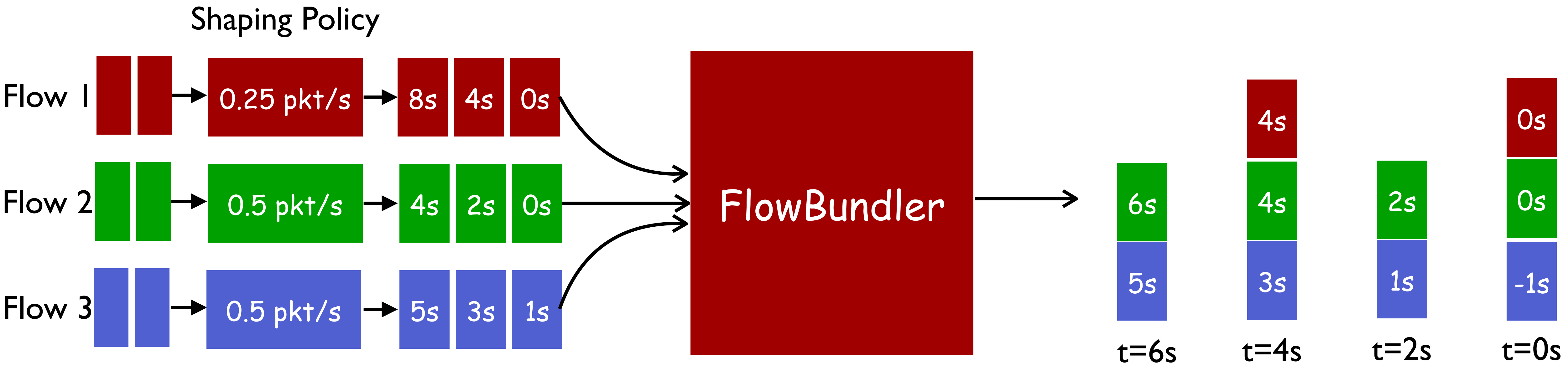
Output:
inter-flow-batched/paced packets

Goal of FlowBundler:

- Batching inter-flow packets
- Eliminating inner-flow bursts
- O(1) enqueue and dequeue time

Challenge

Question: How to efficiently place and extract inter-flow-batched packets



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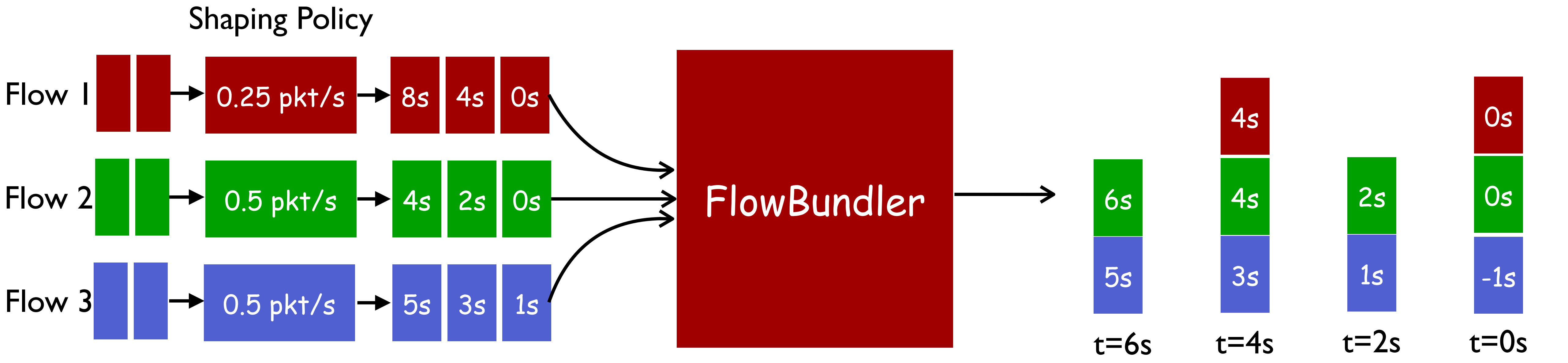

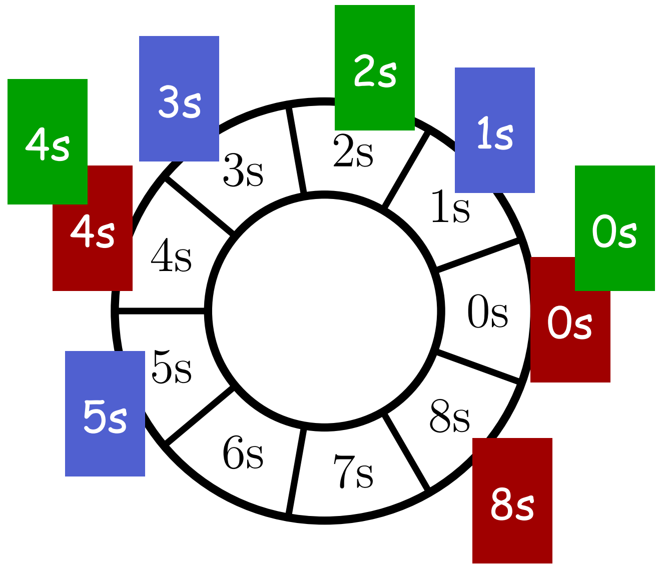

Timing Wheel:

✗ CPU inefficient: Multiple dequeue operations for a single batch

Challenge

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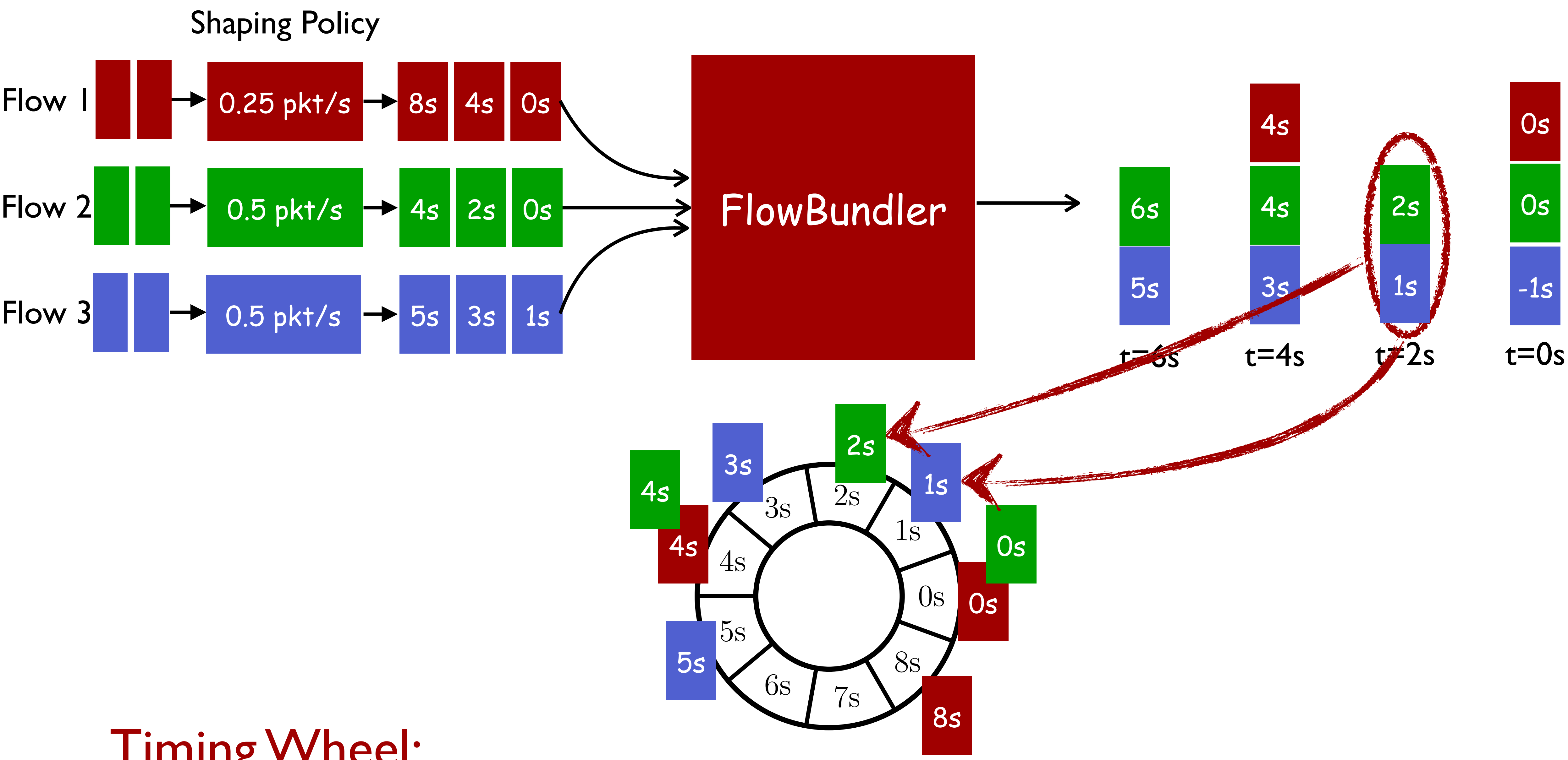

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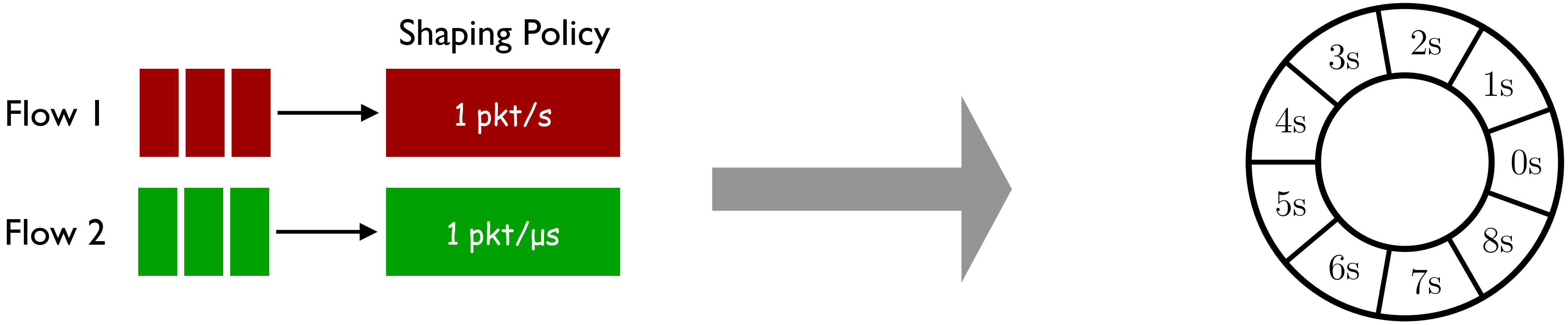


Granularity: 1s
# Slots: 9

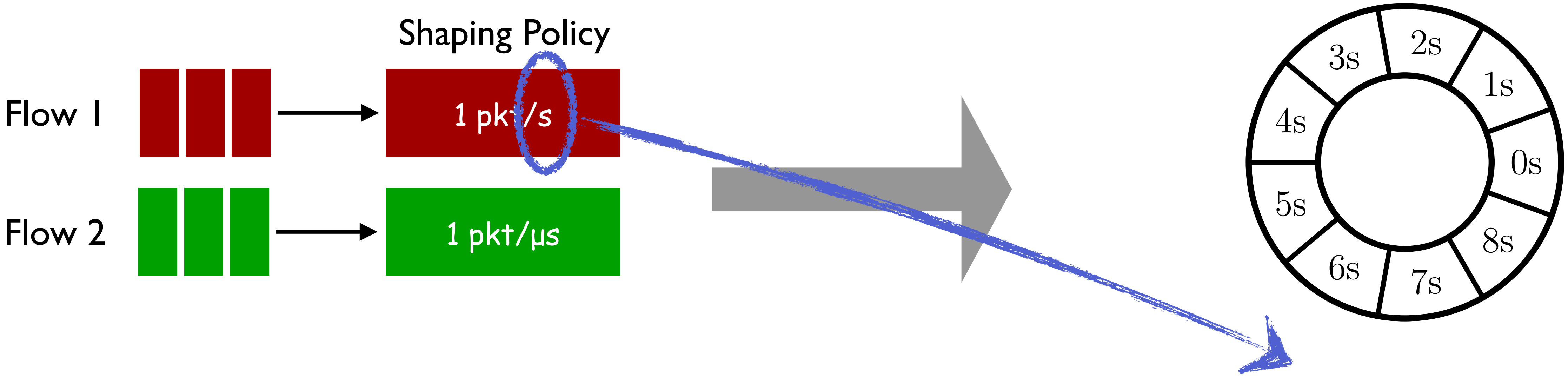
Timing Wheel:

✗ CPU inefficient: Multiple dequeue operations for a single batch

✗ Memory inefficient: Huge memory requirement

Challenge

Question: How to efficiently place and dequeue inter-flow-batched packets



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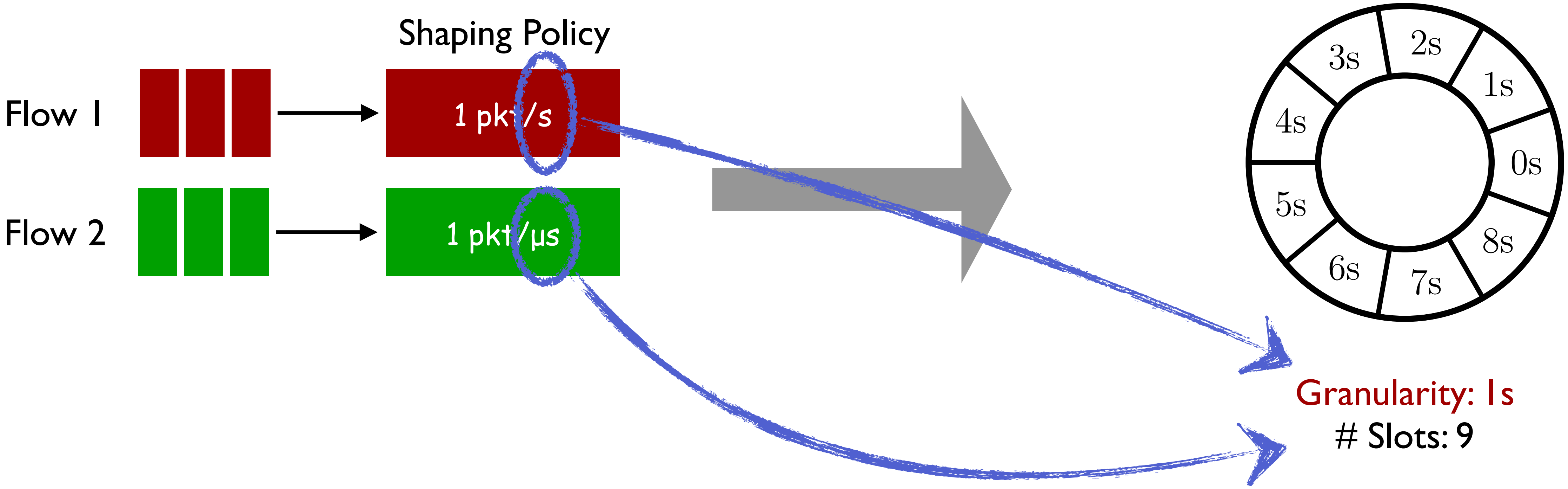

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Challenge

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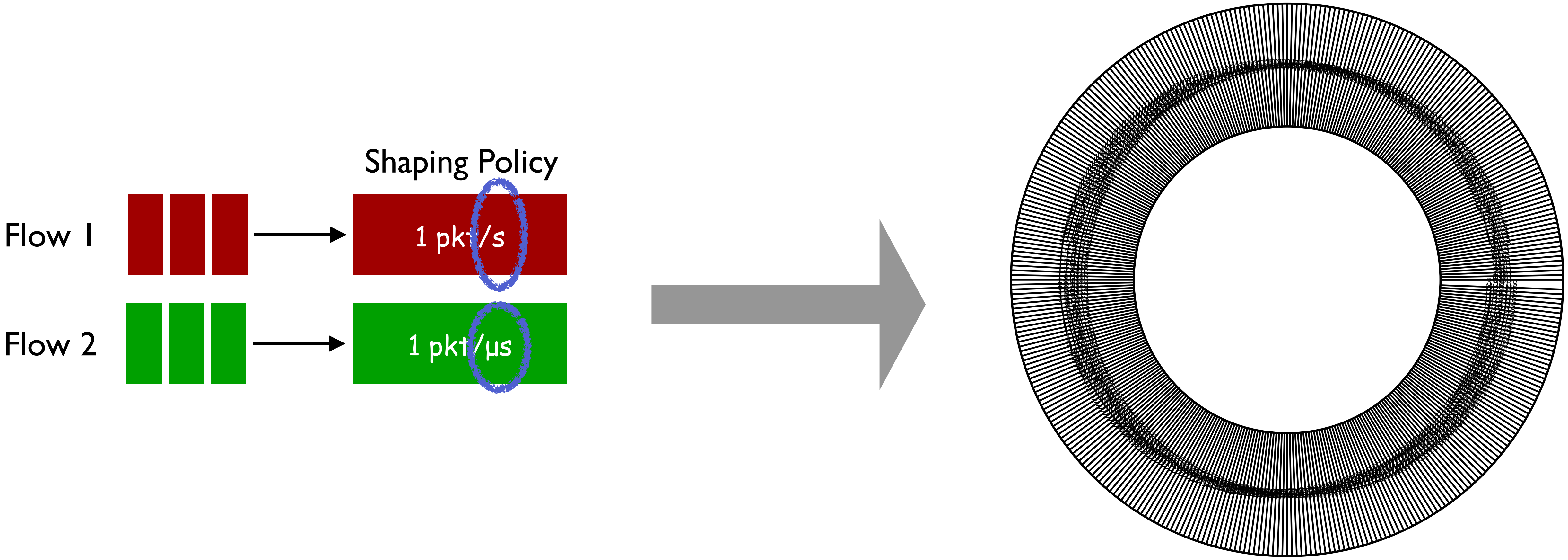


Granularity: 1 μs
# Slots: 9×10^6

Timing Wheel:

✗ CPU inefficient: Multiple dequeue operations for a single batch

✗ Memory inefficient: Huge memory requirement

Challenge

Question: How to efficiently place and extract inter-flow-batched packets

🤔 How to achieve fine granularity and wide time-range simultaneously?

Challenge

Question: How to efficiently place and extract inter-flow-batched packets

🤔 How to achieve fine granularity and wide time-range simultaneously?

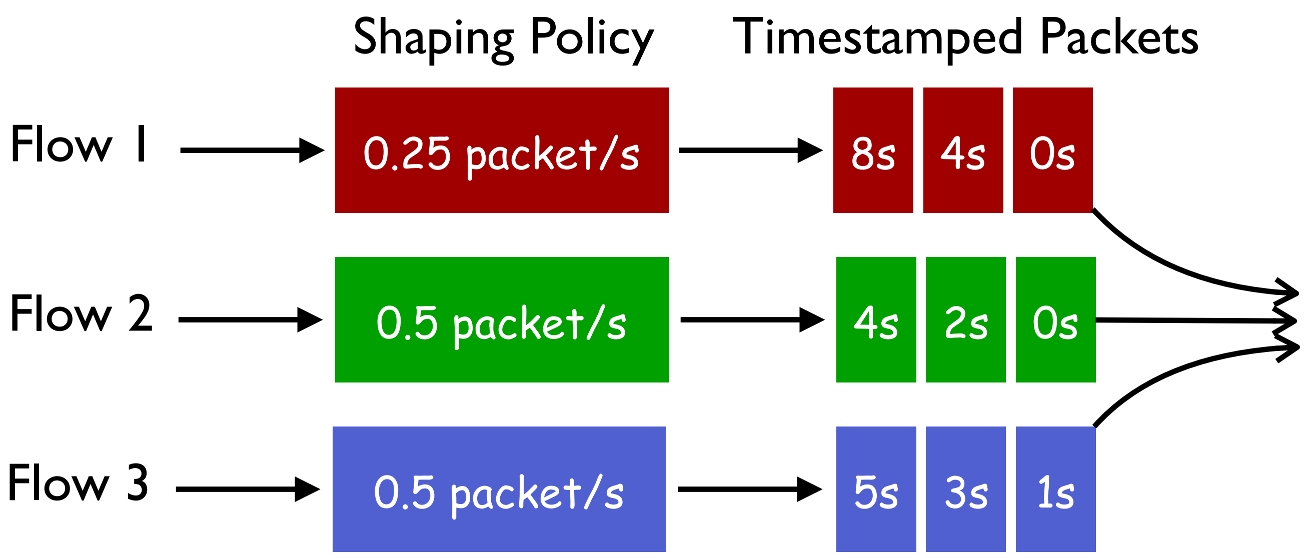
↓

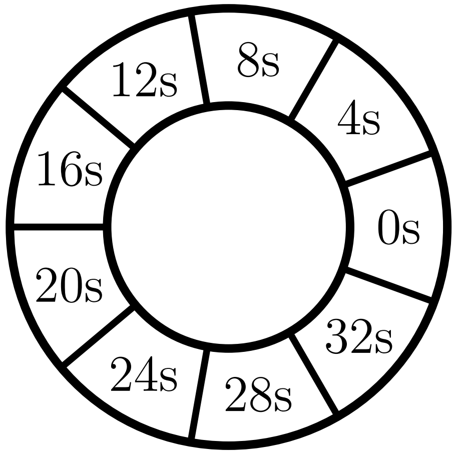
💡 Water meter

Challenge

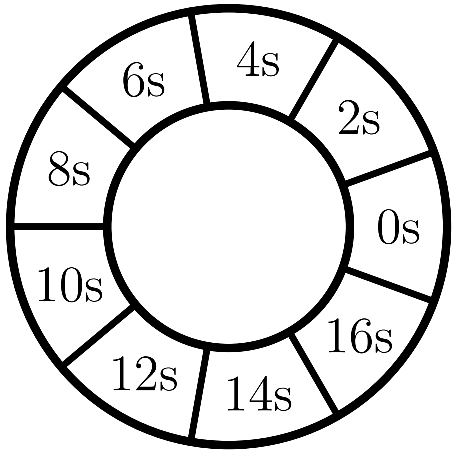
Question: How to efficiently place and extract inter-flow-batched packets

Answer: Muti-level Timing Wheel

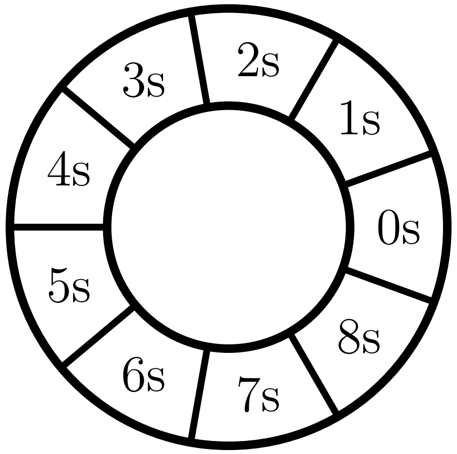




Granularity: 4s
Rate: 0.25 packet/s



Granularity: 2s
Rate: 0.5 packet/s

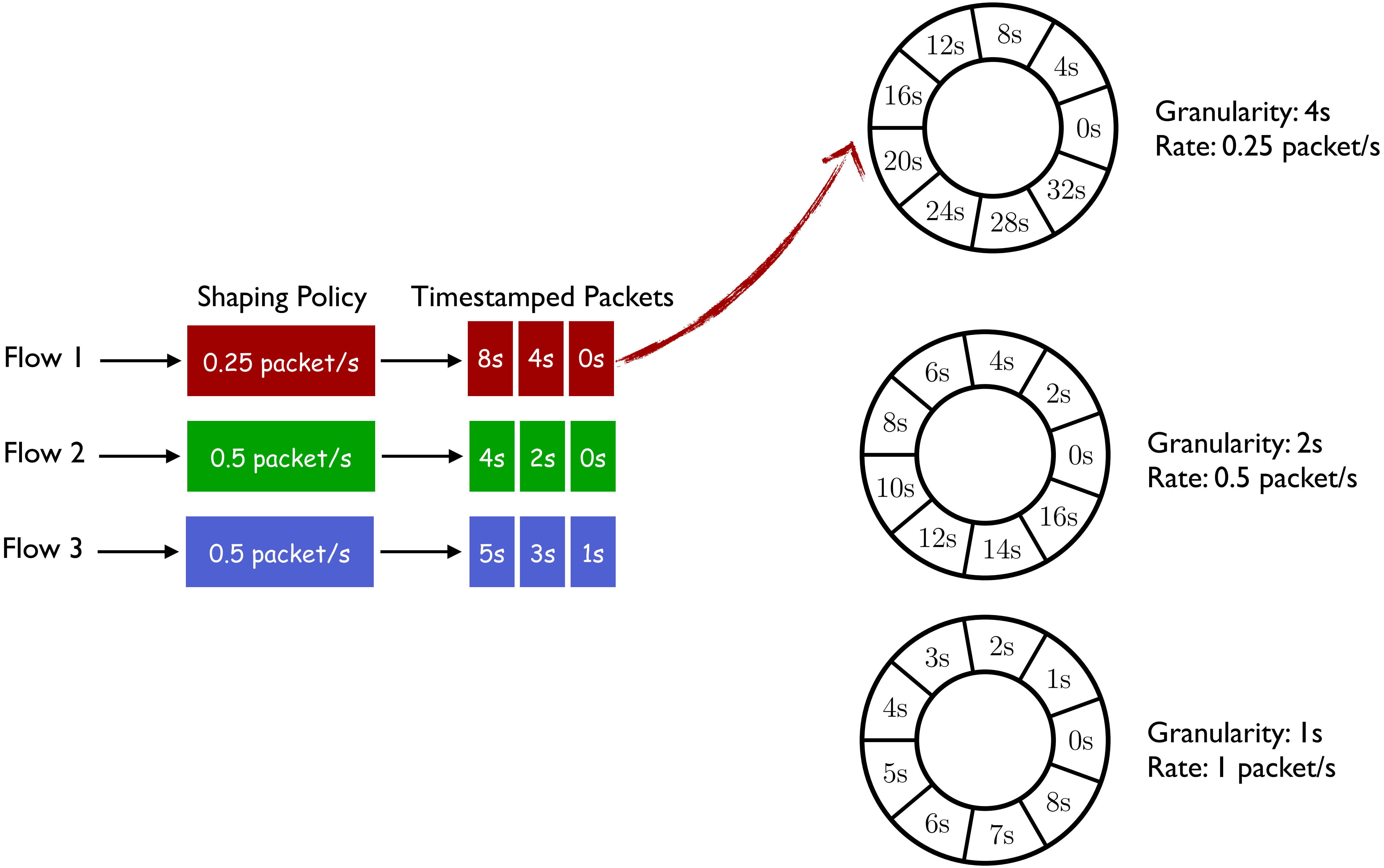


Granularity: 1s
Rate: 1 packet/s

Muti-level Timing Wheel (MLTW)

❶ Put packet into the queue whose granularity best matches the flow’s shaping rate

❷ Gather inter-flow-batched packets from different timing wheels



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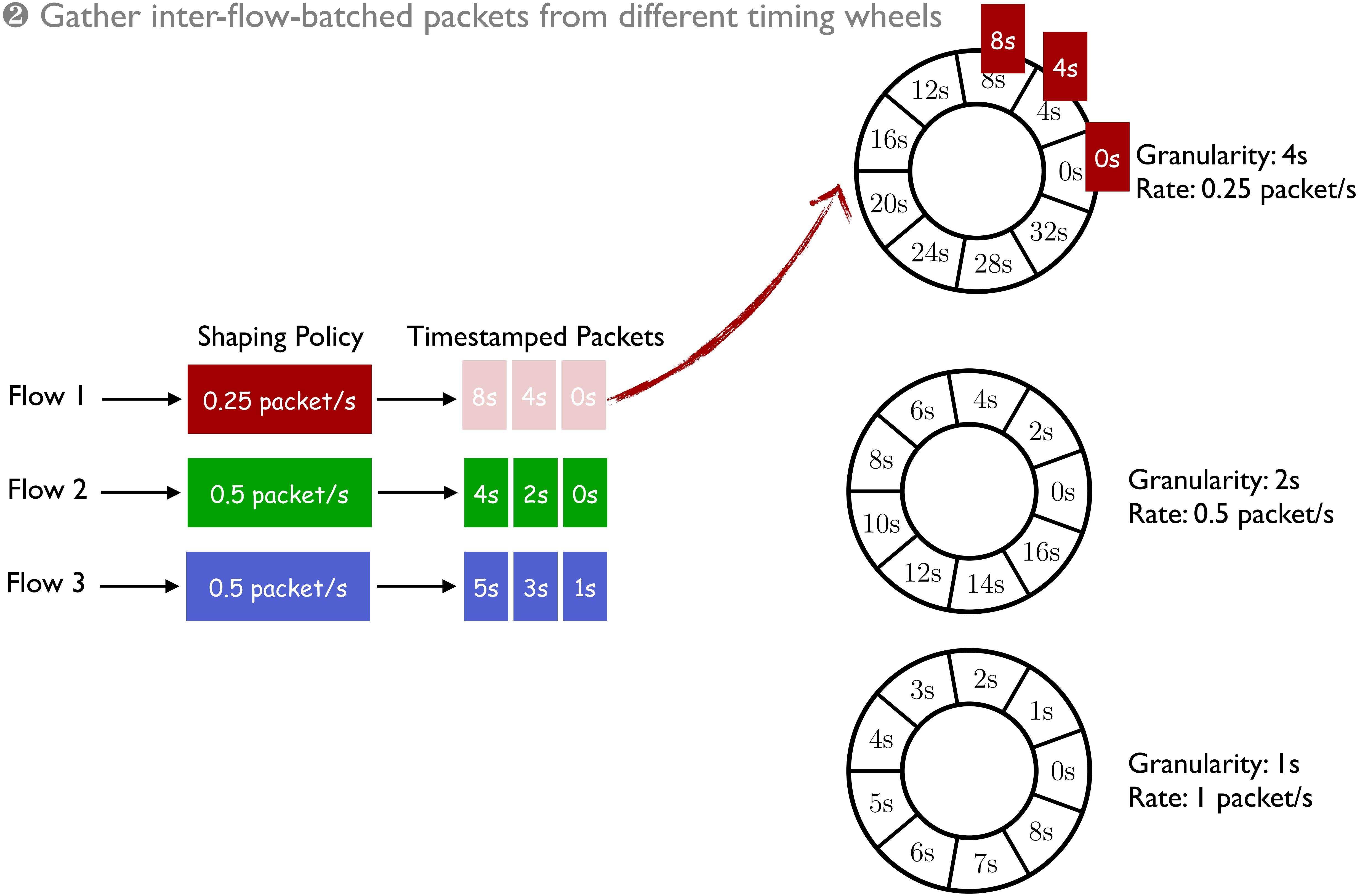

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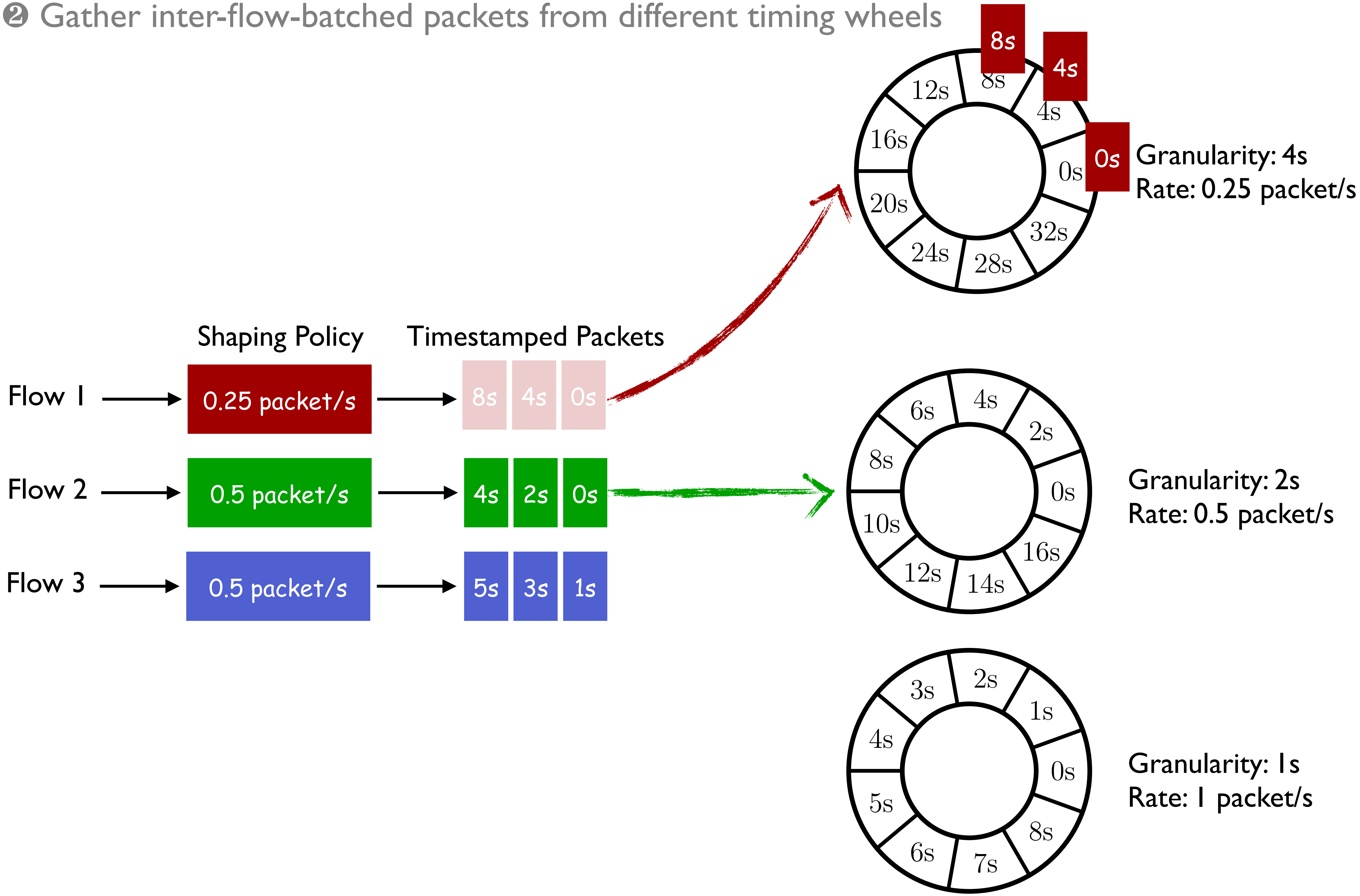

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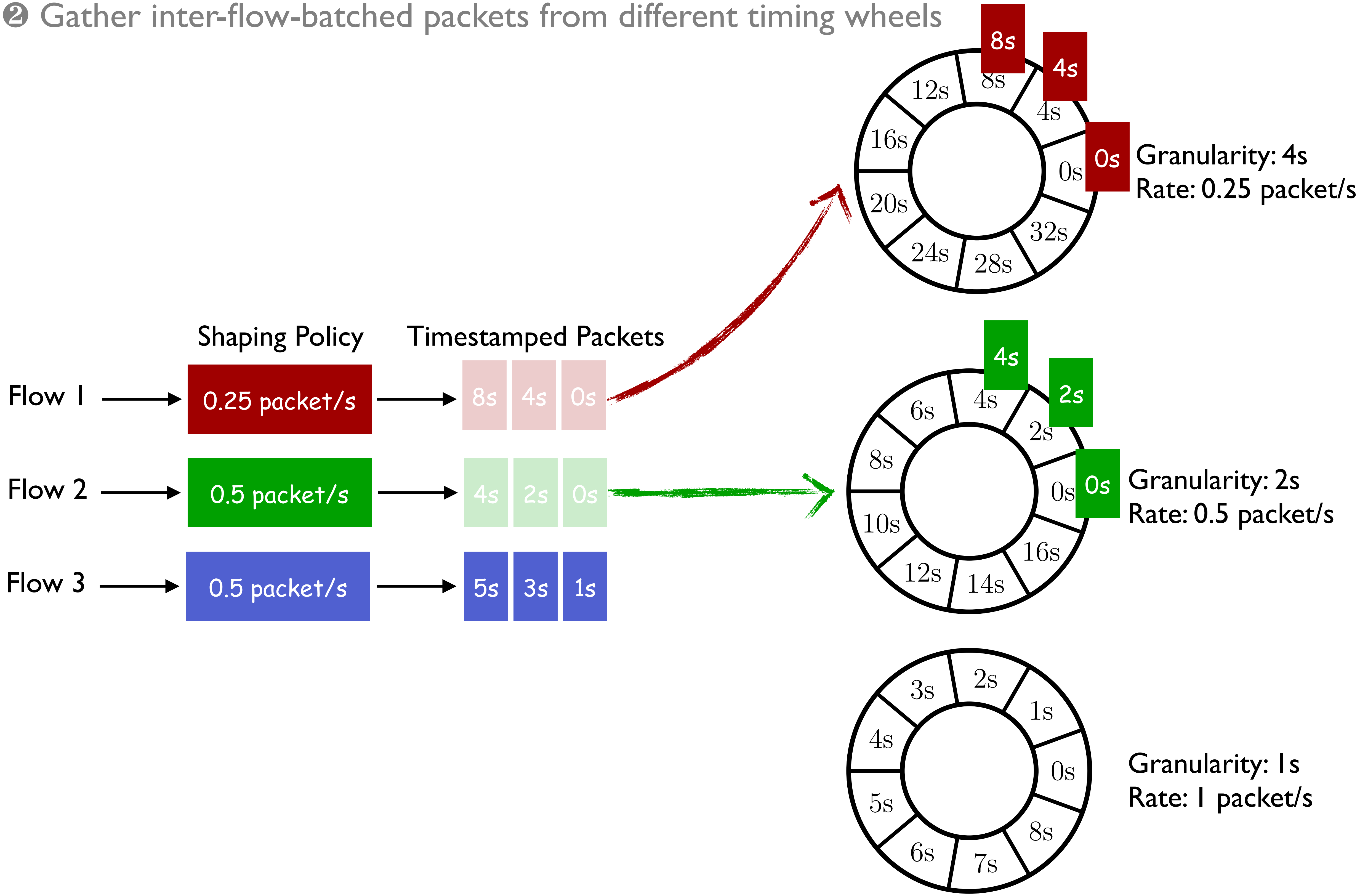
Shaping Policy

Timestamped Packets

Flow 1 → 0.25 packet/s → 8s 4s 0s

Flow 2 → 0.5 packet/s → 4s 2s 0s

Flow 3 → 0.5 packet/s → 5s 3s 1s

Granularity: 4s
Rate: 0.25 packet/s

Granularity: 2s
Rate: 0.5 packet/s

Granularity: 1s
Rate: 1 packet/s

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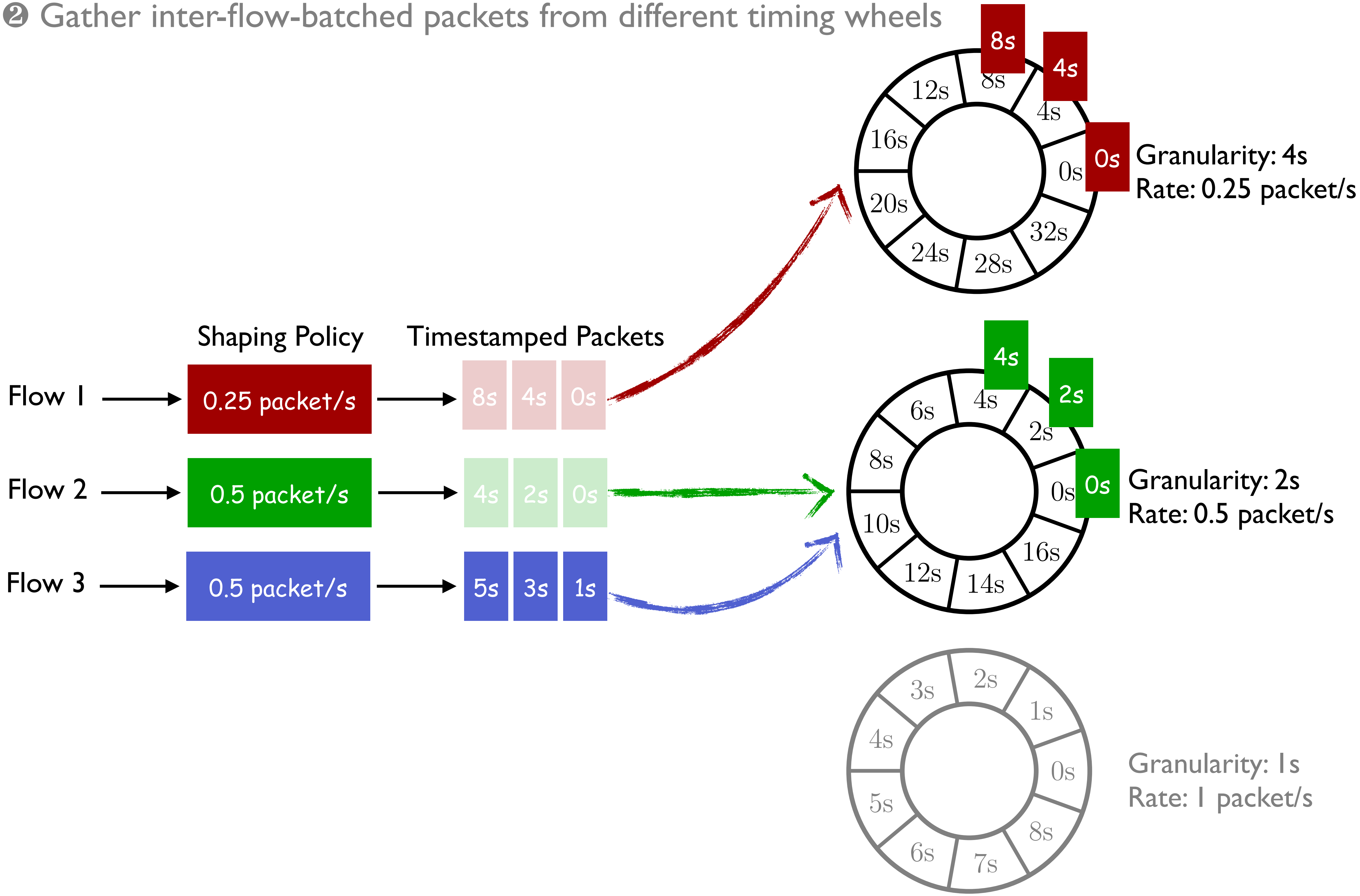

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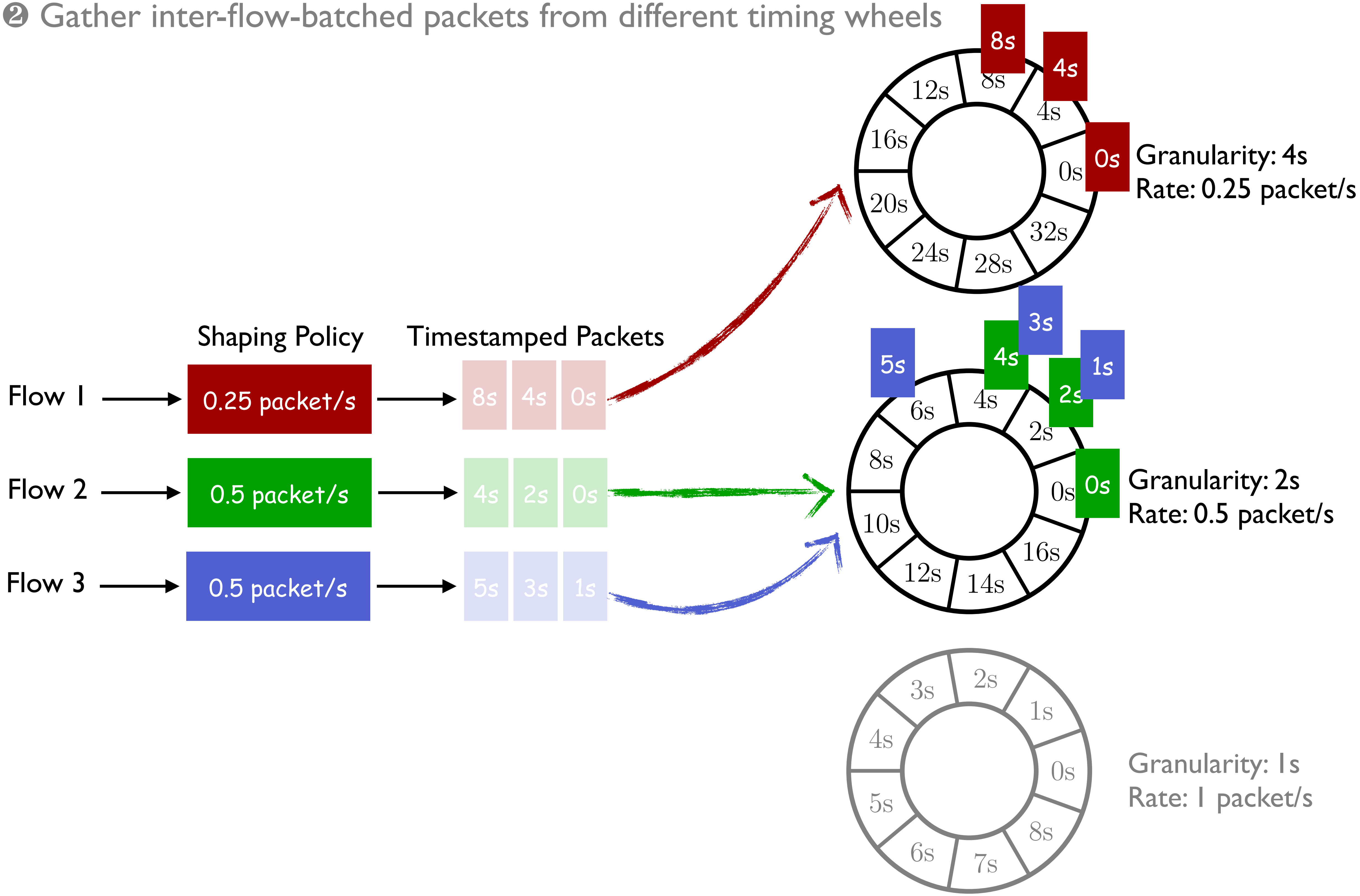

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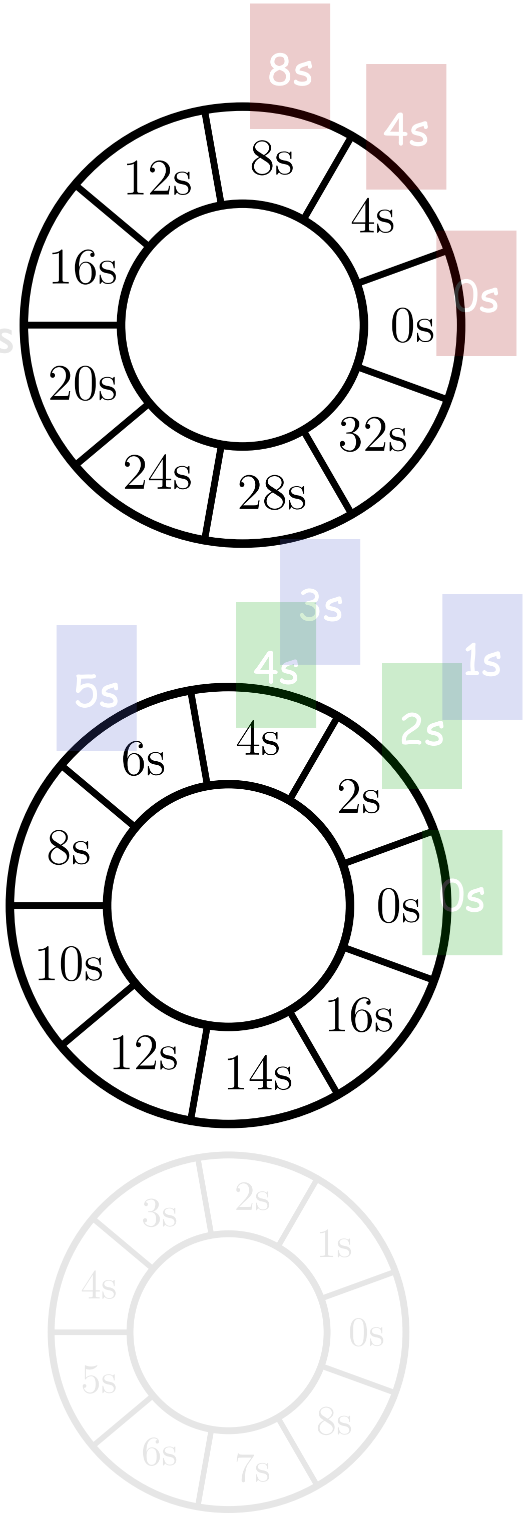

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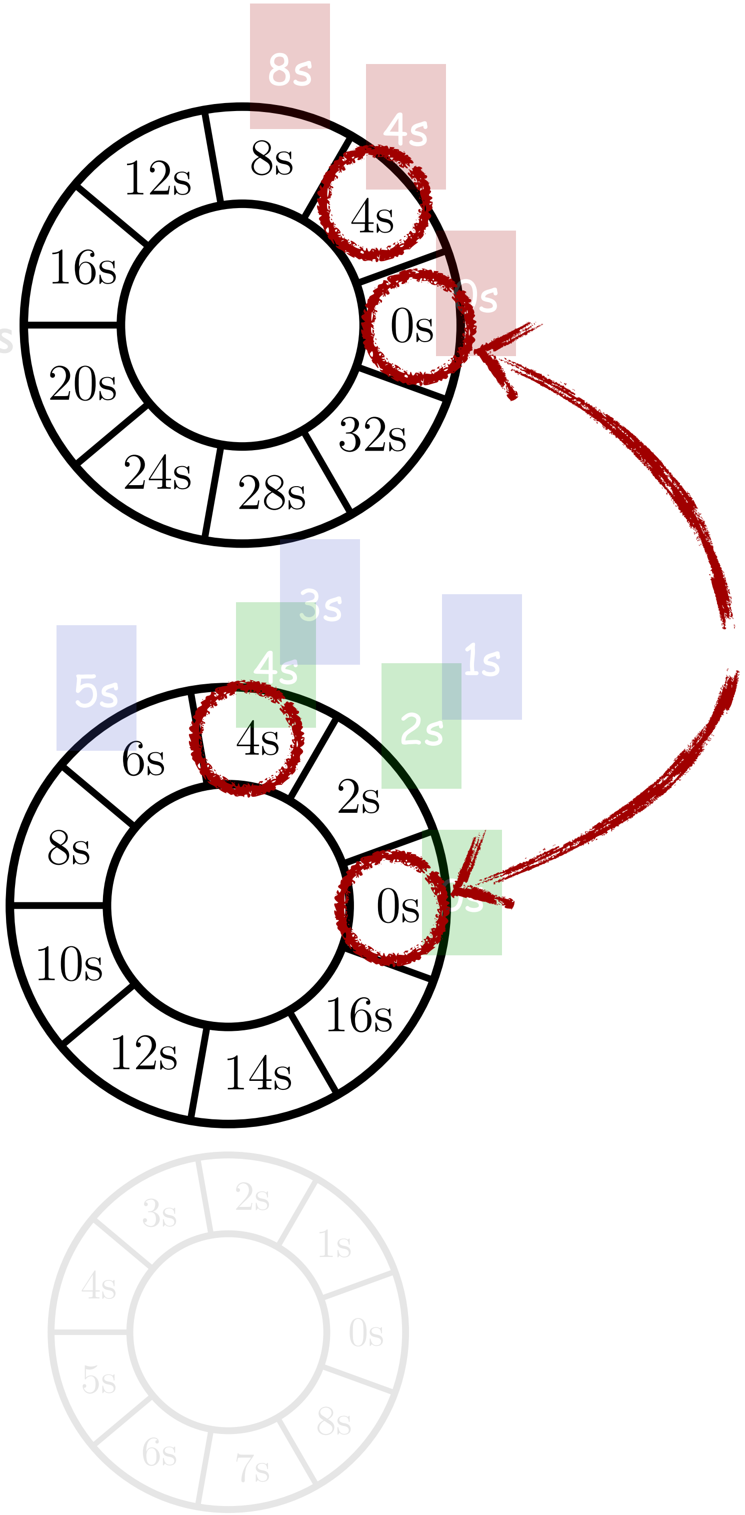

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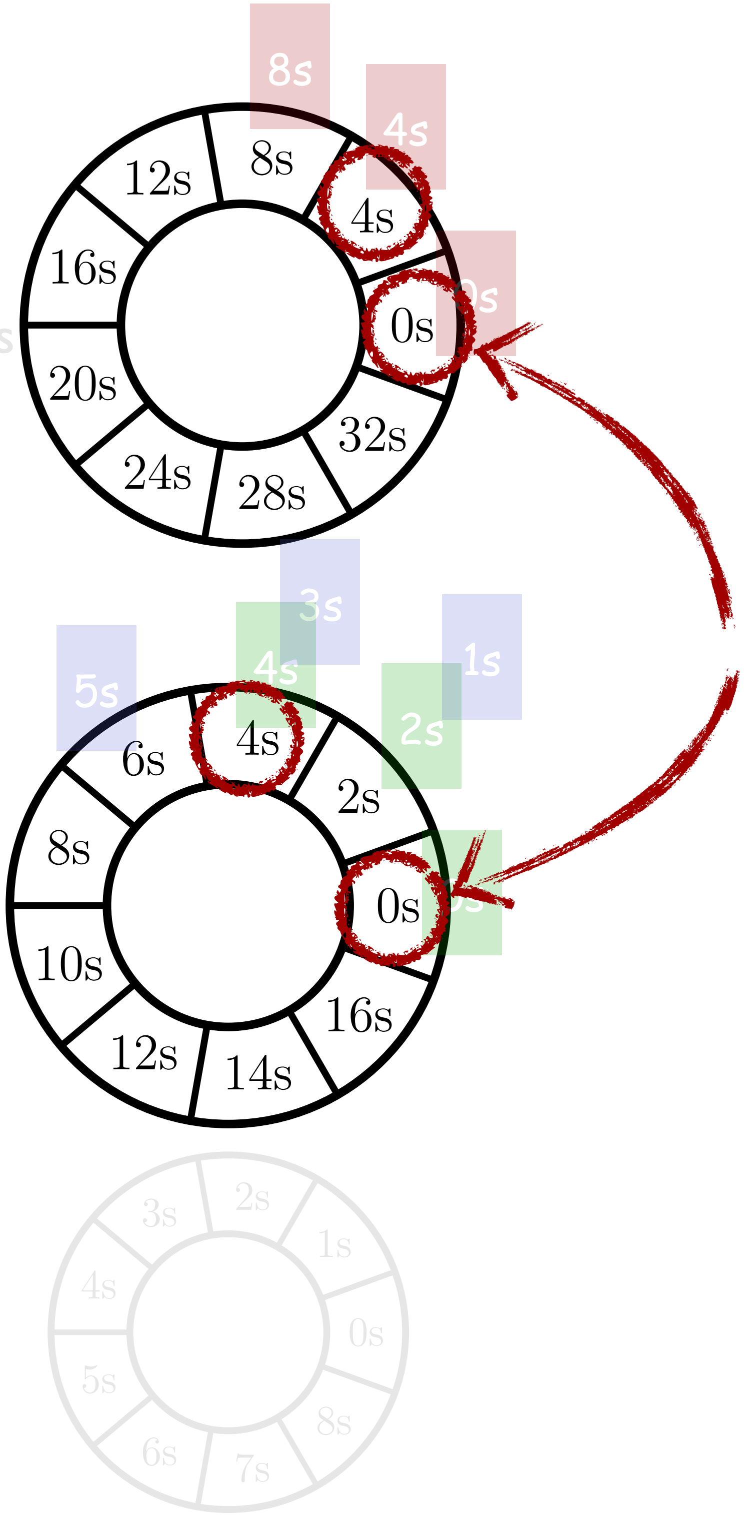

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Granularity: 1s
Rate: 1 packet/s

- Have the same timestamp → Sent at the same time

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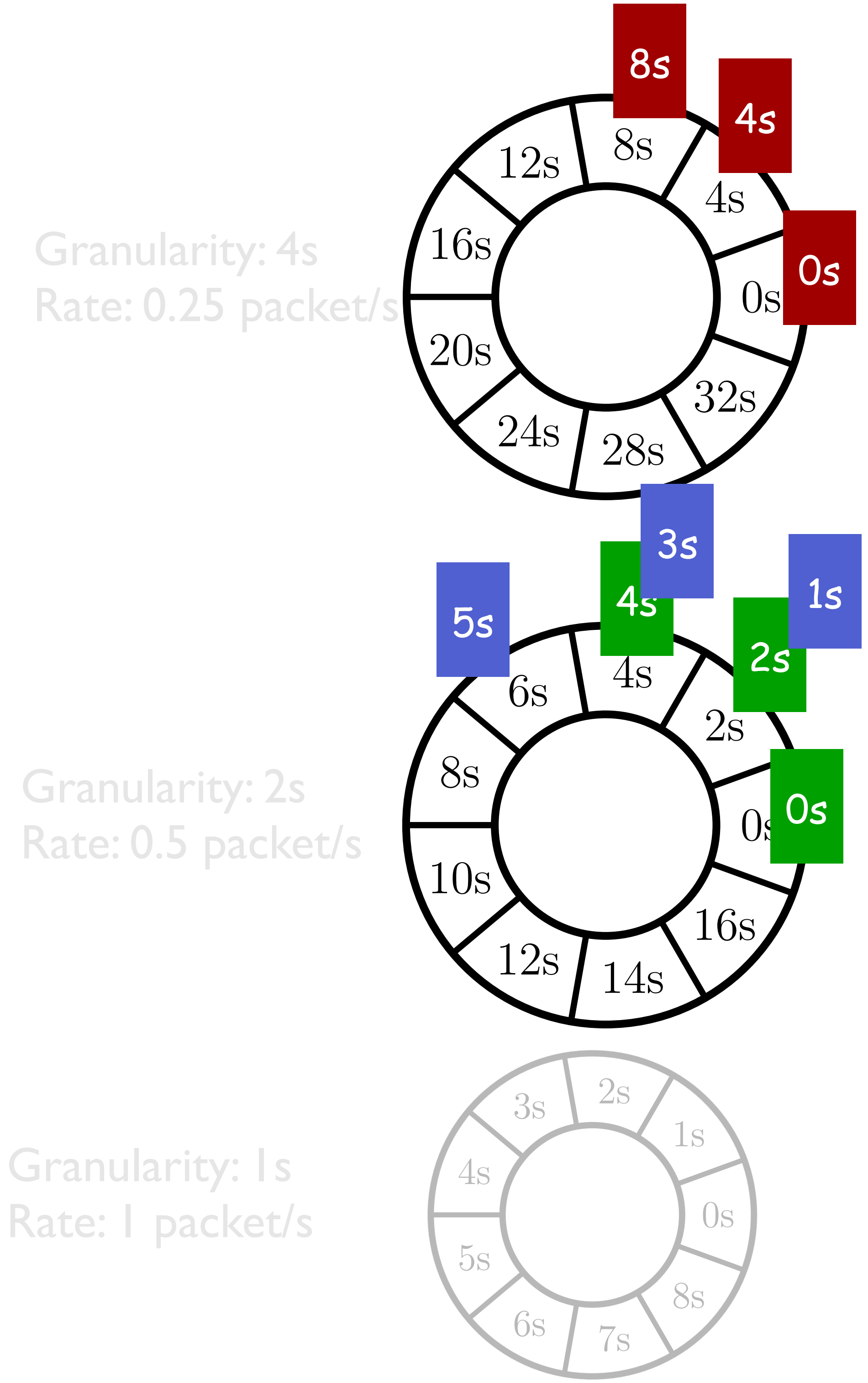

- Have the same timestamp → Sent at the same time
- Gather these packets into the same slot
  ✓ Place inter-flow-batched packets together
  ✓ Reduce # of dequeue operations

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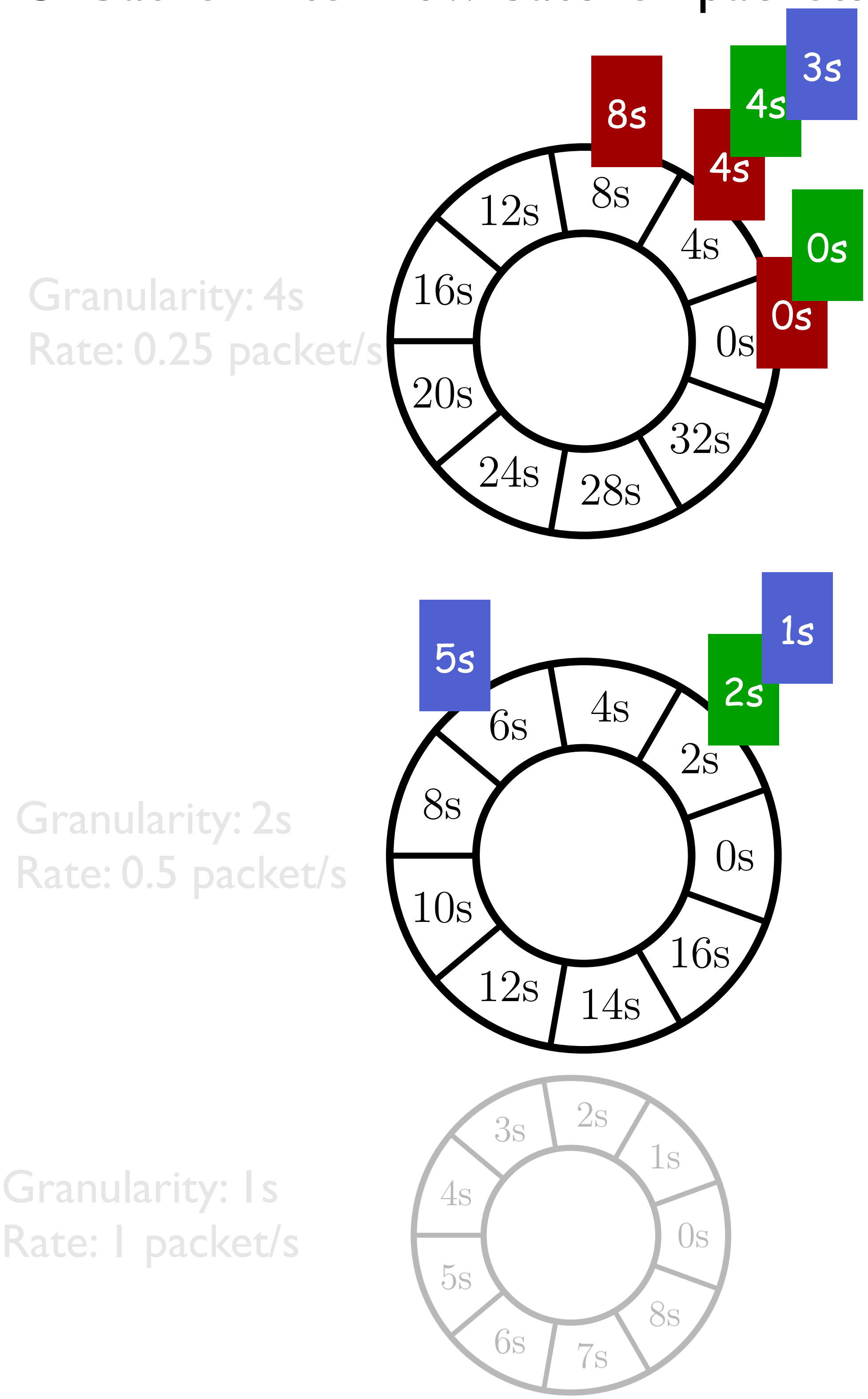
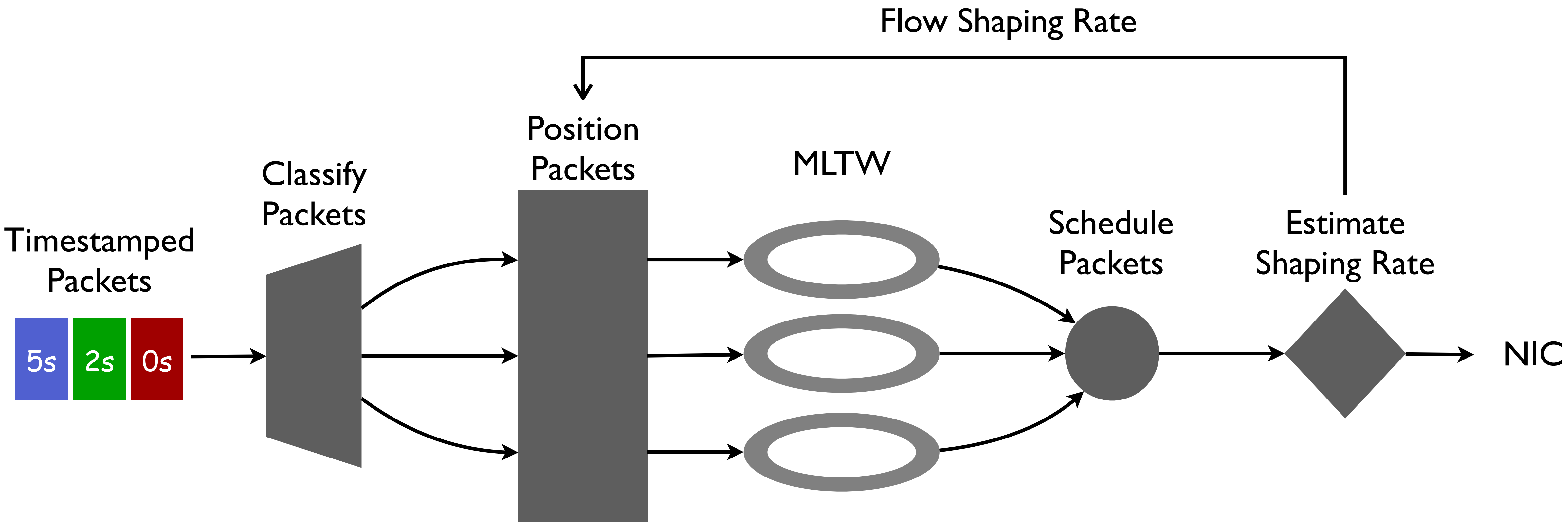


- Have the same timestamp → Sent at the same time
- Gather these packets into the same slot
  - ✓ Place inter-flow-batched packets together
  - ✓ Reduce # of dequeue operations

Putting Together: FlowBundler



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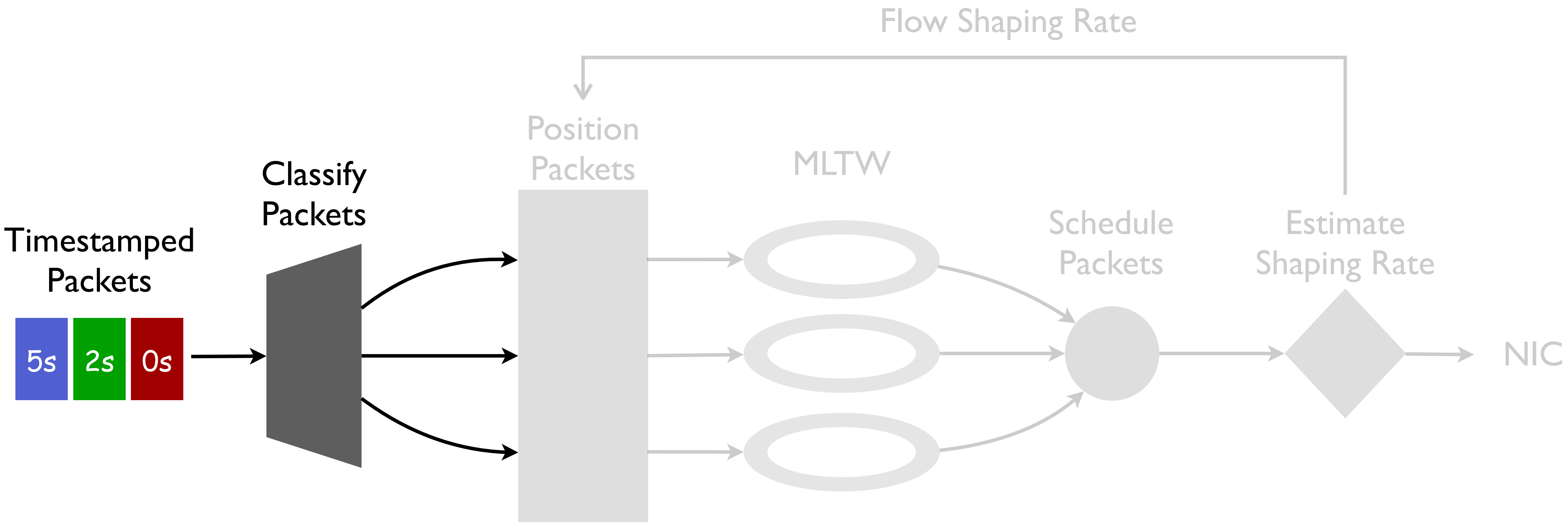
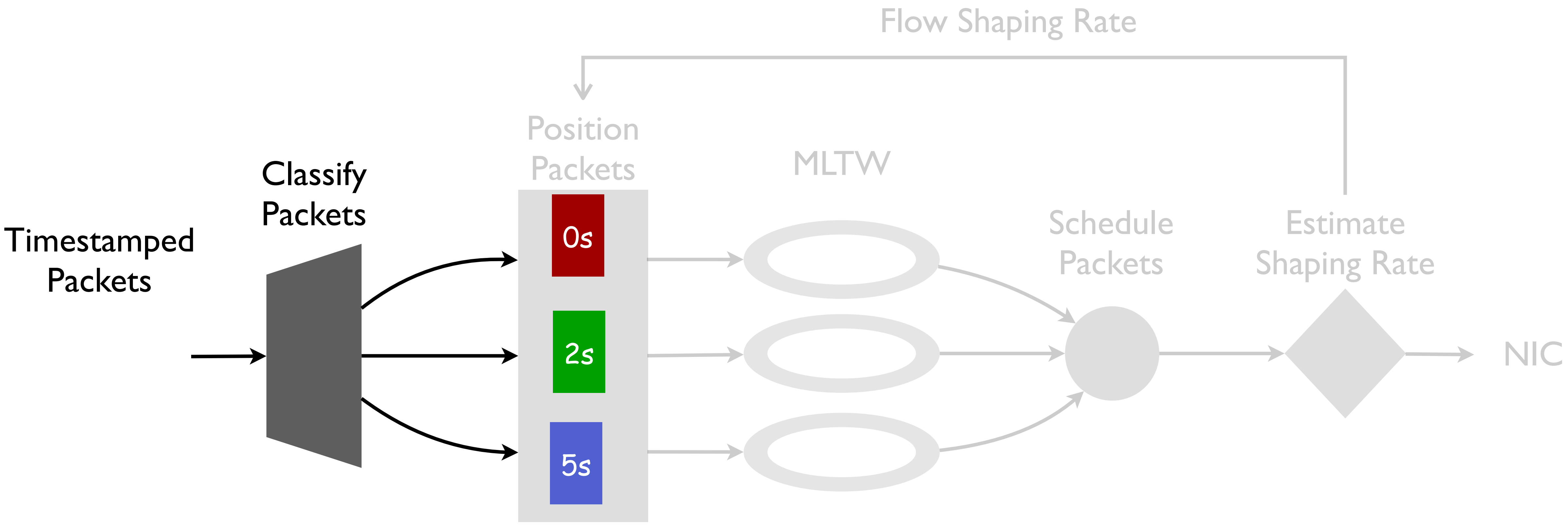


❶ Classify packets into flows

Putting Together: FlowBundler



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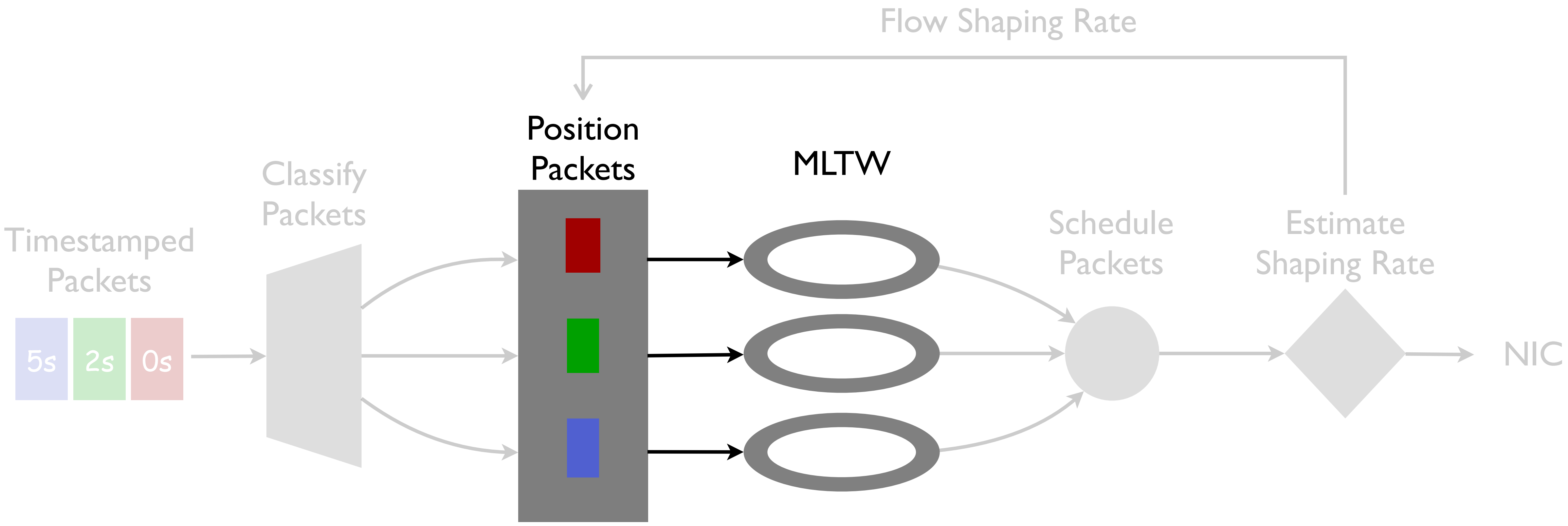
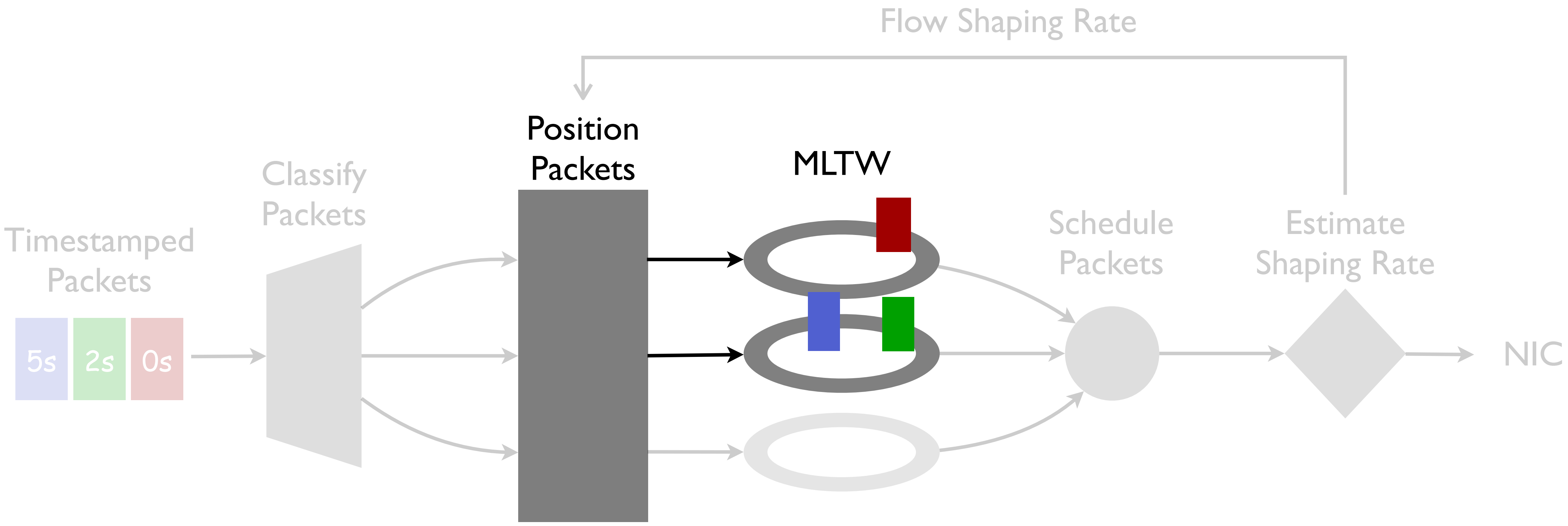


❶ Classify packets into flows

❷ Place packets into MLTW based on flow shaping rate and timestamp

Putting Together: FlowBundler



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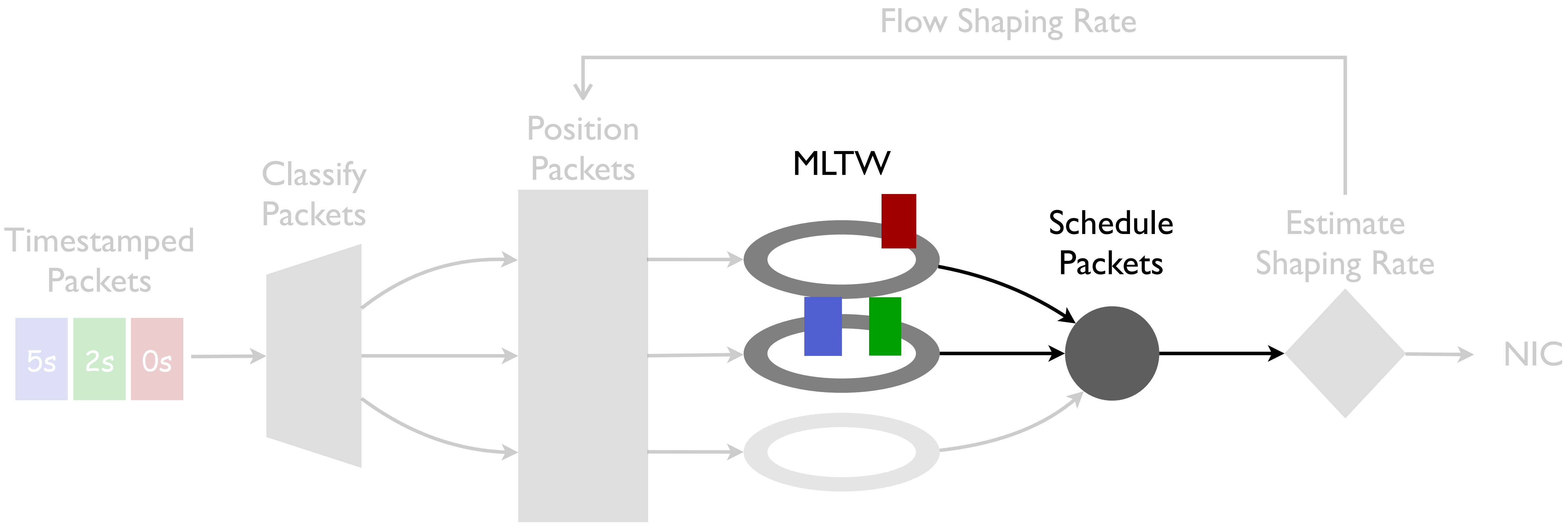

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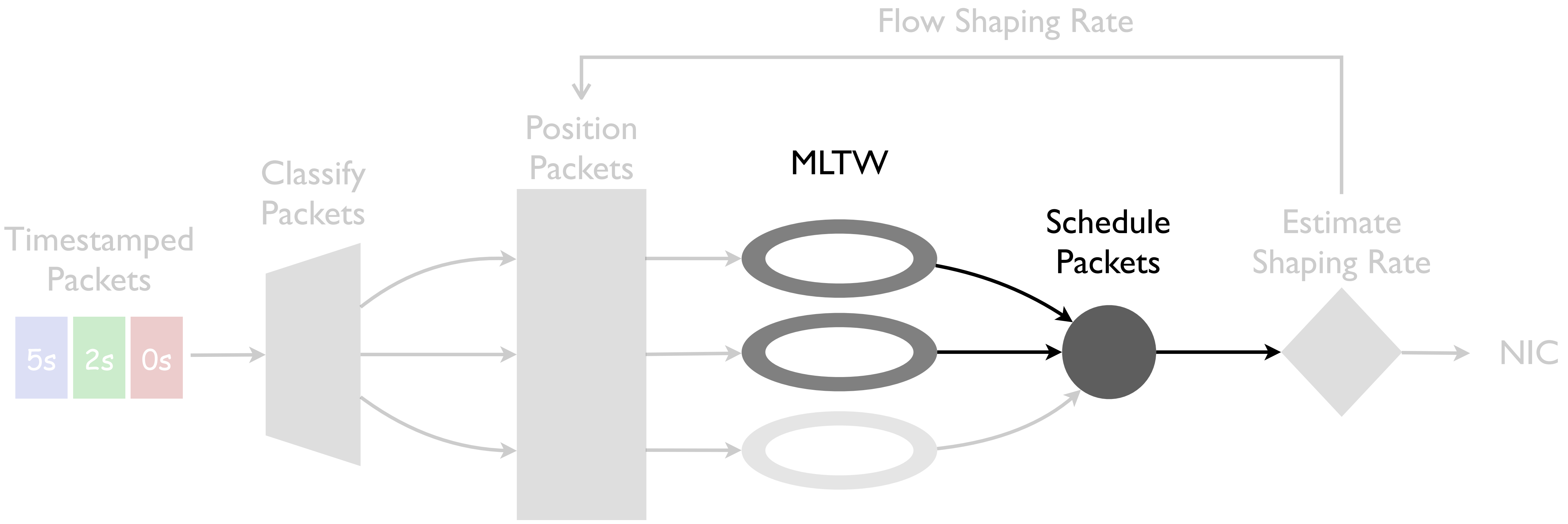

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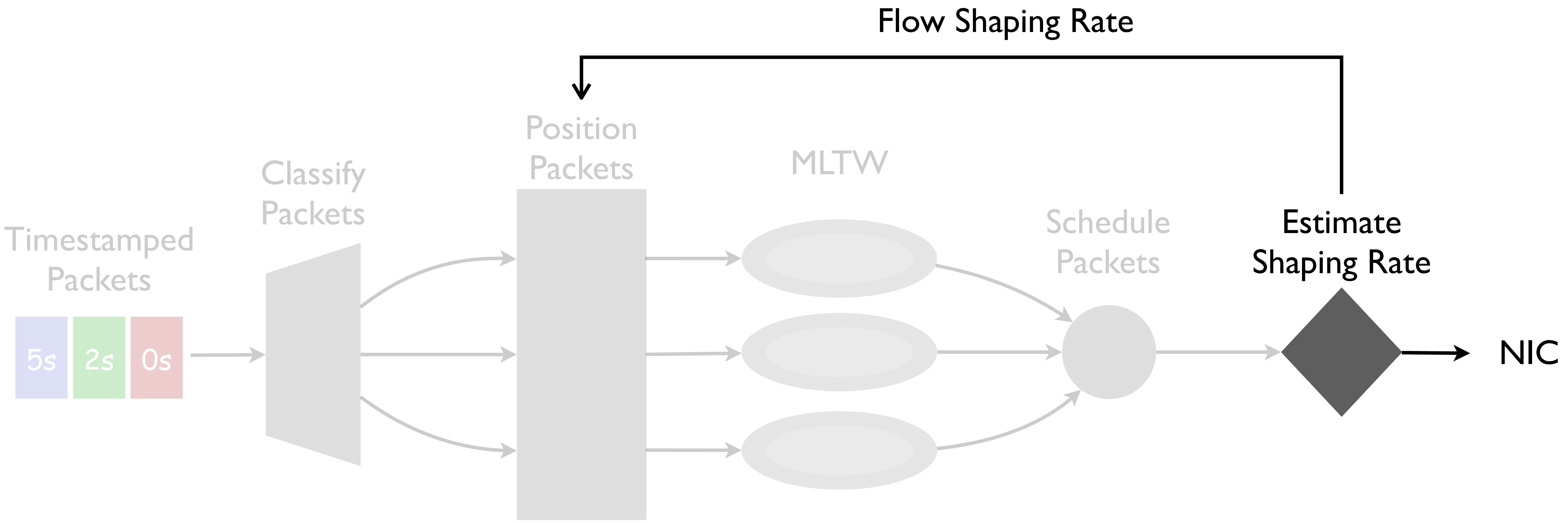


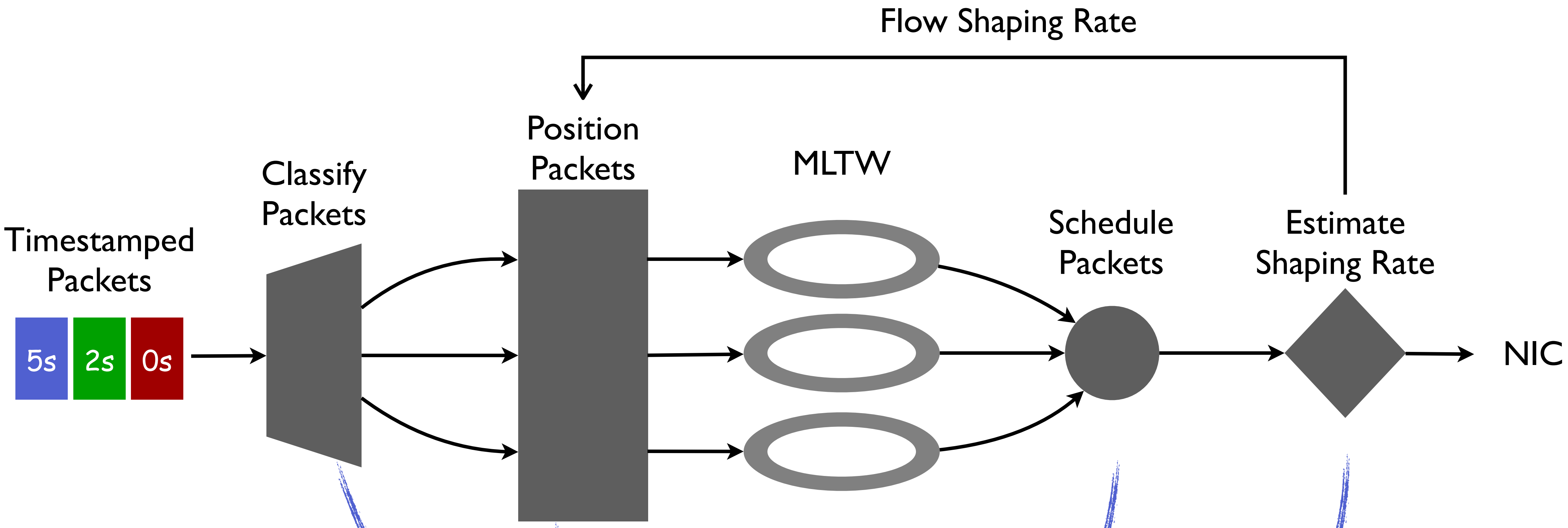
❶ Classify packets into flows

❷ Place packets into MLTW based on flow shaping rate and timestamp

❸ Dequeue packets from MLTW based on current time

❹ Estimate the shaping rate of each flow

Putting Together: FlowBundler



All operations can be achieved with O(1) time complexity
(More Details in the Paper)

Implementation

- Kernel
  - As a Linux queueing discipline

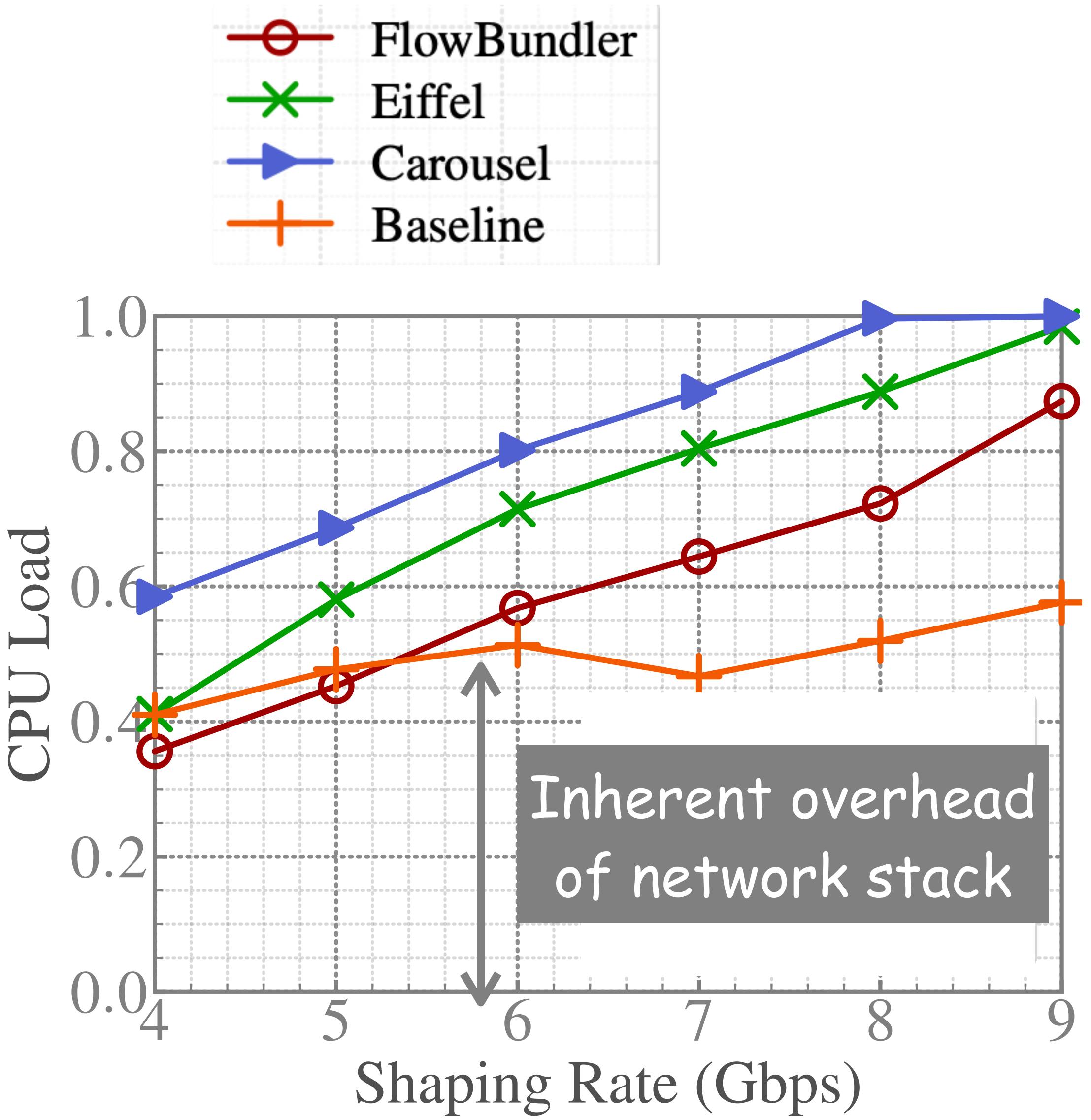
- Userspace
  - Based on BESS/DPDK (a kind of Software NIC)

Open source: https://github.com/ants-xjtu/FlowBundler

Evaluation

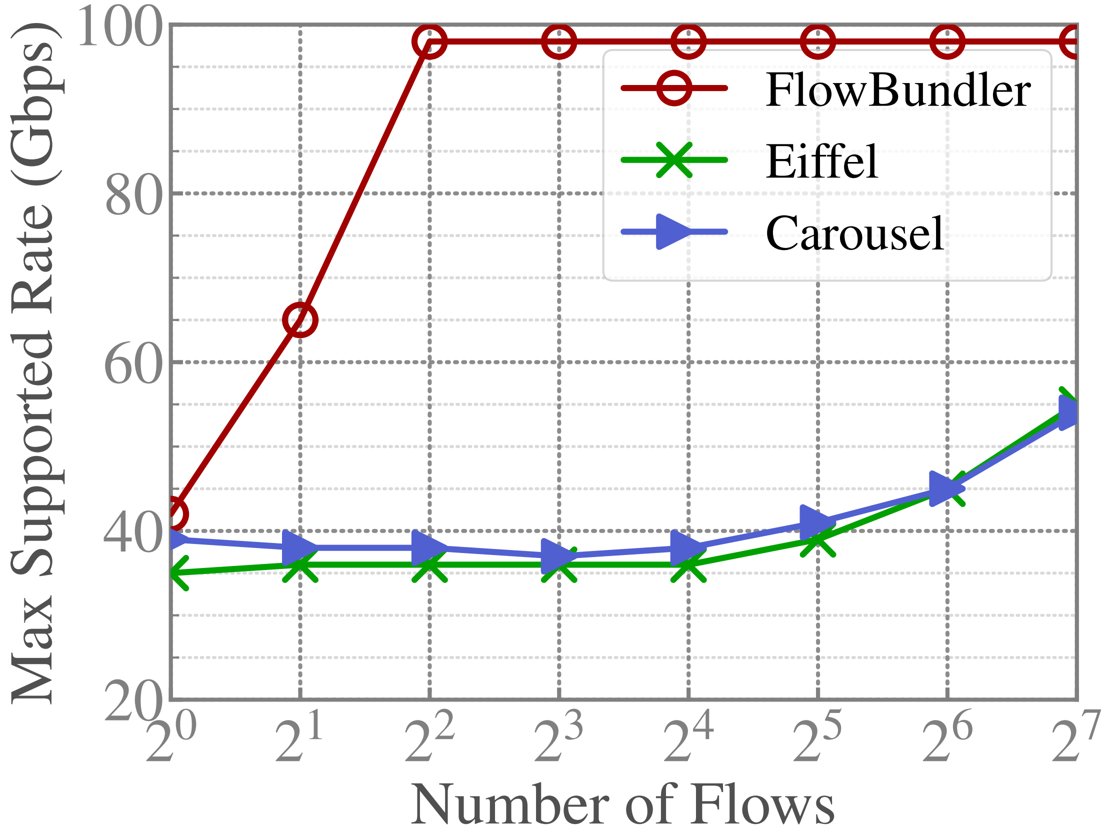
- Compared Schemes
  - Carousel[SIGCOMM'17]
  - Eiffel[NSDI'19]
- Metrics
  - CPU efficiency
  - Memory efficiency
  - Transmission performance

Evaluation — CPU Efficiency



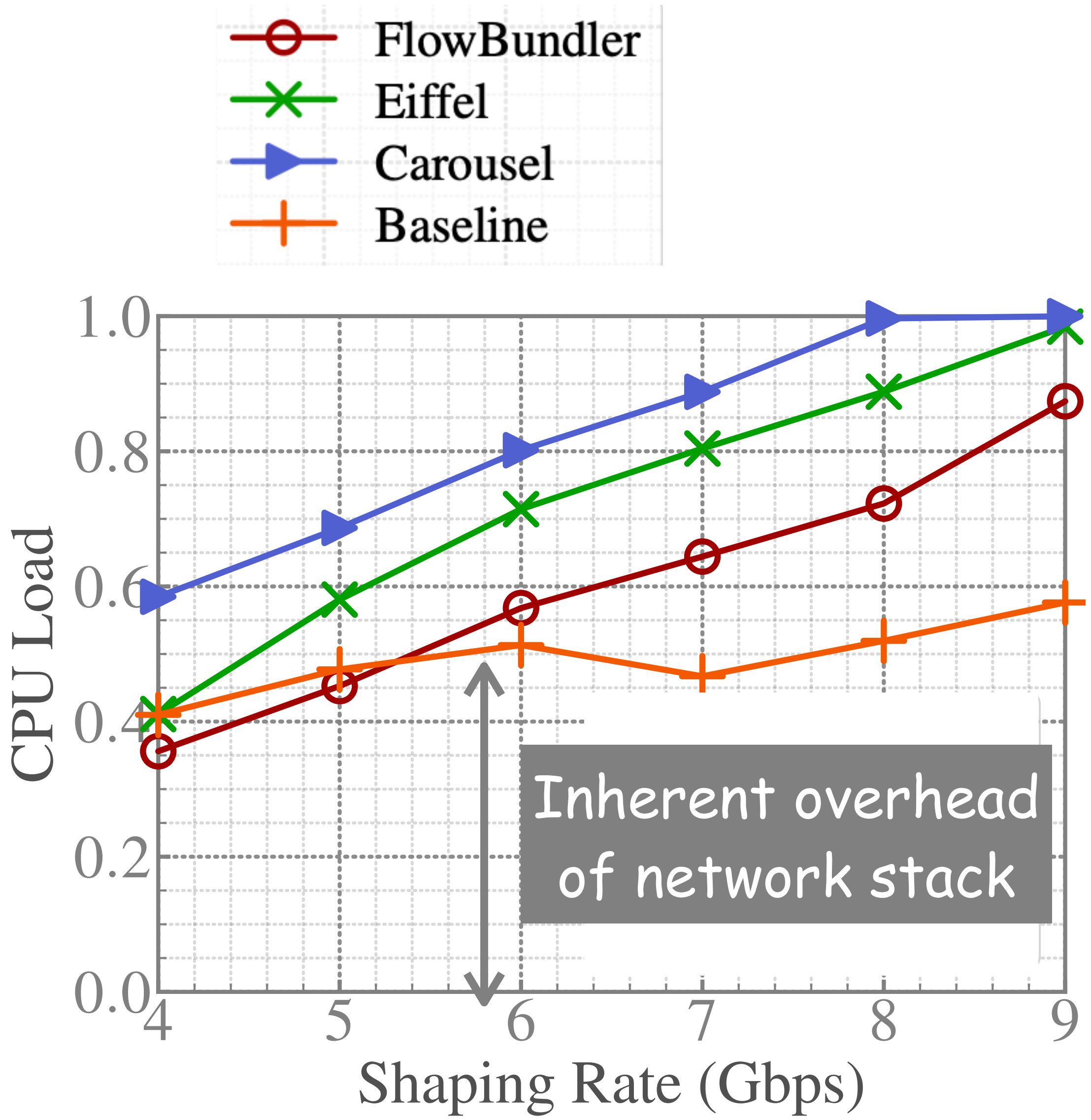
Inherent overhead of network stack

Kernel



Userspace

Evaluation — CPU Efficiency



Inherent overhead of network stack

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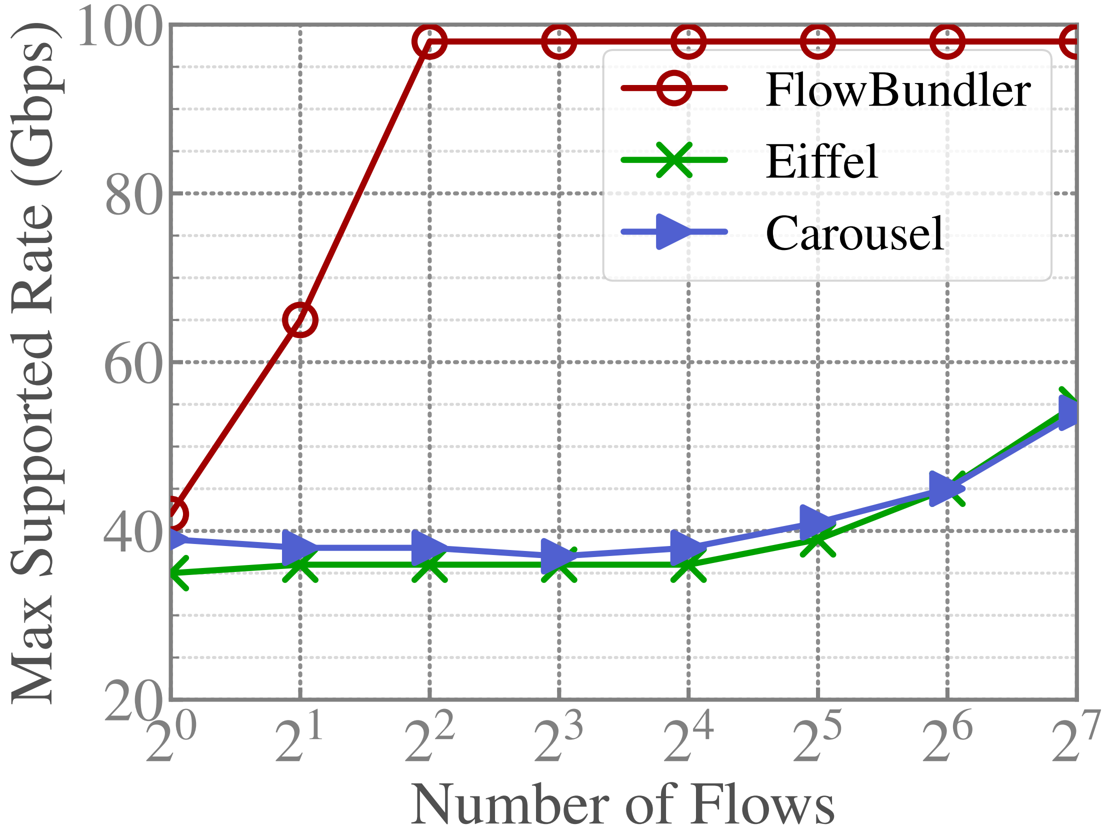
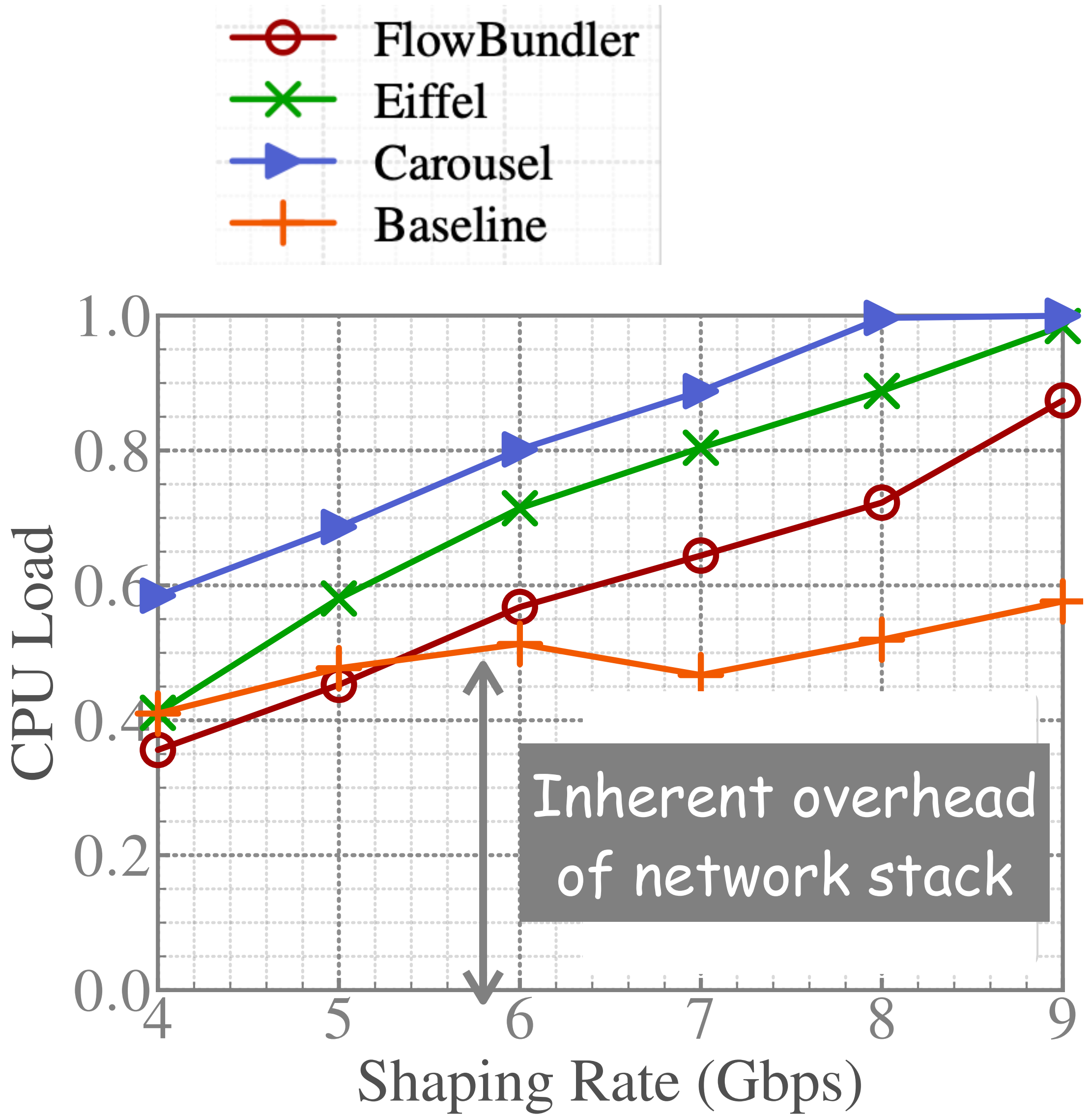


Userspace

~20% lower cpu load

Evaluation — CPU Efficiency



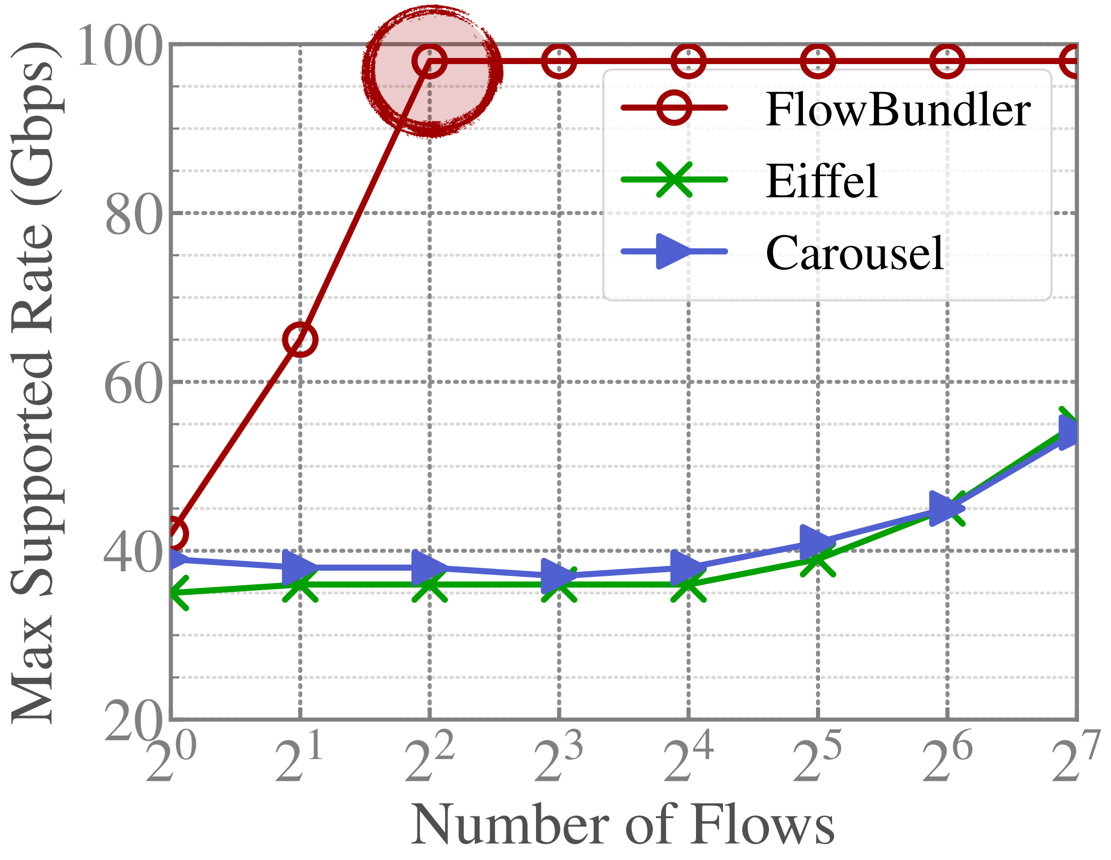
Inherent overhead of network stack

Kernel

~20% lower cpu load

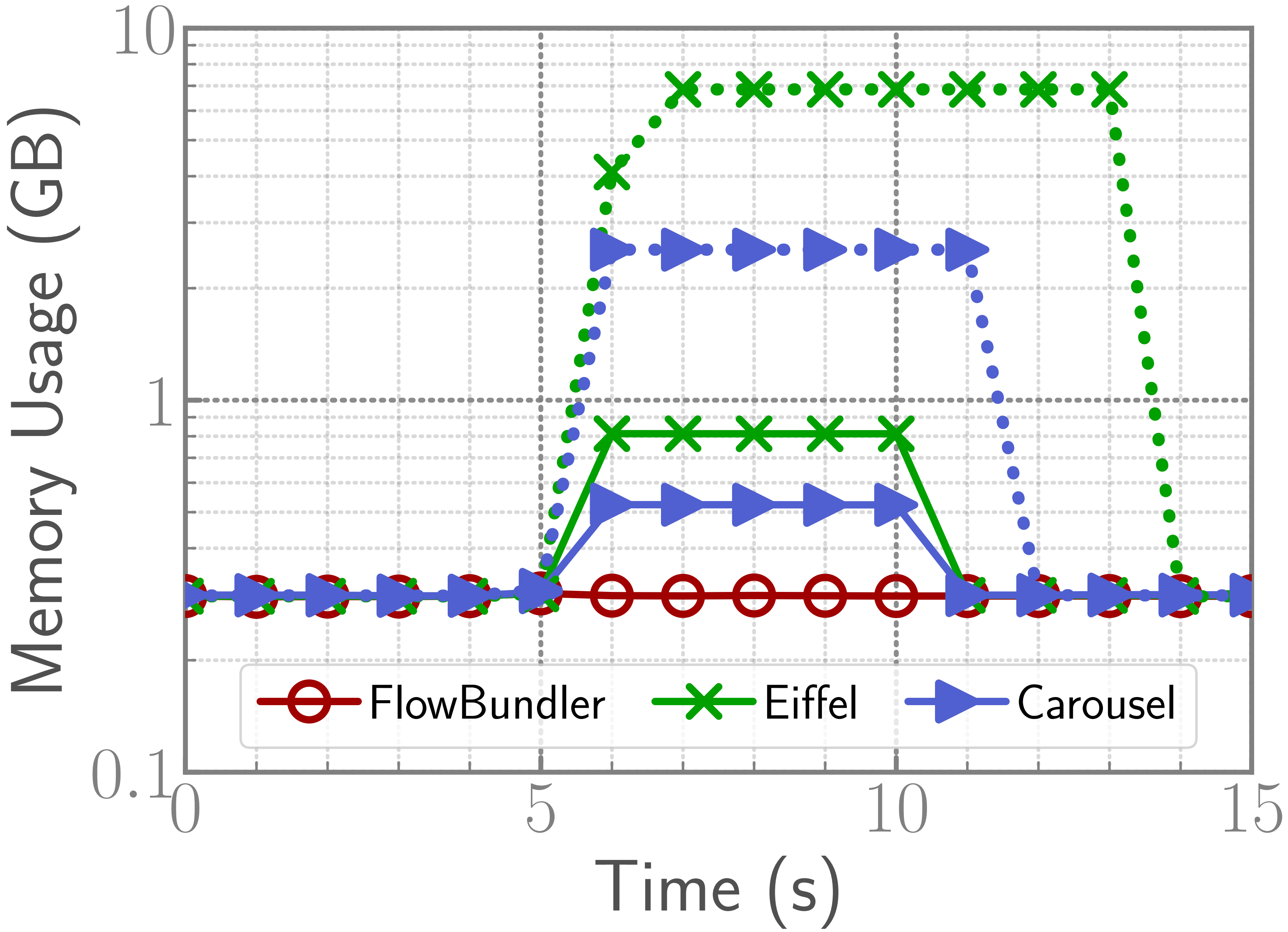
Near 100Gbps shaping speed with 4 flows

~2.6x higher shaping speed



Userspace

Evaluation — Memory Efficiency (kernel)



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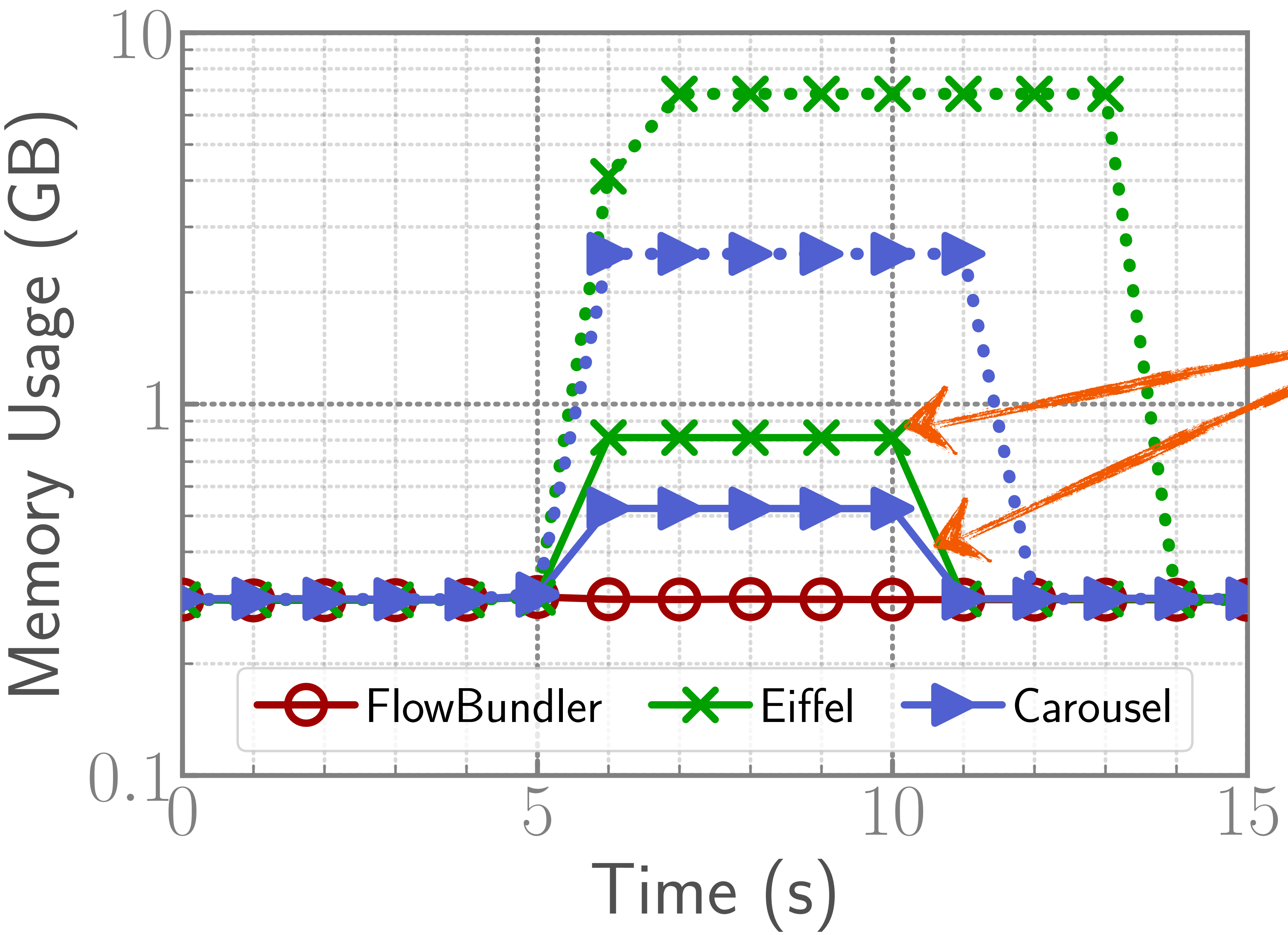
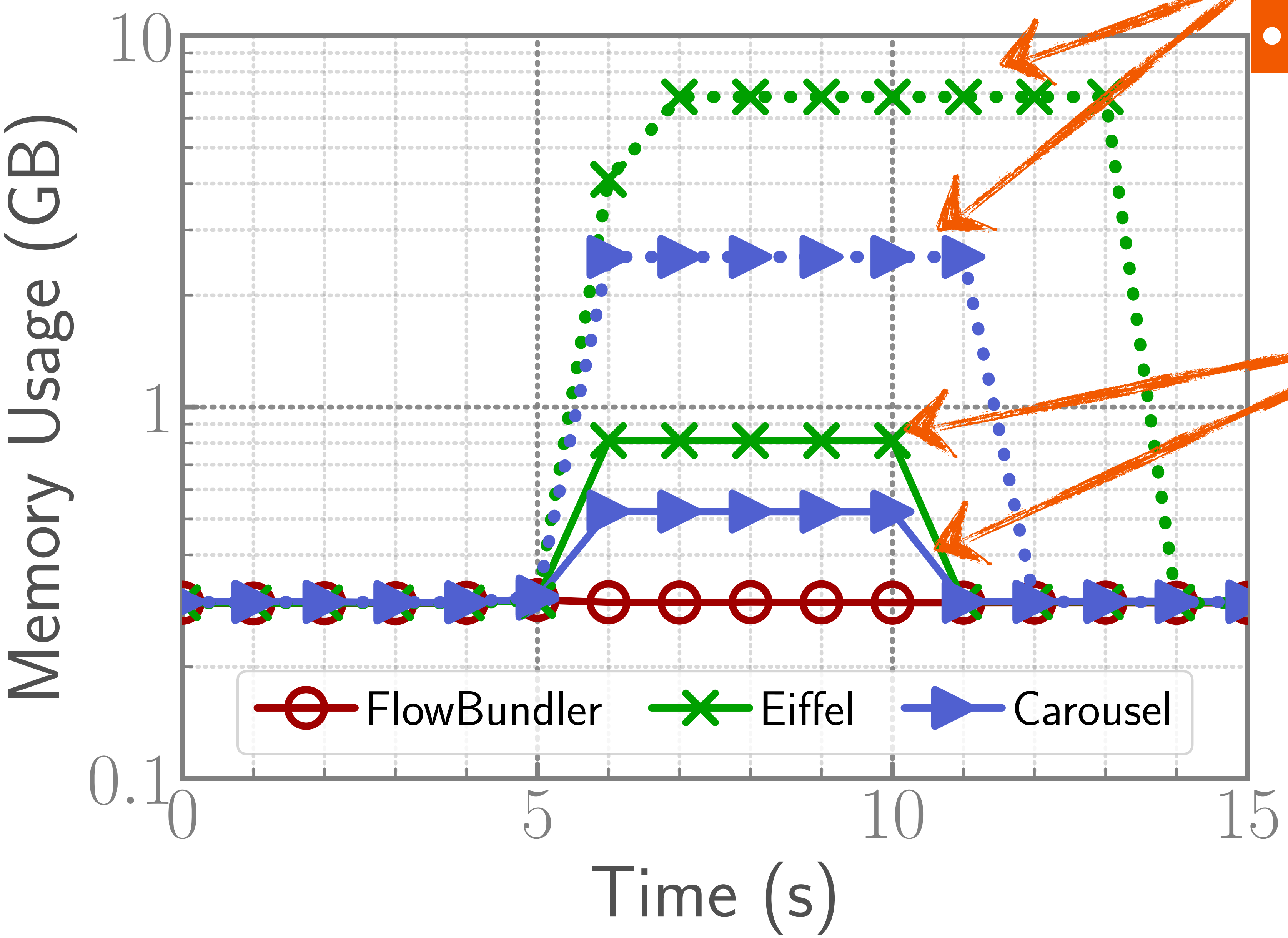


Eiffel/Carousel:

- 1µs granularity
- 0.5GB/0.2GB memory usage

Evaluation — Memory Efficiency (kernel)



Eiffel/Carousel:

- 0.1 µs granularity
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Eiffel/Carousel:

- 1 µs granularity
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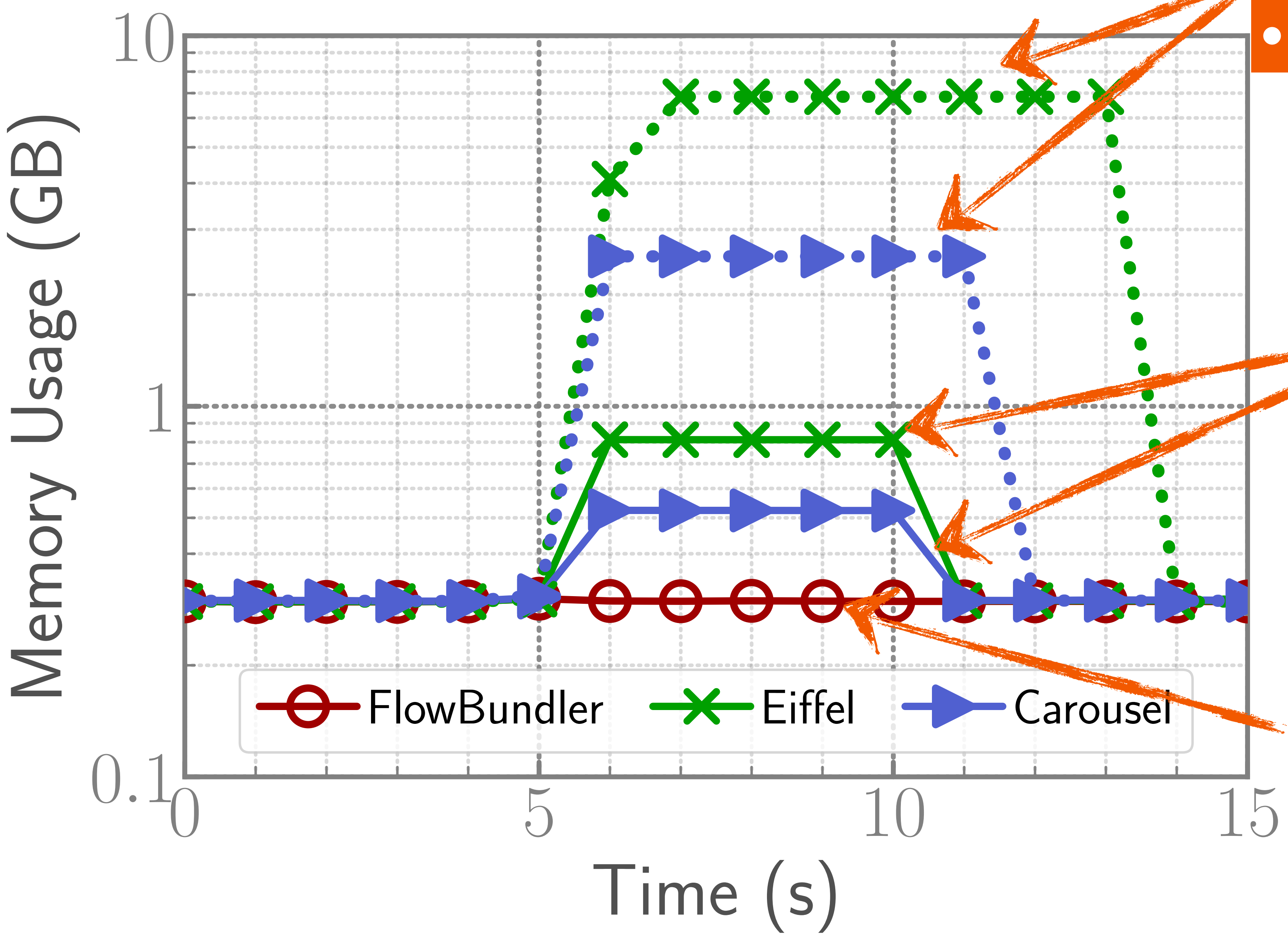
Evaluation — Memory Efficiency (kernel)



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Eiffel/Carousel:

- 1µs granularity
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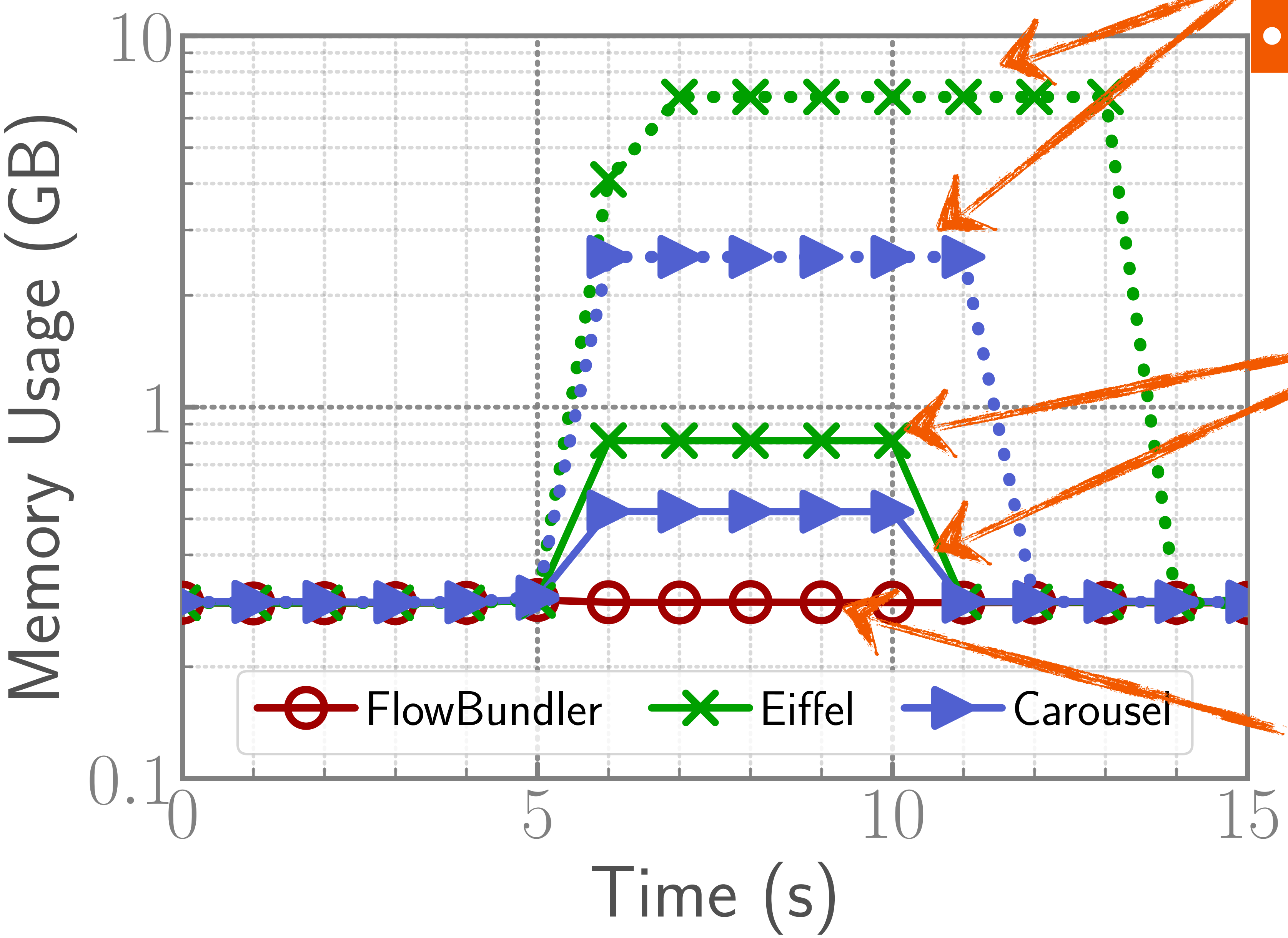
FlowBundler:

- 1ns granularity
- 1.1MB memory usage

Evaluation — Memory Efficiency (kernel)



Eiffel/Carousel:

- 0.1µs granularity
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Eiffel/Carousel:

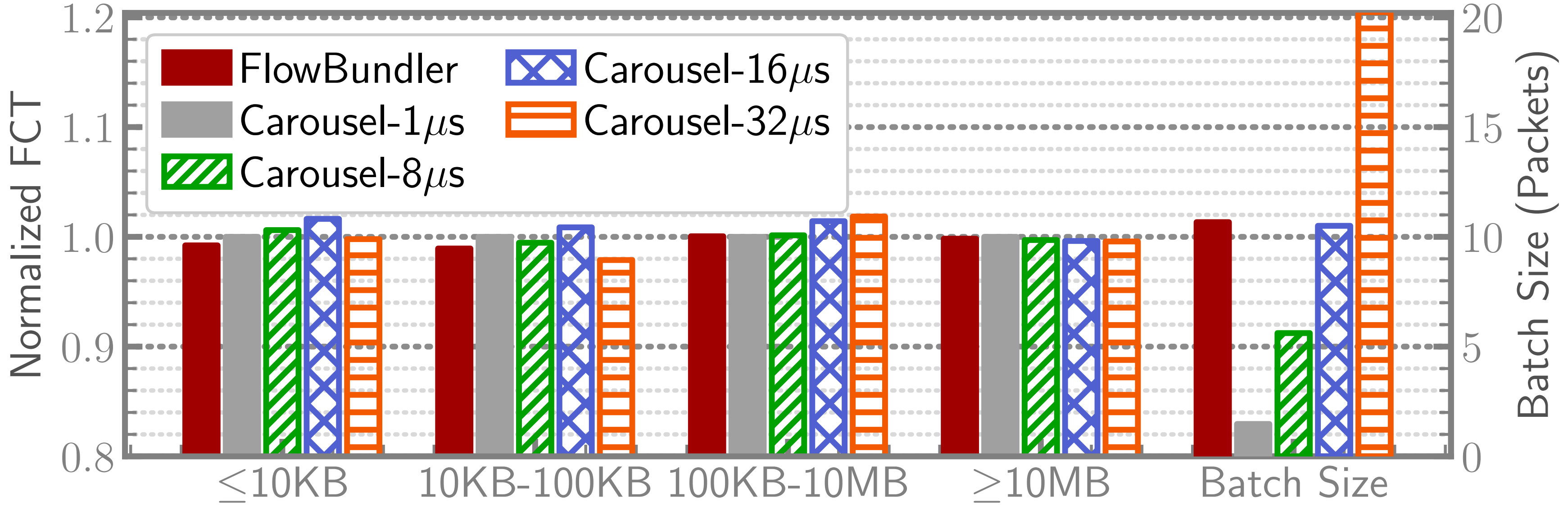
- 1µs granularity
- 0.5GB/0.2GB memory usage

FlowBundler:

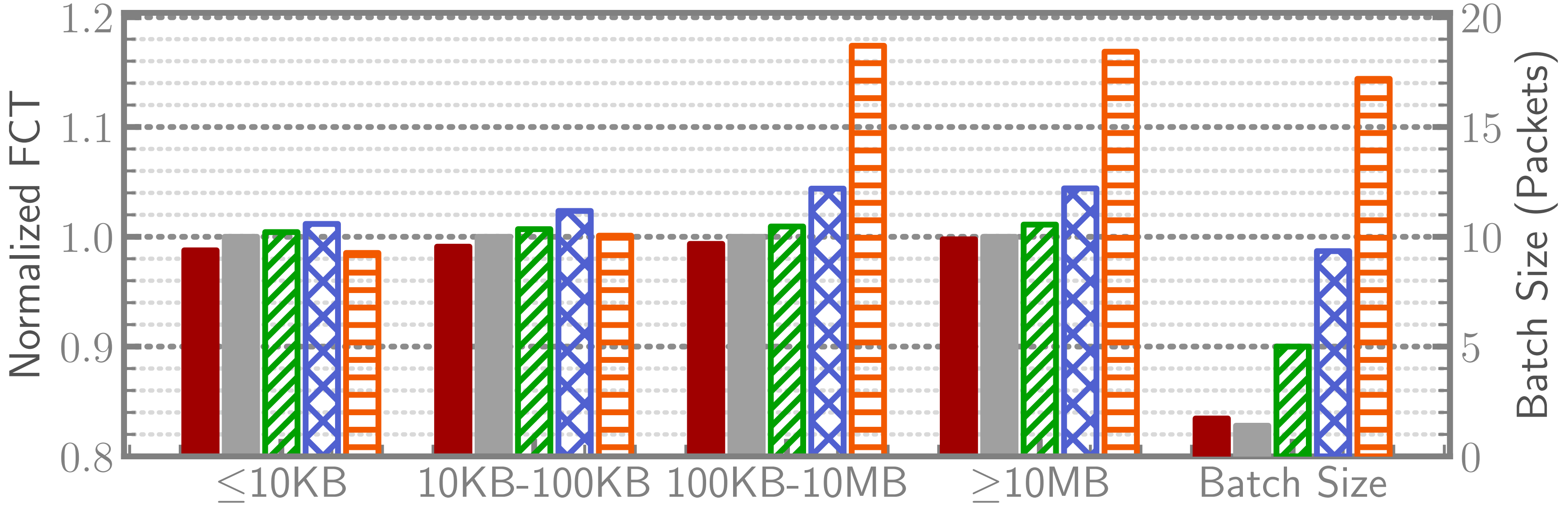
- 1ns granularity
- 1.1MB memory usage

Three orders of magnitude less memory usage

Evaluation — Transmission Performance



Fan-out Flows



One-to-one Flows

Batch packet transmissions without harming transmission performance

Conclusion

- FlowBundler utilizes inter-flow batching to achieve efficient traffic shaping

- FlowBundler utilizes Multi-level Timing Wheel, which can achieve fine-grained shaping while accommodating wide-time-range packets

- FlowBundler can achieve near 100Gbps shaping speed

Questions?