PRISM: Streamlined Packet Processing for Containers with Flow Prioritization

(ICDCS '22)

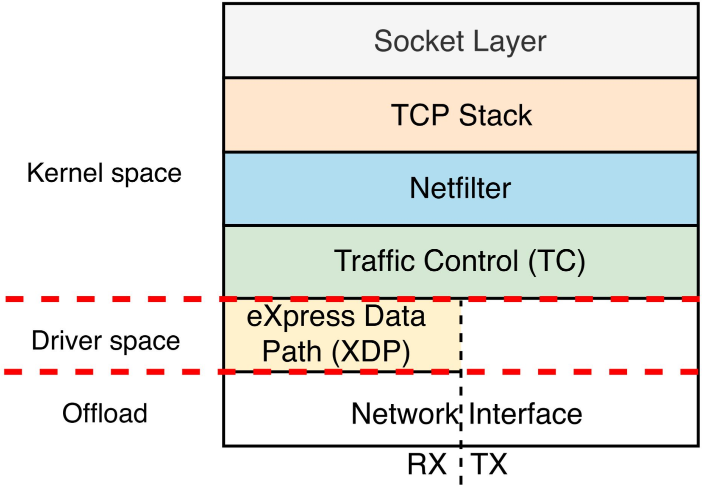
Manish Munikar[1], Jiaxin Lei[2], Hui Lu[2], Jia Rao[1]

[1] *University of Texas at Arlington*

[2] *Binghamton University*

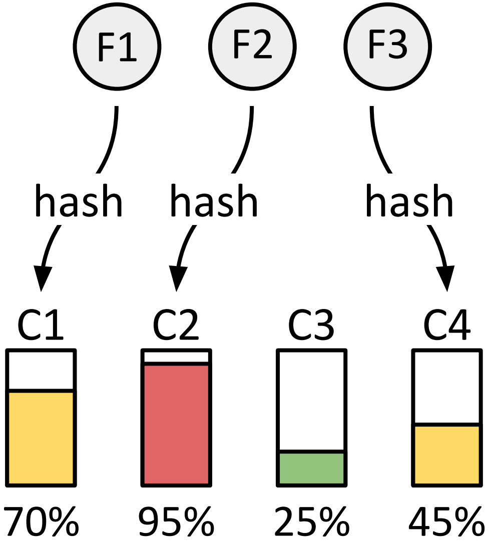
Kernel network stack has been very successful …

- Easy **abstraction** for network I/O
    - Generic sockets interface
- Flexible and **modular**
- Open-source, **stable**, **secure** and **reliable**
- Designed to provide overall efficiency
- Successful for more than **three decades**!



… until recently?

- Network devices are getting faster ***faster***
  - 10 Gbps (*2002*) → 200 Gbps (*2017*)
- CPU speed is stagnating at 2–3 GHz
  - Scaling **horizontally** instead
- Kernel network stack has been trying to keep up...
  - Packet steering to support multi-core
  - NAPI for dynamic interrupt/poll mode
  - Packet coalescing / batching
  - Checksum offloading
- **New bottleneck** for high-performance network applications



Container networks

- Containers are revolutionizing cloud
  - Lightweight OS-level virtualization
  - Higher consolidation density
  - Faster and easier to manage
- Communicate using overlay network
  - VXLAN encapsulation

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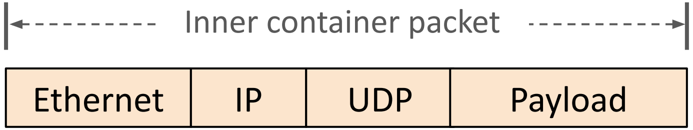

Inner container packet

Ethernet	IP	UDP	Payload

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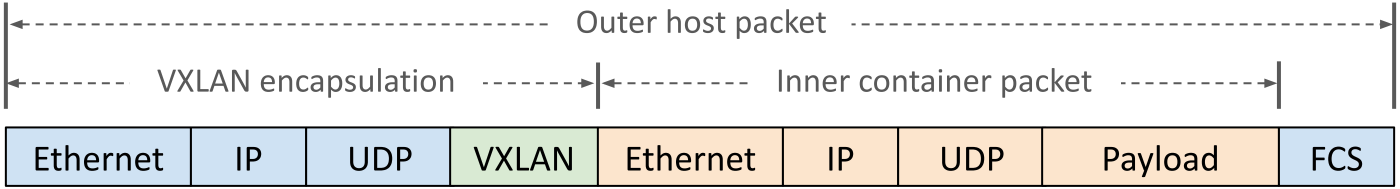

Outer host packet

VXLAN encapsulation

Inner container packet

Ethernet	IP	UDP	VXLAN	Ethernet	IP	UDP	Payload	FCS

Cloud application types

Cloud application types

- Bulk data transfer
  - File transfer, backup, sync
  - Video streaming
  - Many/large packets
  - **Throughput-sensitive**

NETFLIX

hadoop

amazon
S3

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NETFLIX

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amazon S3

- Request-Response
  - Web / database request, RPC
  - Control plane signals
  - Few/small packets
  - Latency-sensitive

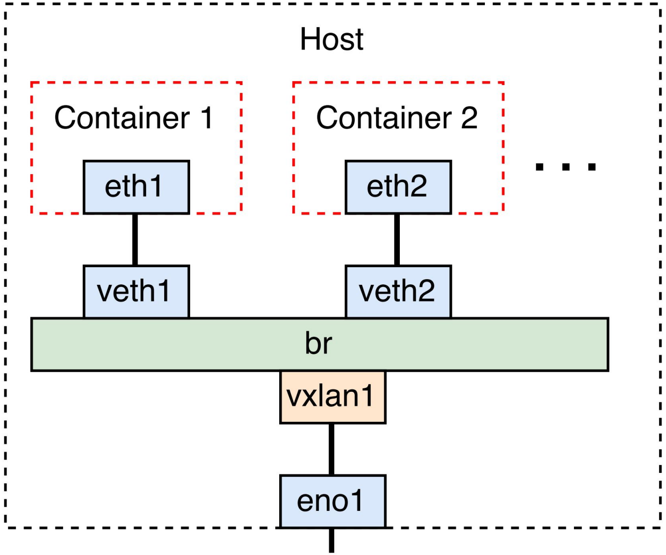
Memcached

NGINX

{ REST:API }

BGP

Container packet processing



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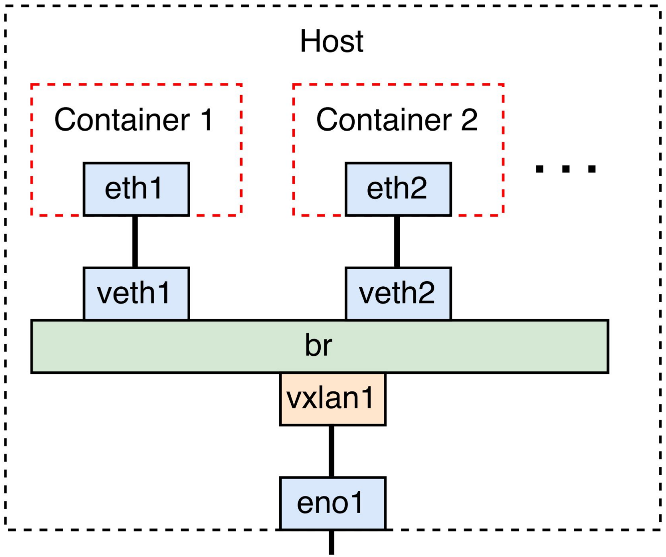

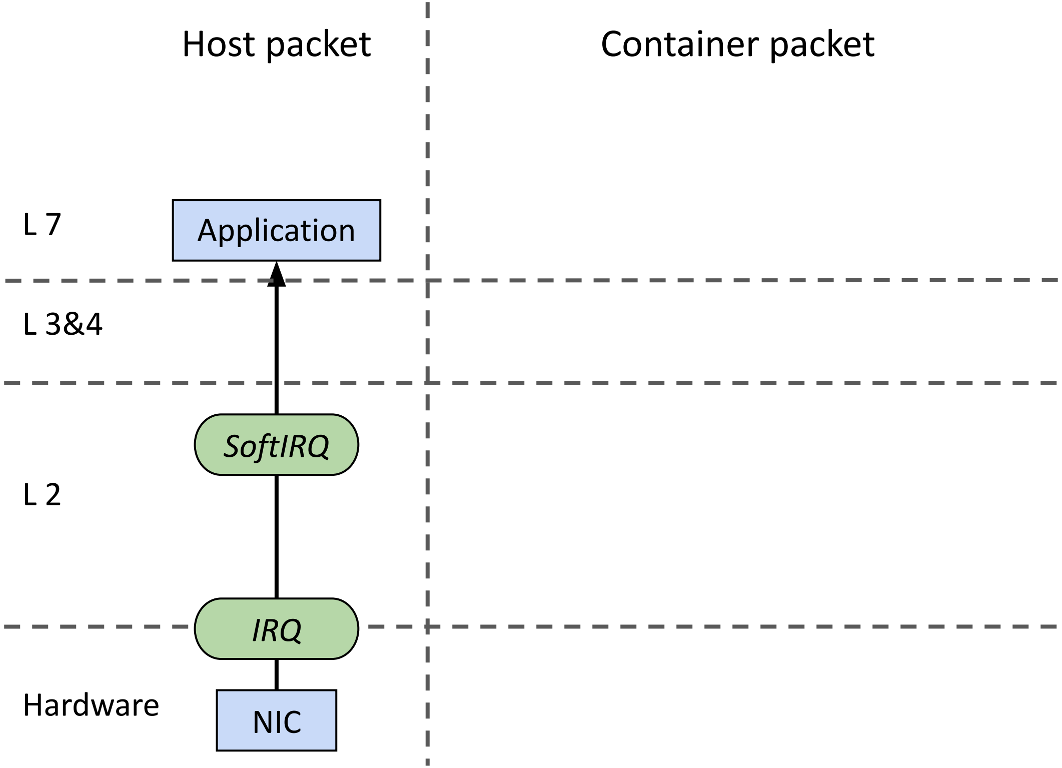

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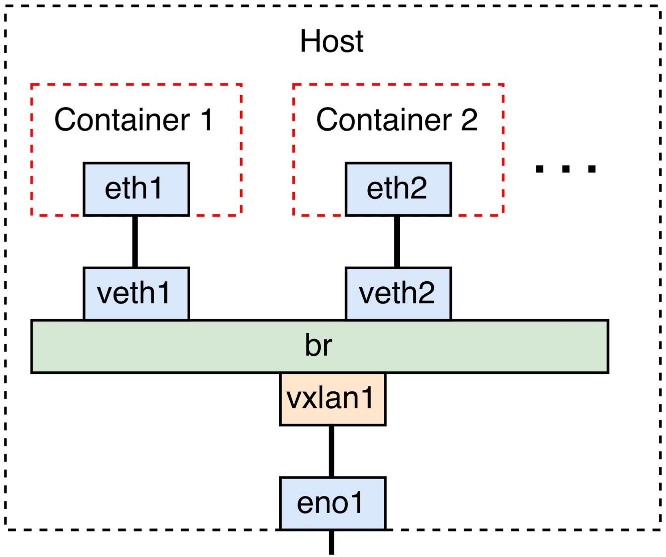

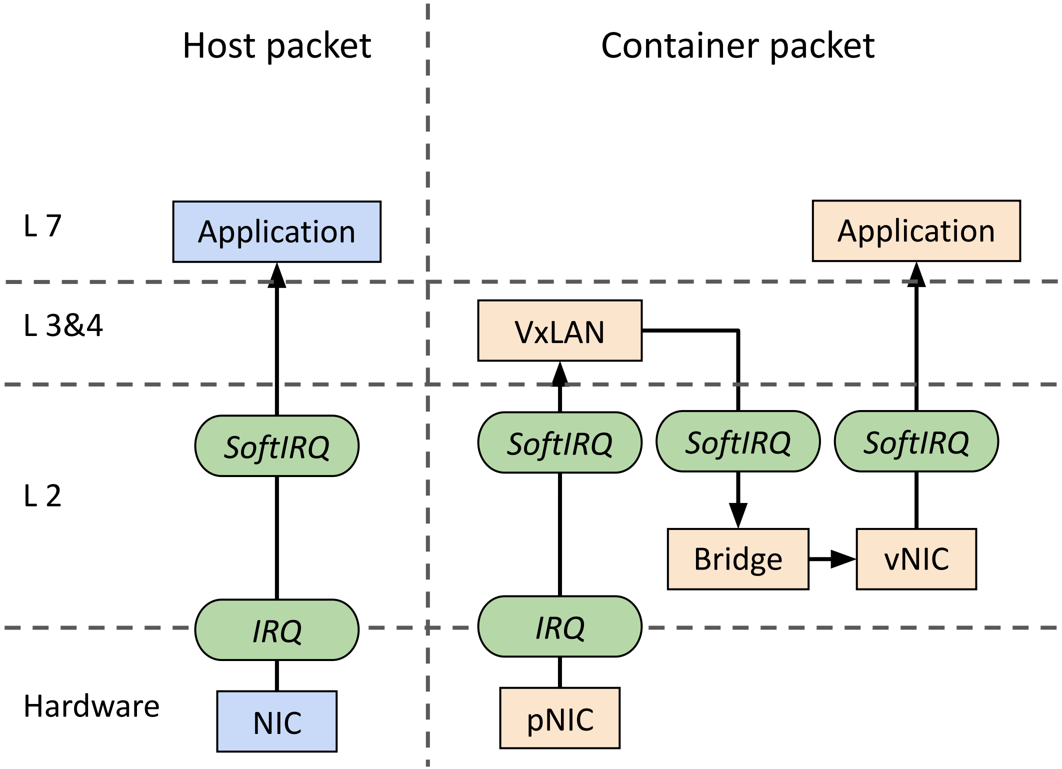

Related works

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- Kernel stack optimizations [RPS, RSS, RFS, FlexSC, ...]
    - System call batching
    - Packet steering / load balancing
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  - Dedicates core for packet polling and uses custom network stack
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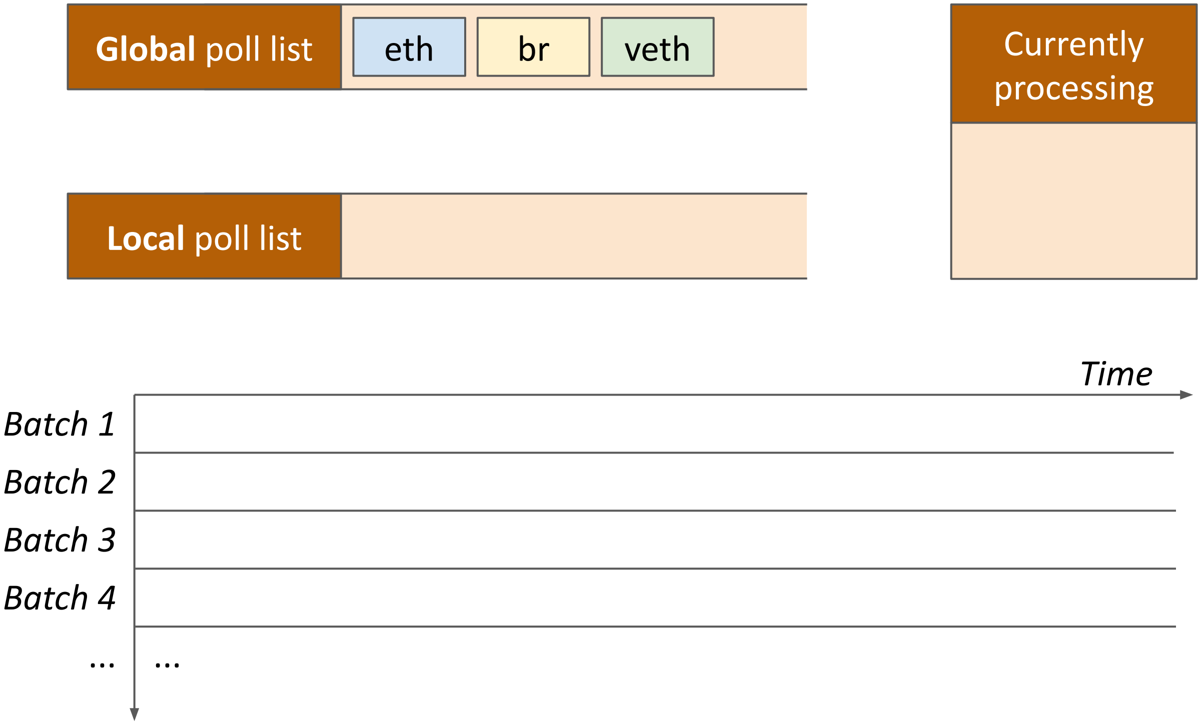
- Container network optimization [Slim, FALCON, FreeFlow, ...]
    - Connection metadata manipulation
    - More fine-grained (flow-device level) packet steering

Interleaved NAPI device processing



Global poll list

eth

br

veth

Local poll list

Currently processing

Time

Batch 1

Batch 2

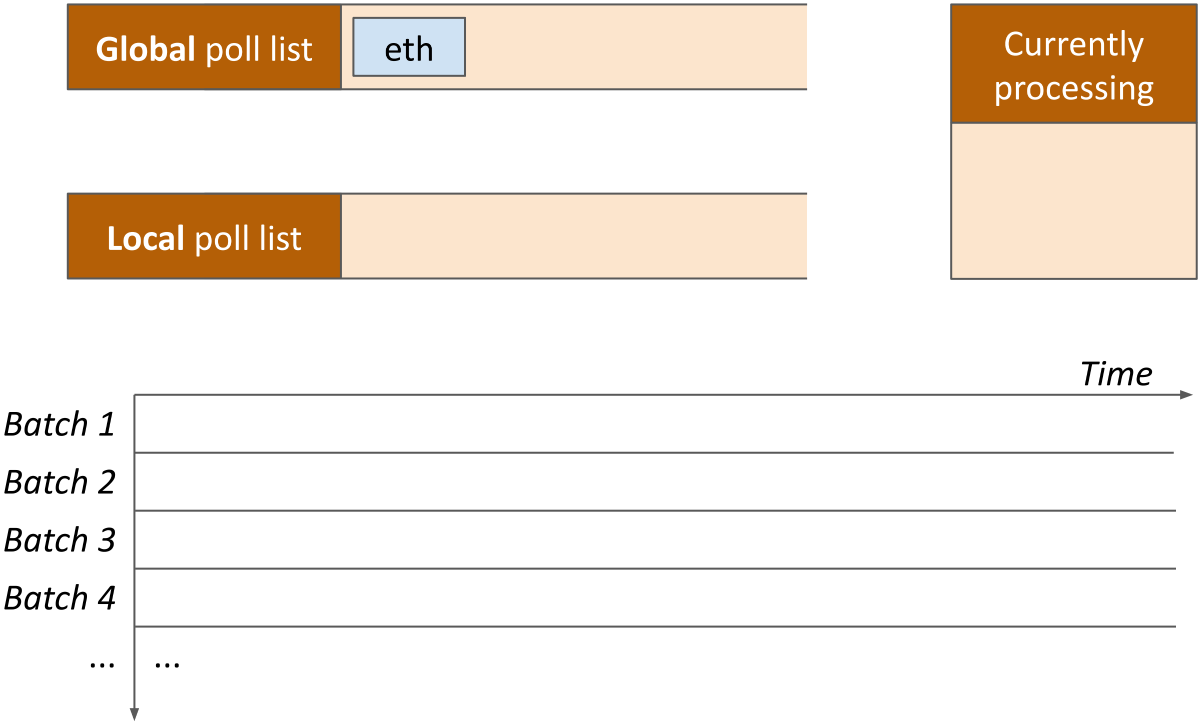
Batch 3

Batch 4

…

…

Interleaved NAPI device processing



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Time

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… …

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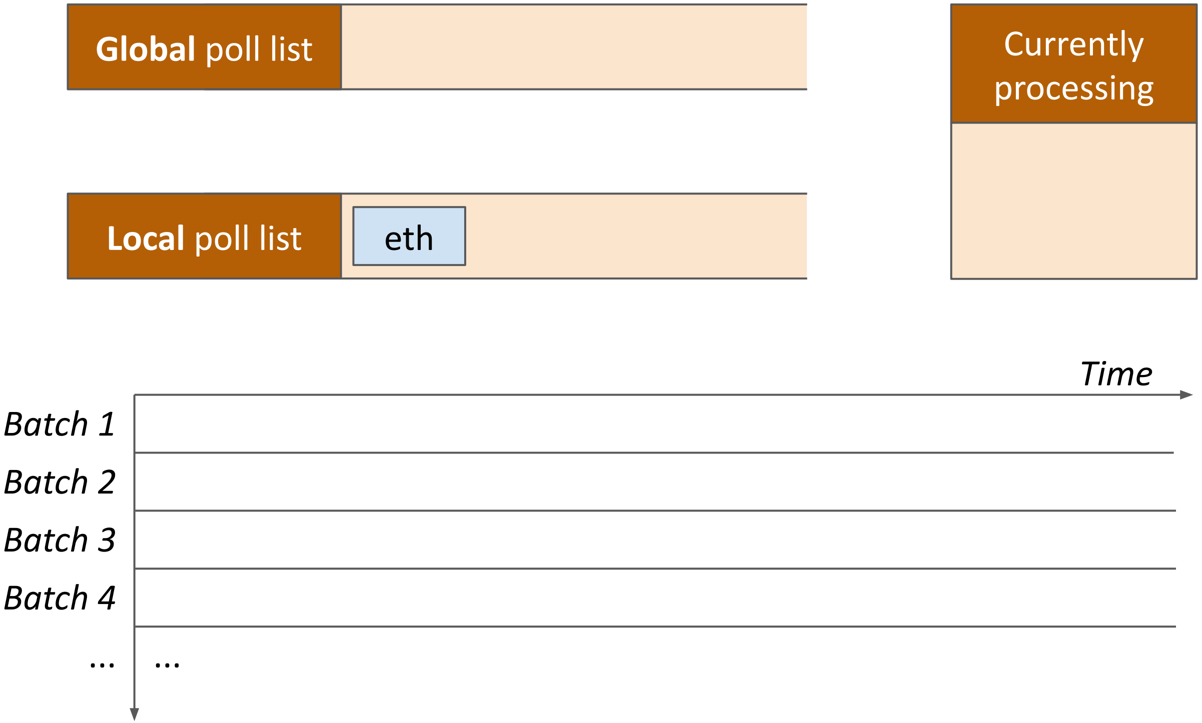

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eth

Currently processing

Time

Batch 1

Batch 2

Batch 3

Batch 4

... ...

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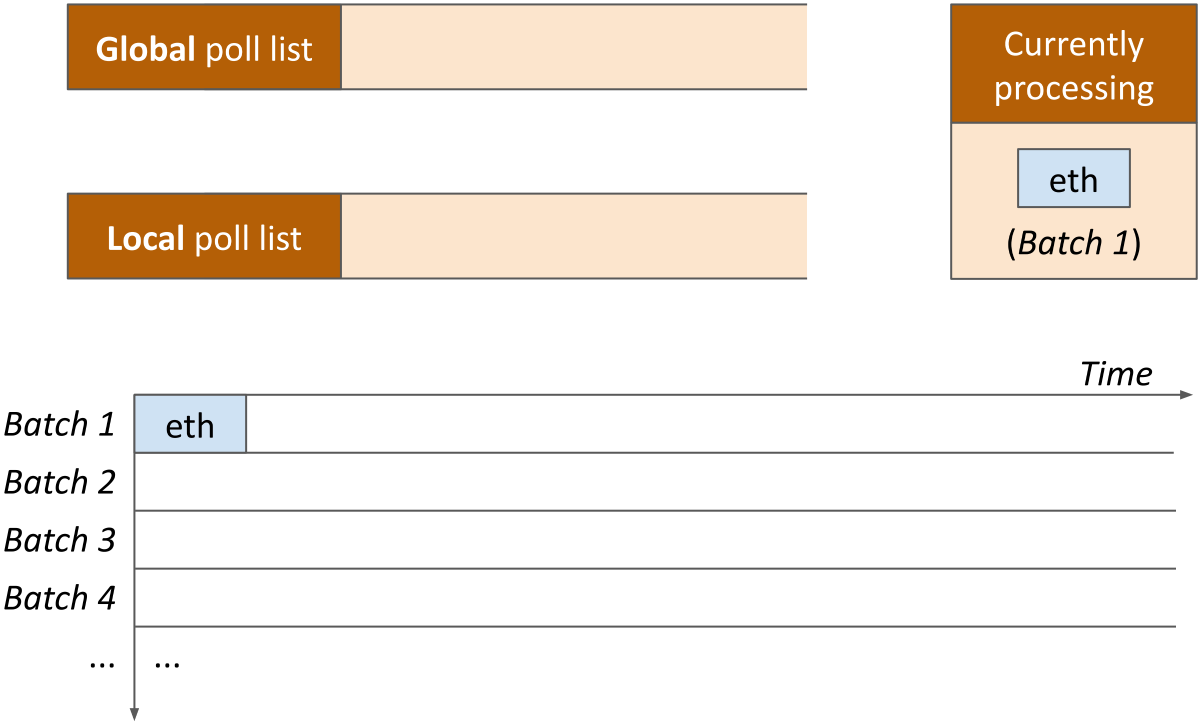

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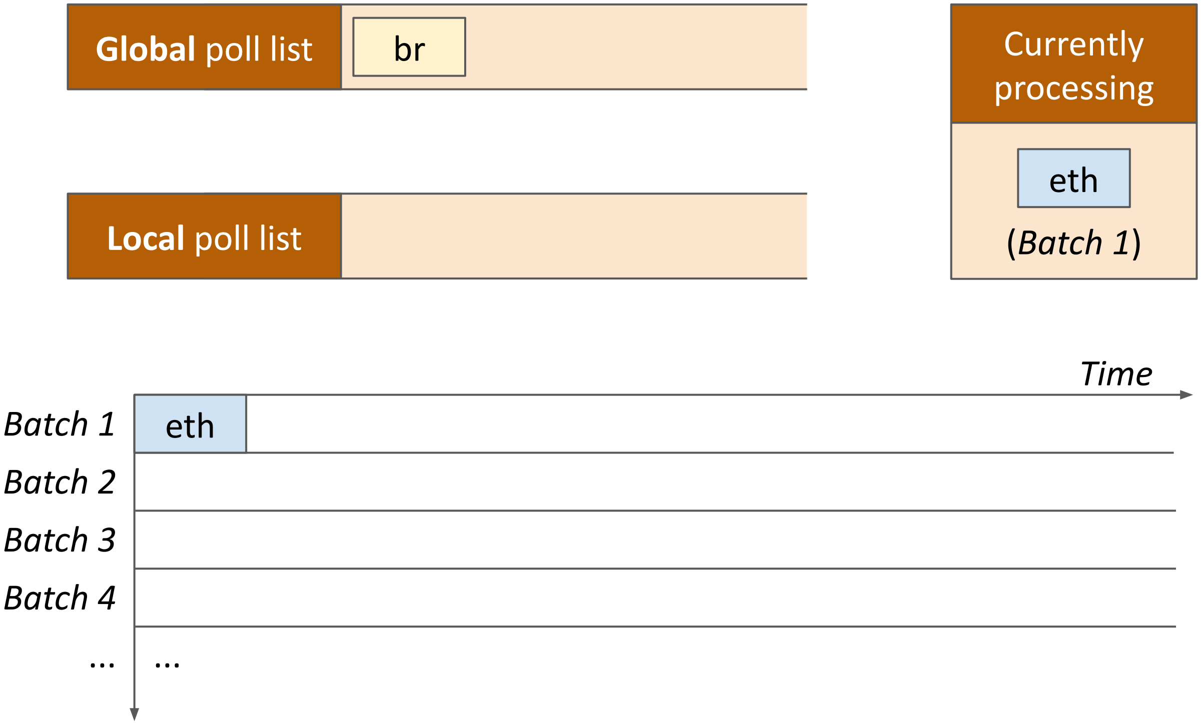

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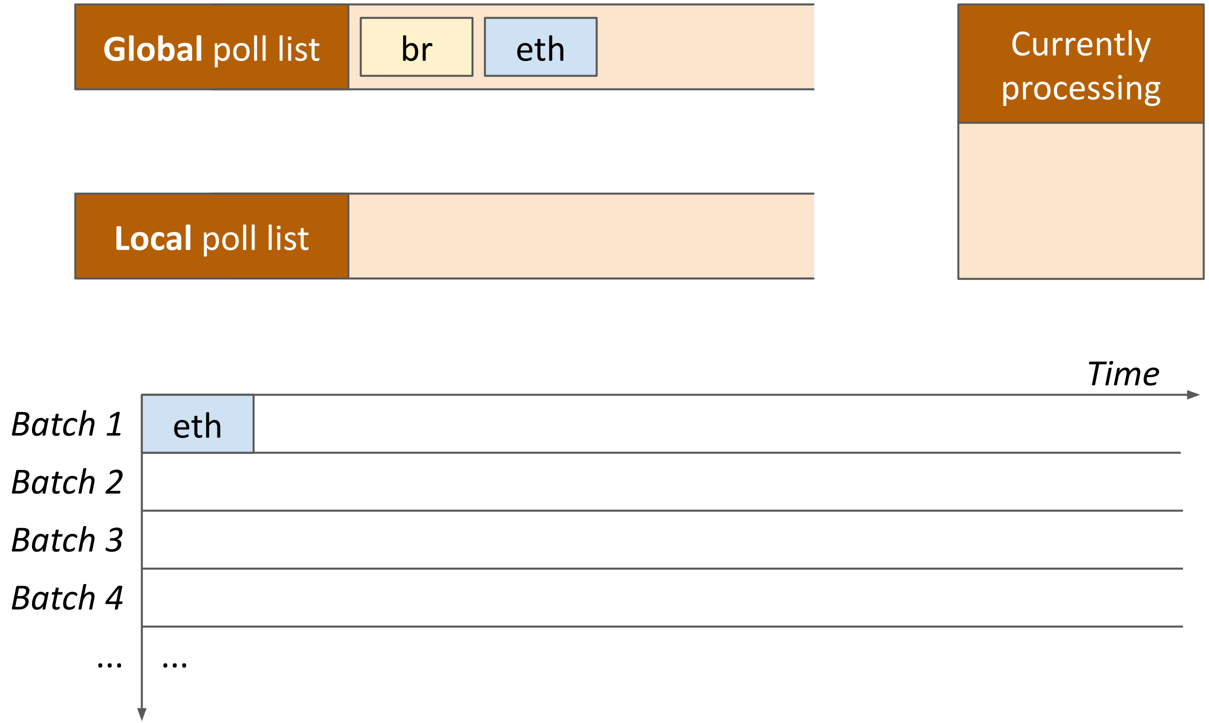

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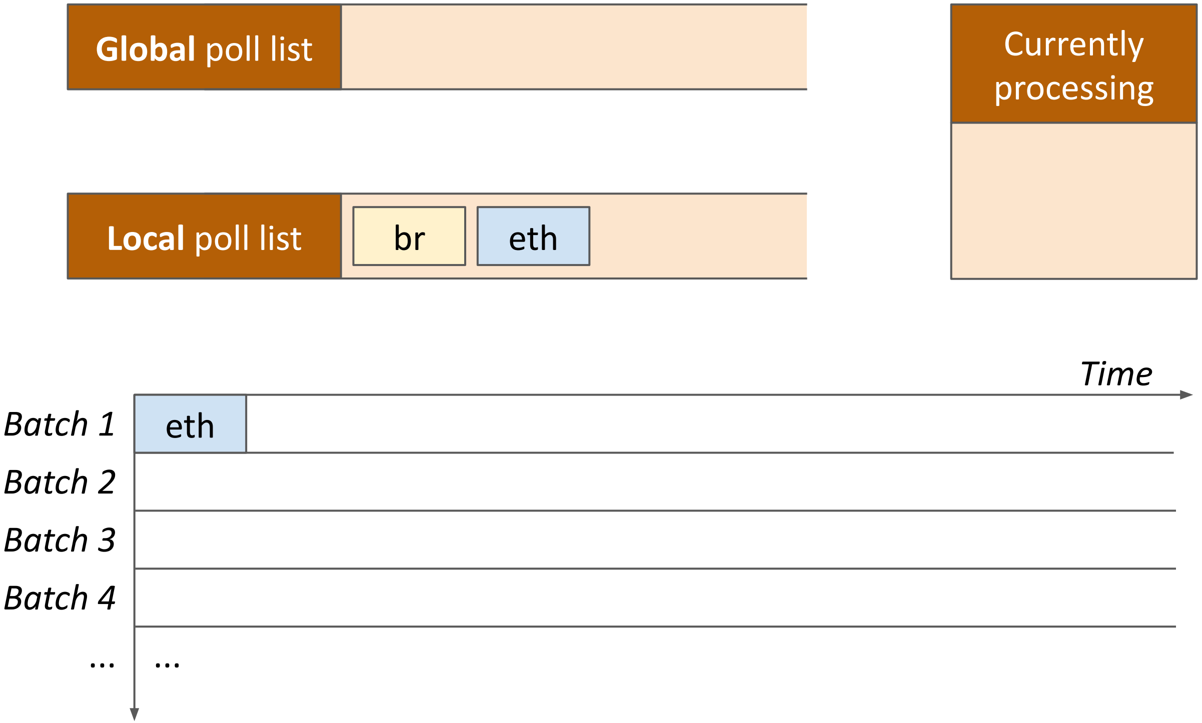

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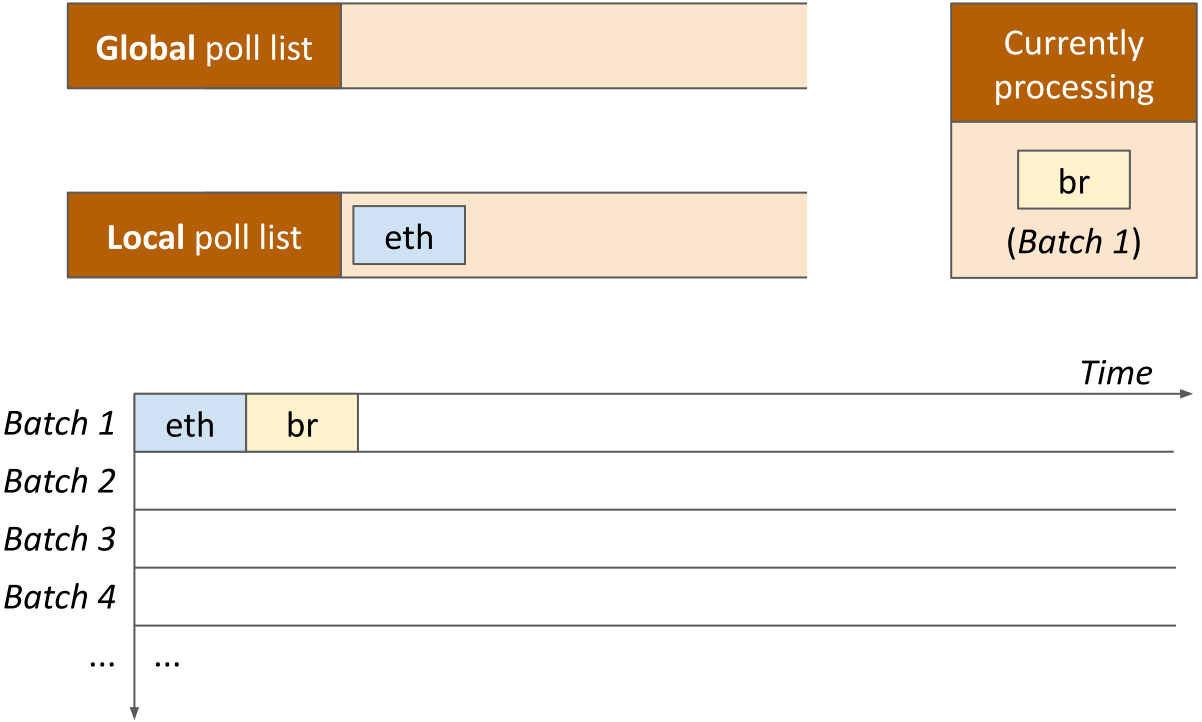

Global poll list

Local poll list

eth

Currently processing

br

(*Batch 1*)

Time

Batch 1 eth br

Batch 2

Batch 3

Batch 4

… …

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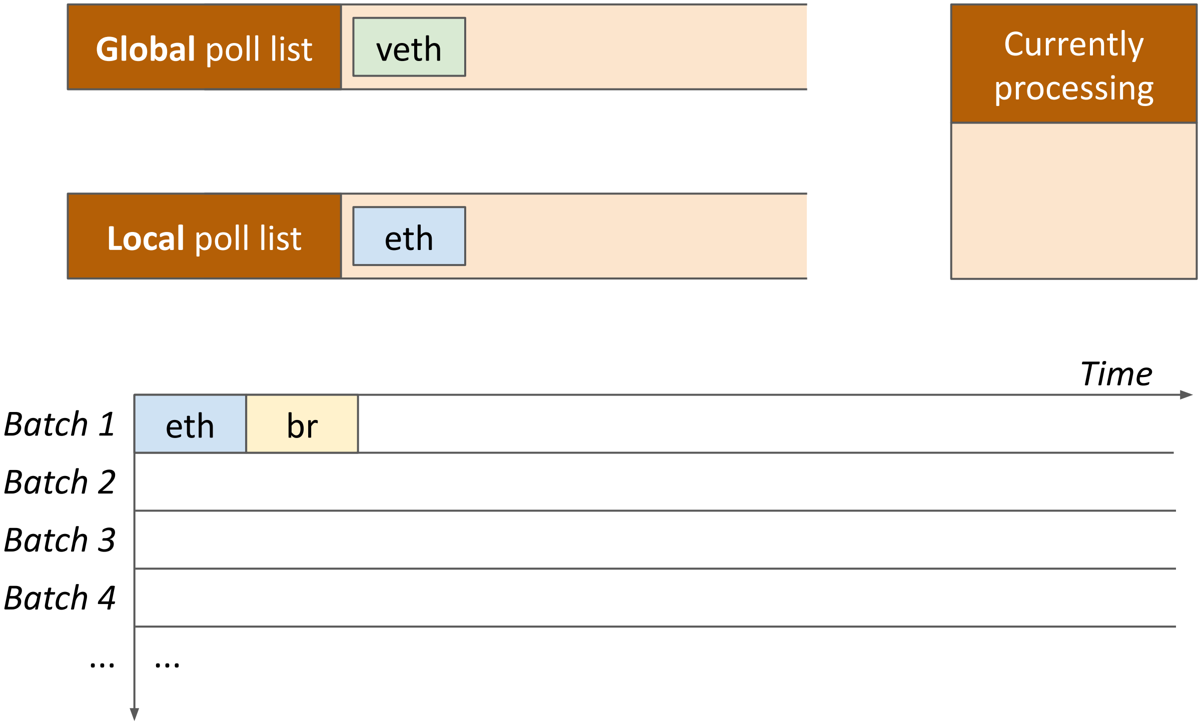

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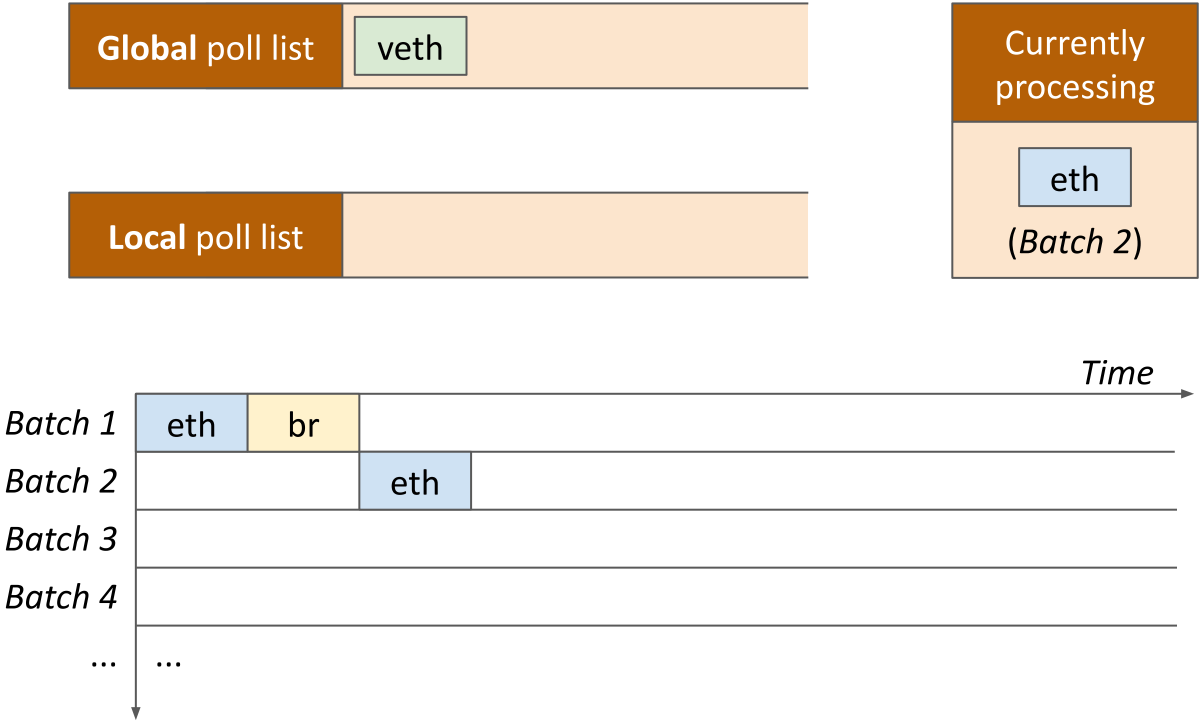

Global poll list

veth

Local poll list

Currently processing

eth

(*Batch 2*)

Time

Batch 1	eth	br	
Batch 2			eth
Batch 3			
Batch 4			
...	...		

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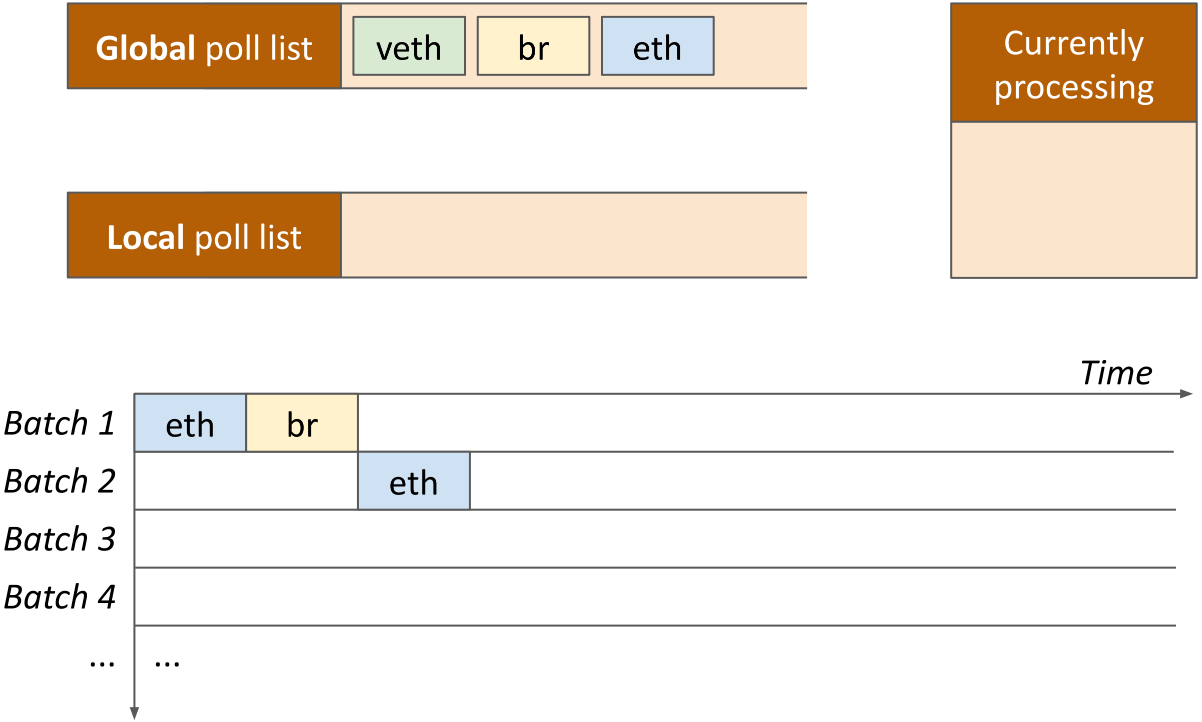

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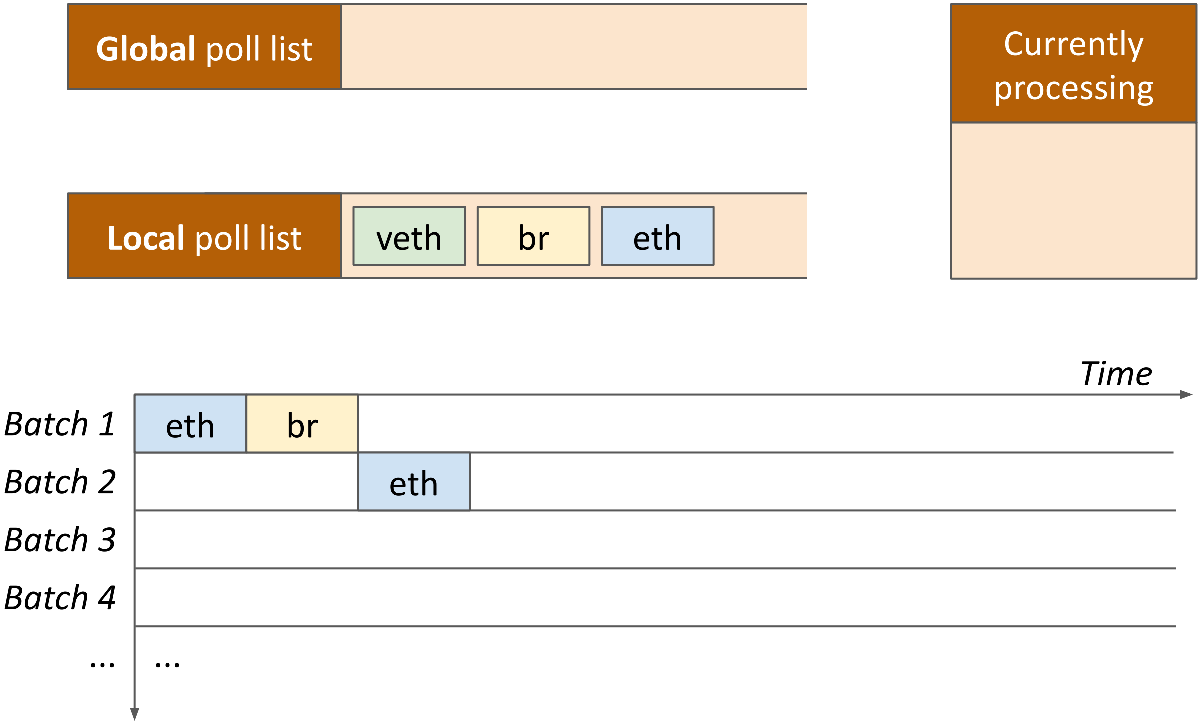

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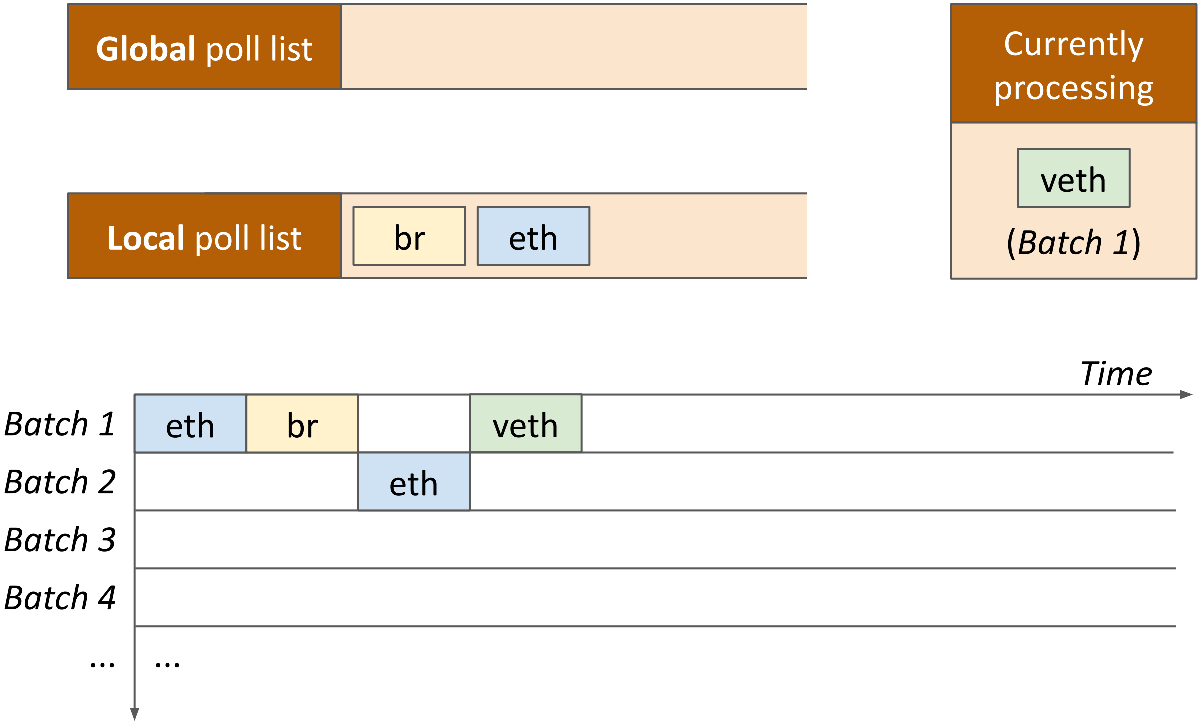

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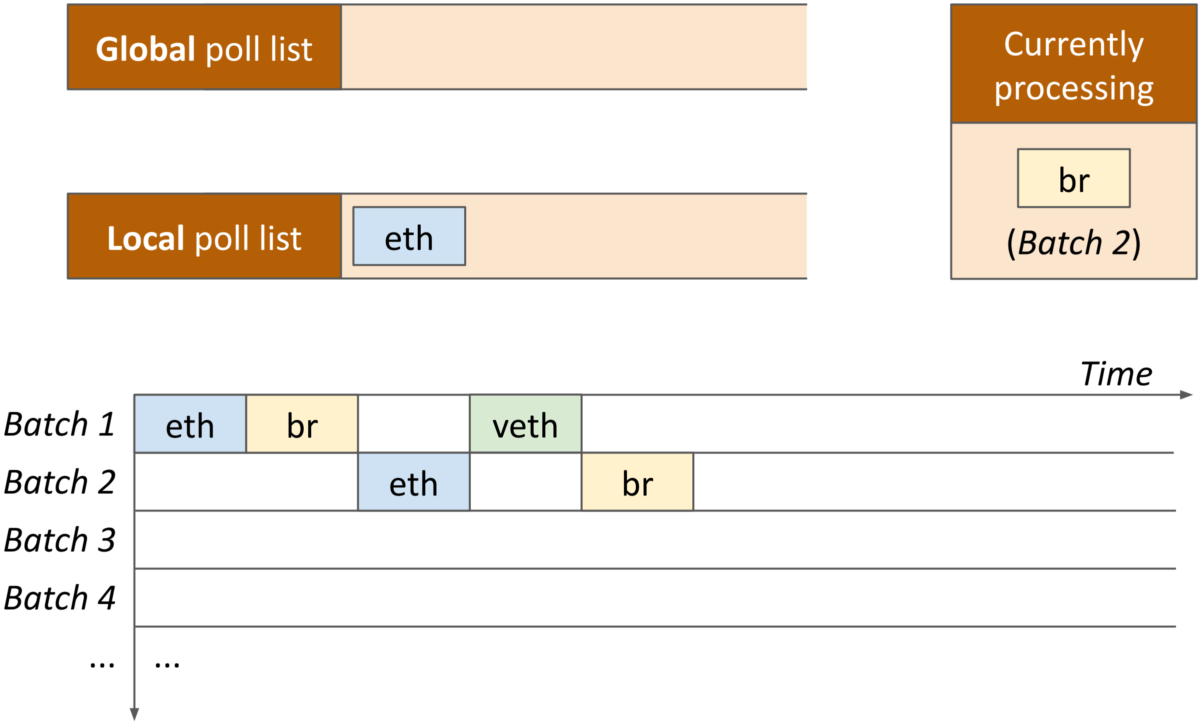

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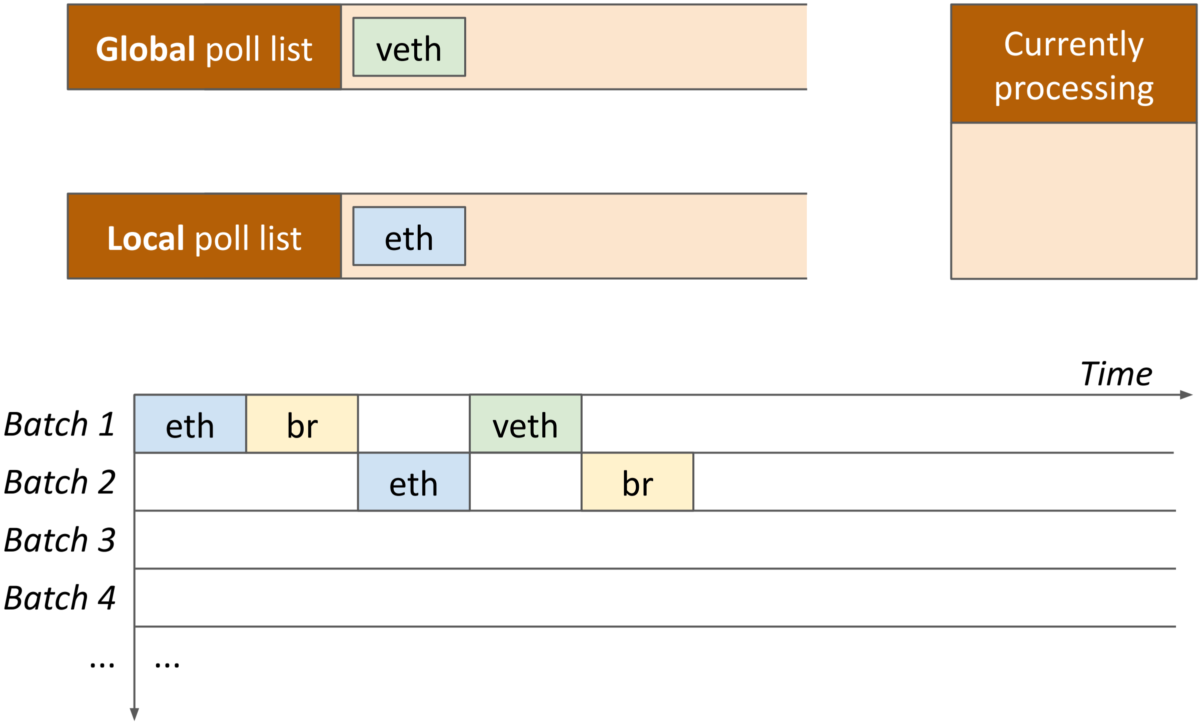

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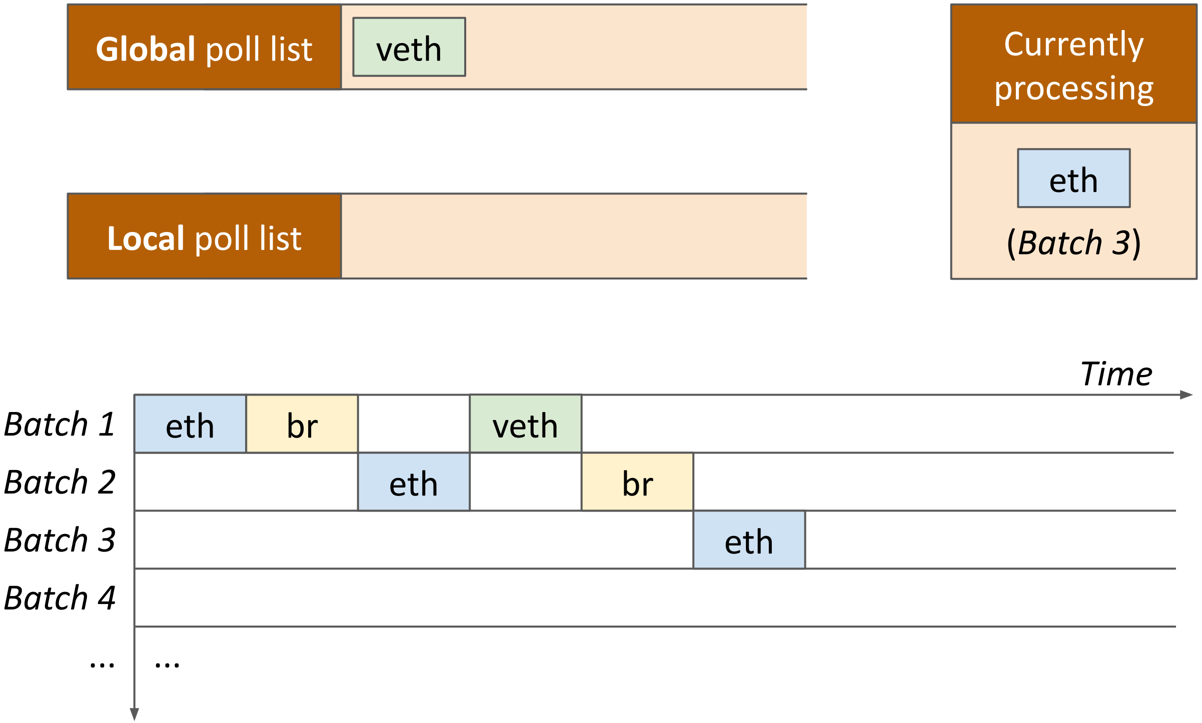


Global poll list: veth

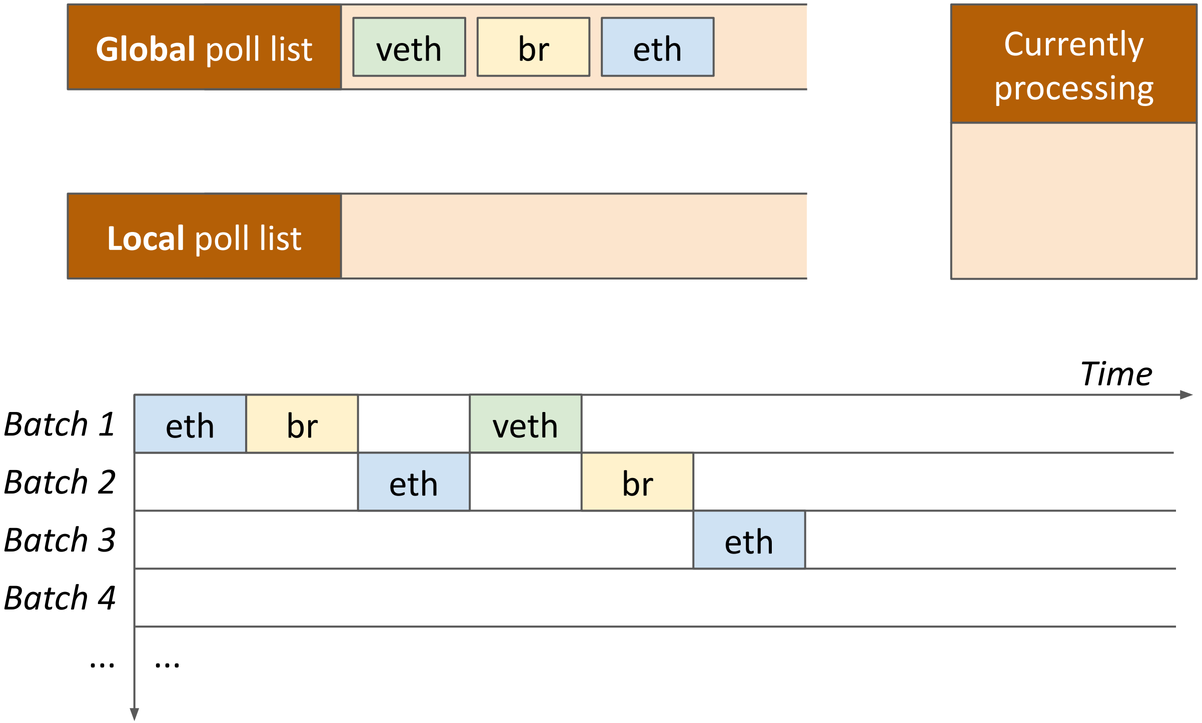
Local poll list:

Currently processing: eth (*Batch 3*)

Time

Batch 1	eth	br		veth		
Batch 2			eth		br	
Batch 3						eth
Batch 4						
…	…					

Interleaved NAPI device processing



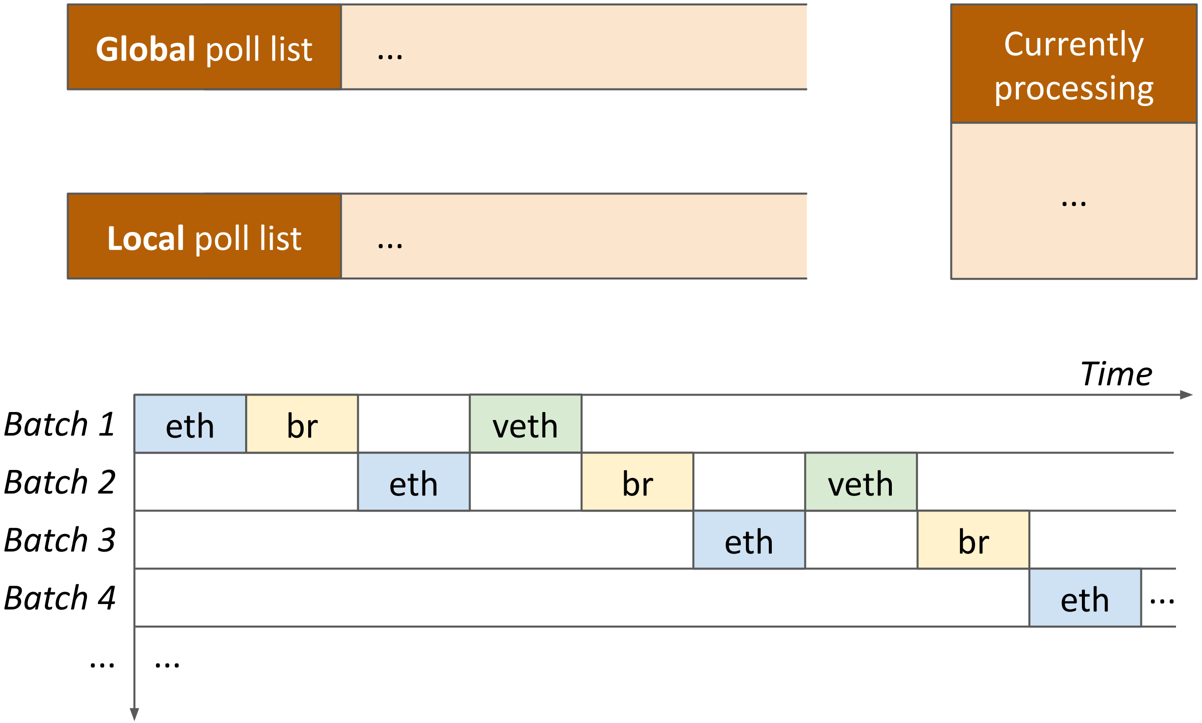
Global poll list: veth | br | eth

Local poll list

Currently processing

							Time
Batch 1	eth	br		veth			
Batch 2			eth		br		
Batch 3						eth	
Batch 4							
…	…						

Interleaved NAPI device processing



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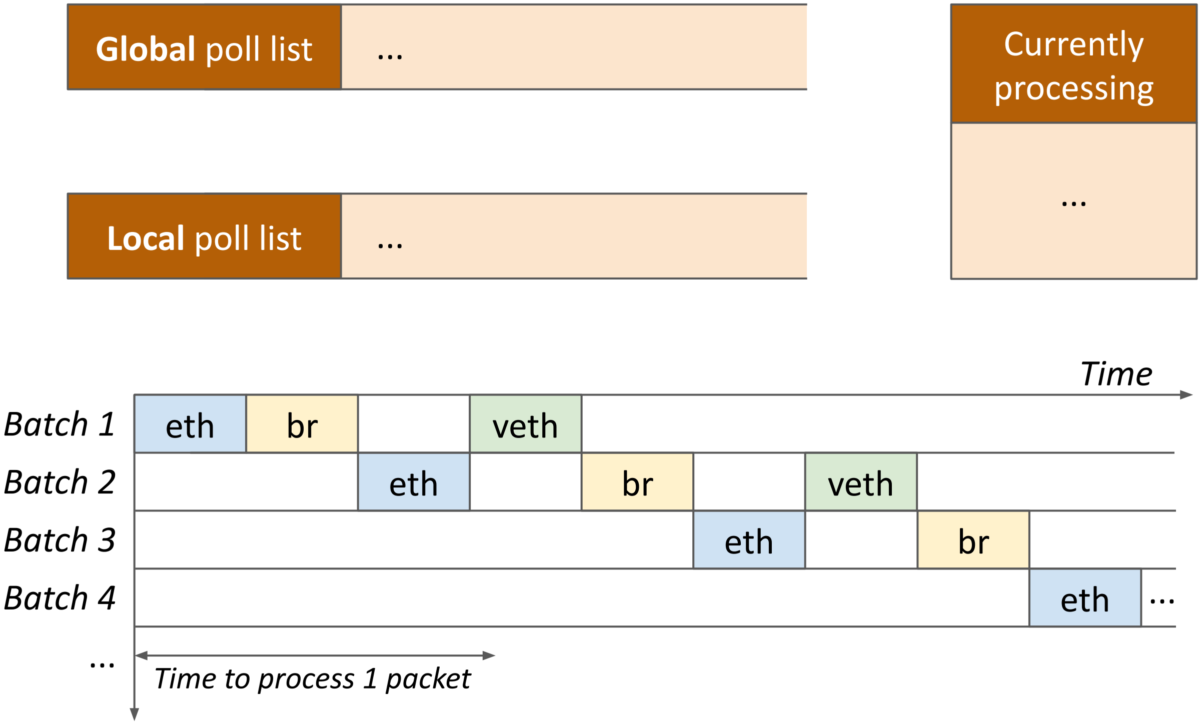
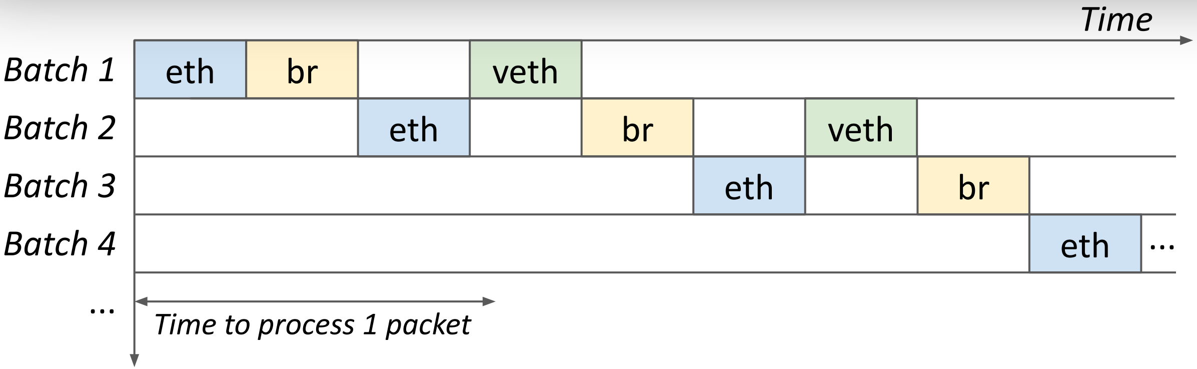


Batch 1	eth	br		veth						
Batch 2			eth		br		veth			
Batch 3						eth		br		
Batch 4									eth	…
…										

Interleaved NAPI device processing

Summary:

Vanilla kernel network stack **hurts latency** due to **interleaved processing** stages of batches.



Batch 1	eth	br		veth						
Batch 2			eth		br		veth			
Batch 3						eth		br		
Batch 4									eth	…
…										

Lack of priority differentiation

- All packets are processed in FIFO order

- *Latency-sensitive* flows get stuck behind long queues filled with *throughput-sensitive* flows

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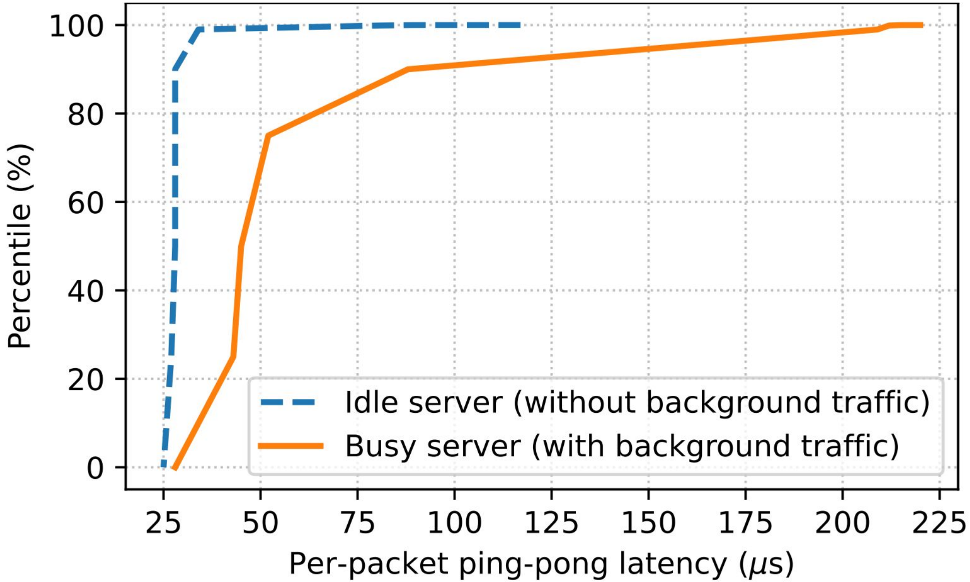

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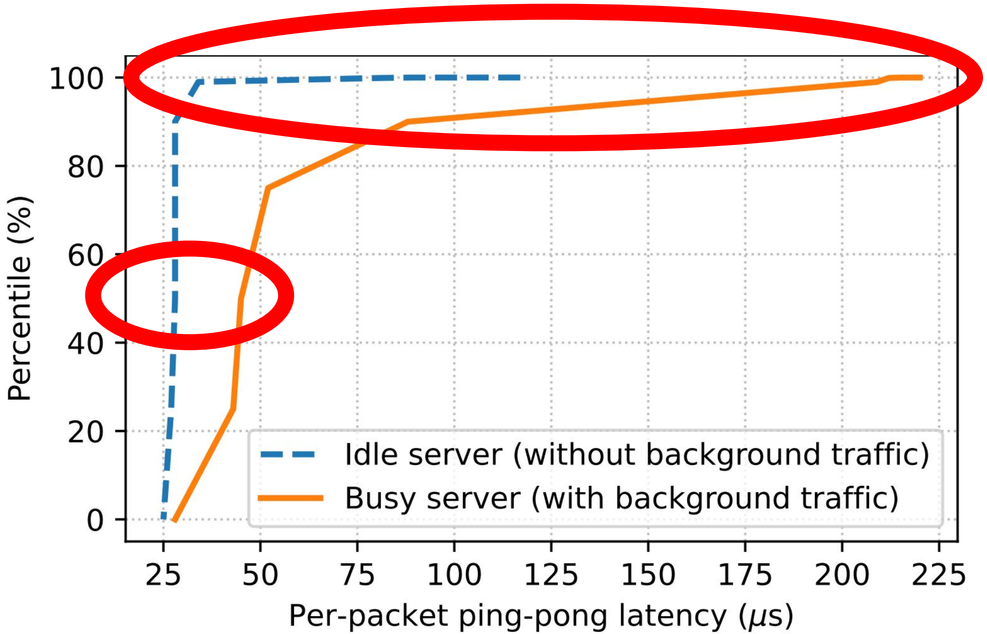

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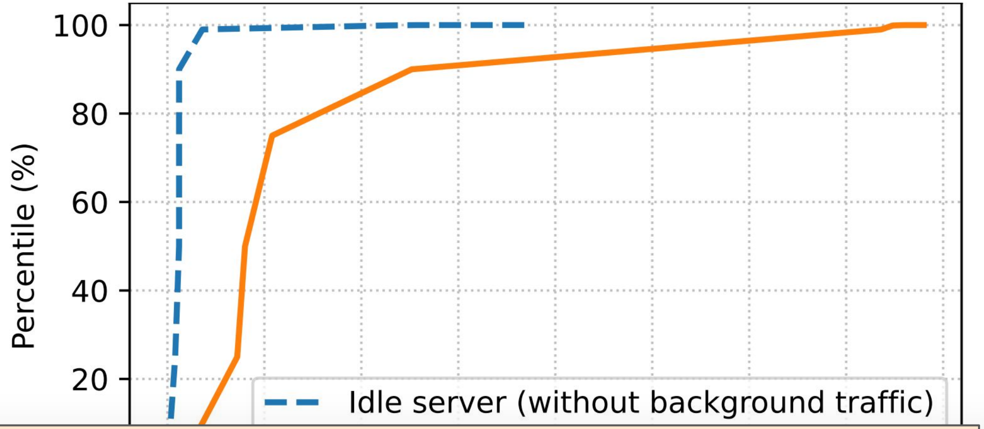

Is it possible to minimize latency of some flows while still offering sufficient throughput for other flows?

PRISM Design

Priority-based **S**trea**m**lined Packet Processing

- Improved NAPI design
- Priority differentiation
- Streamlined NAPI device polling

PRISM Design

Priority-based **S**trea**m**lined Packet Processing

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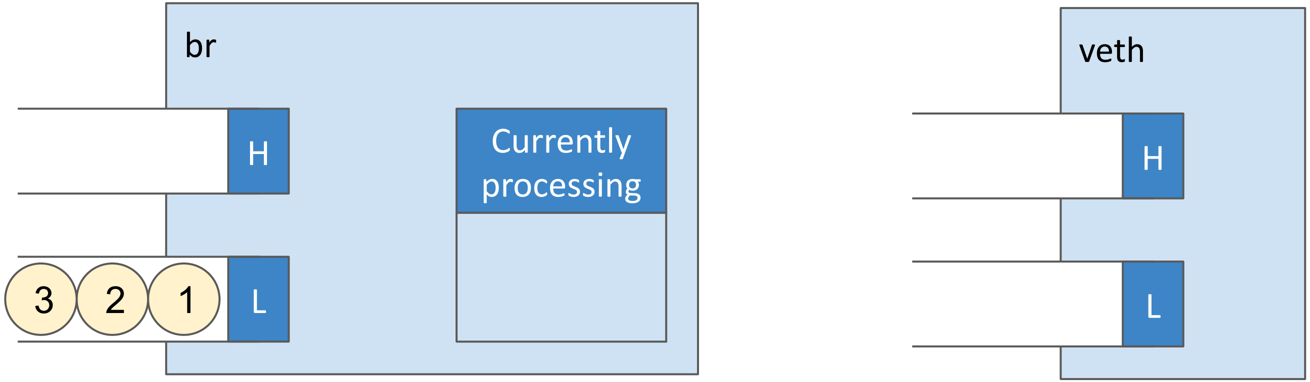
Benefits over kernel-bypass / custom network stack:

- Completely backward compatible
- No expensive hardware needed
- No need to change application code
- Preserves kernel's security, portability, and reliability

Priority differentiation

Priority differentiation



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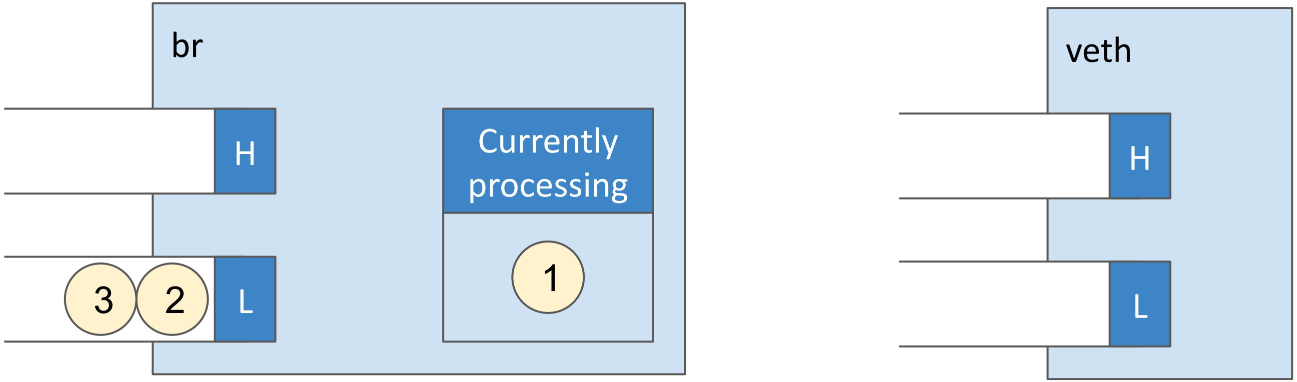

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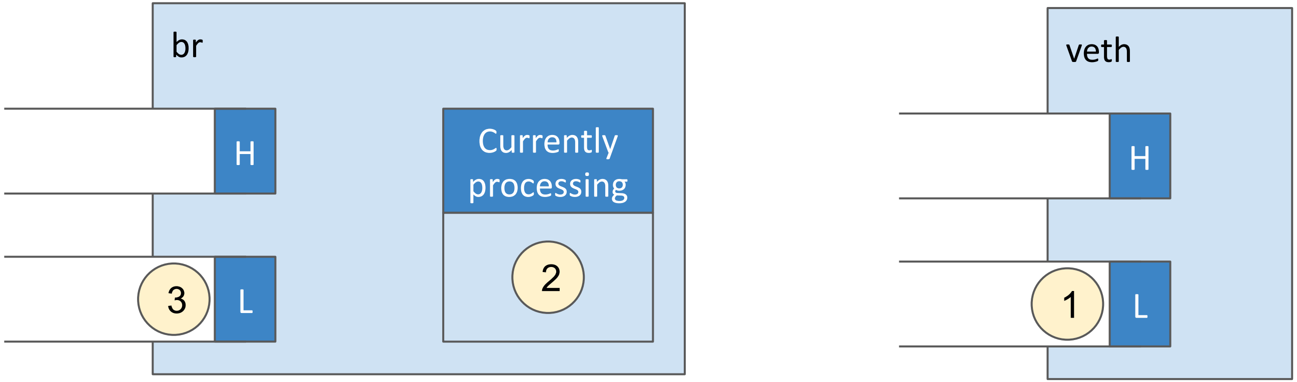

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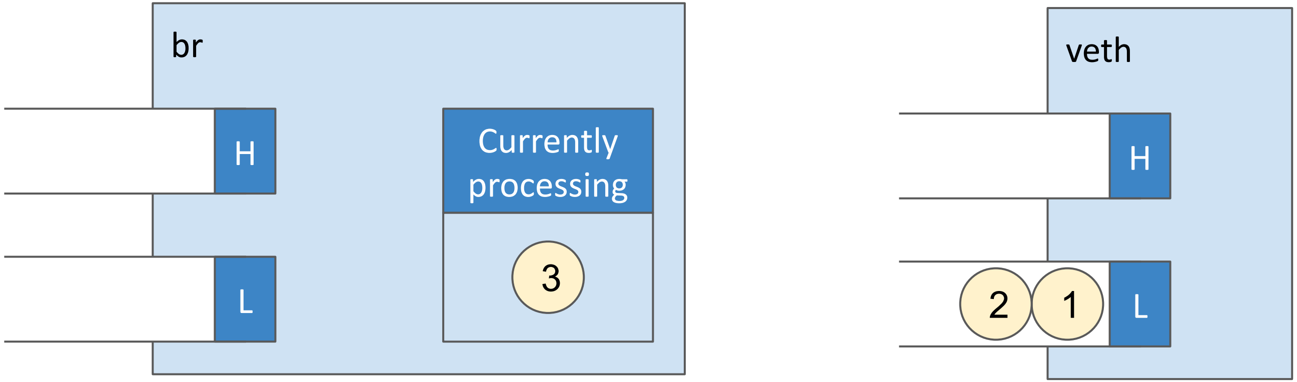

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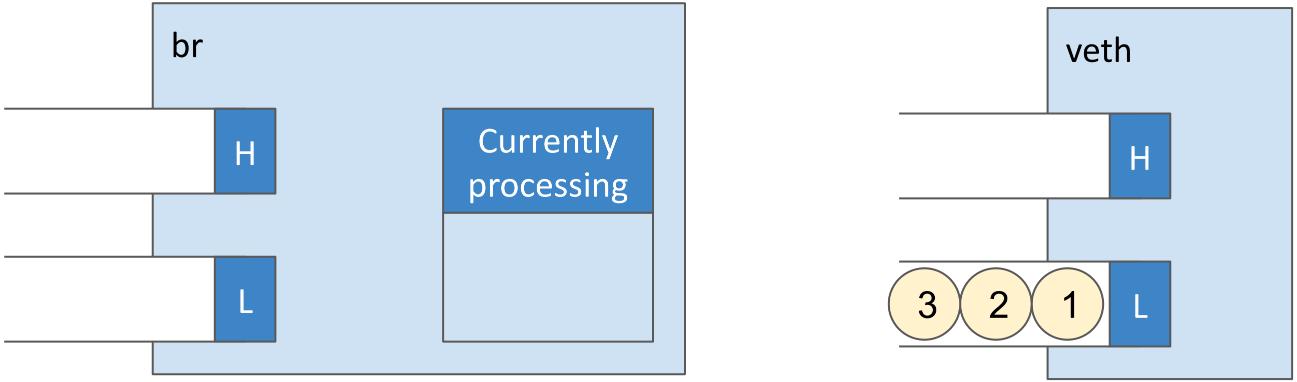

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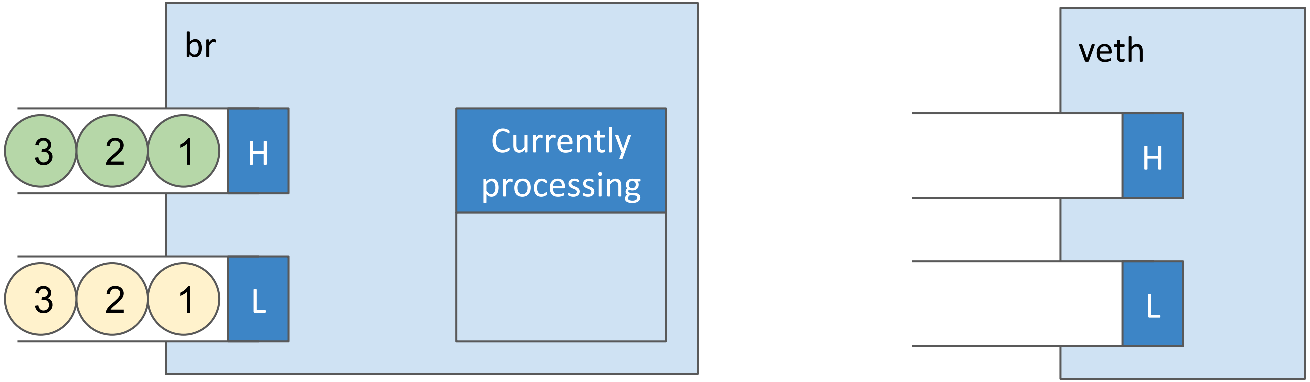

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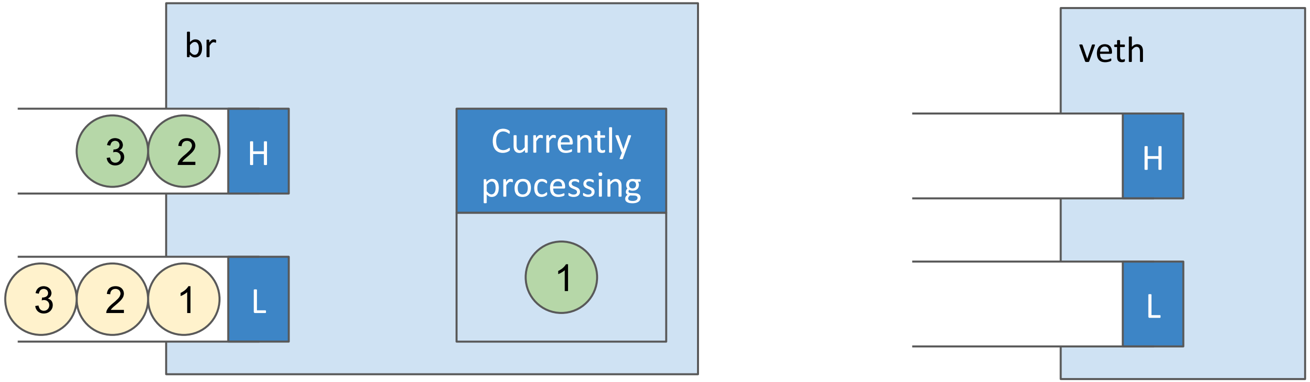

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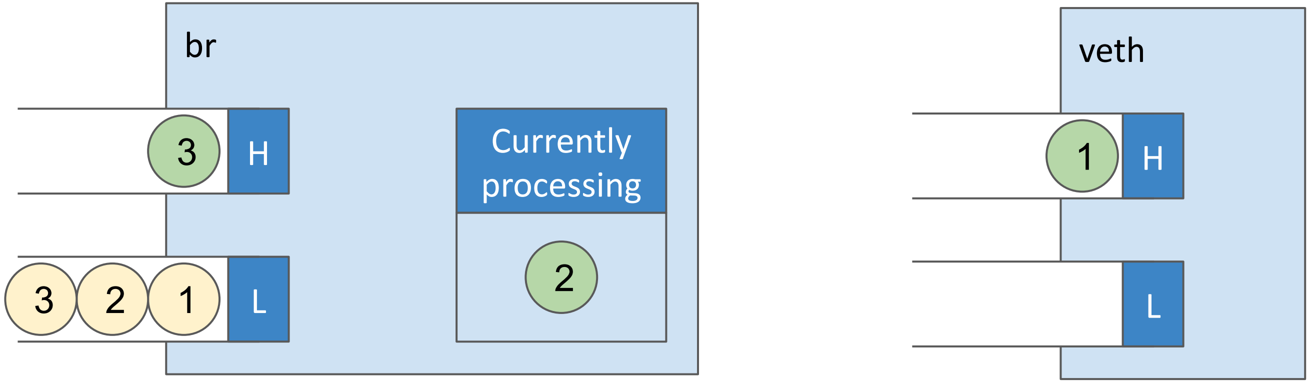

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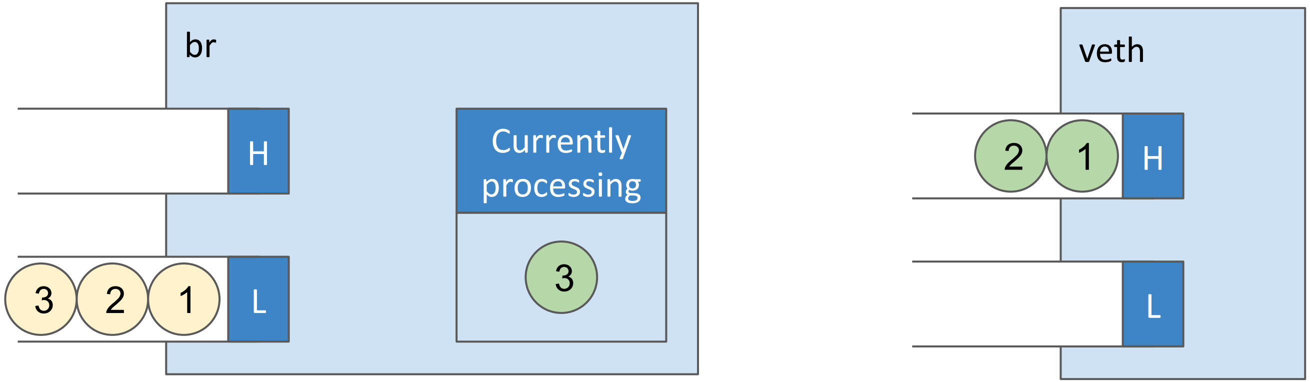

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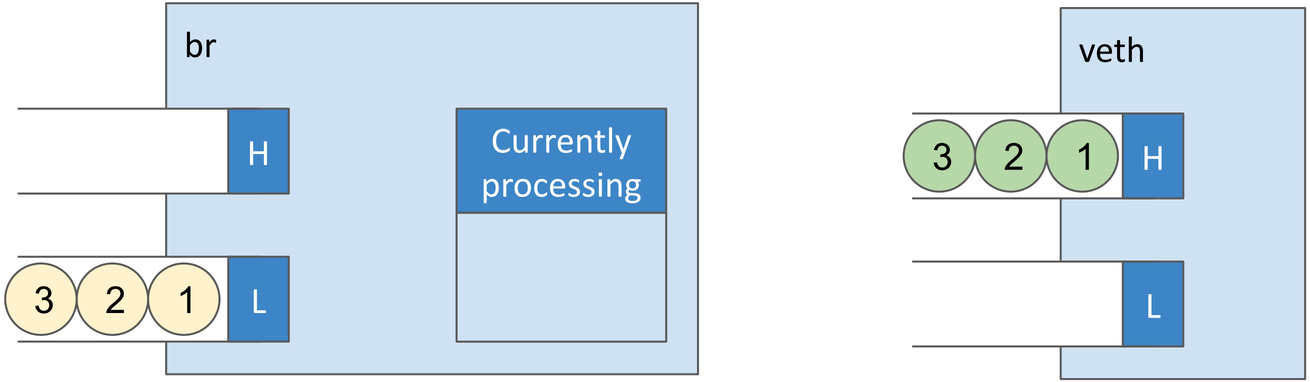


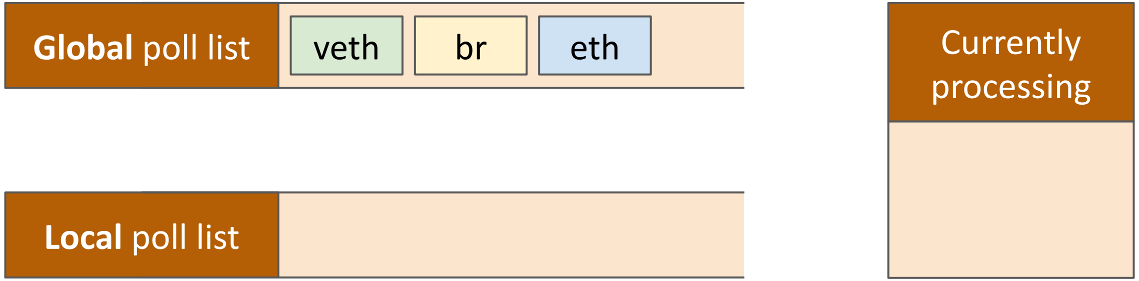
Priority differentiation

PRISM enables priority differentiation by:

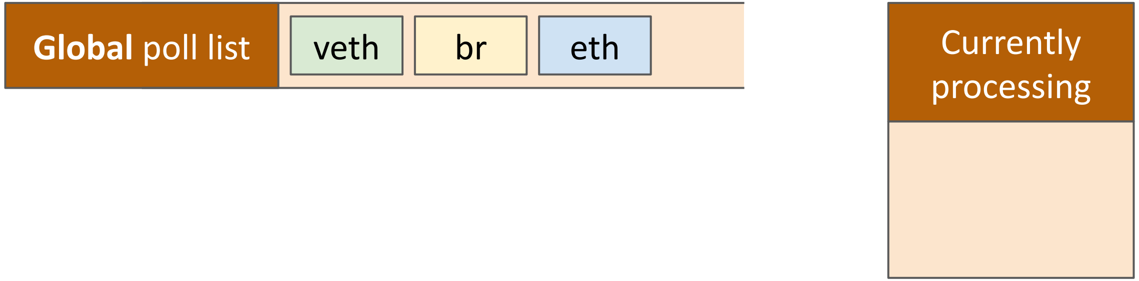
- Using a dedicated high-priority packet queue
- Batch-level preemption

PRISM-batch

PRISM-batch


Global poll list
veth
br
eth
Local poll list
Currently processing

PRISM-batch



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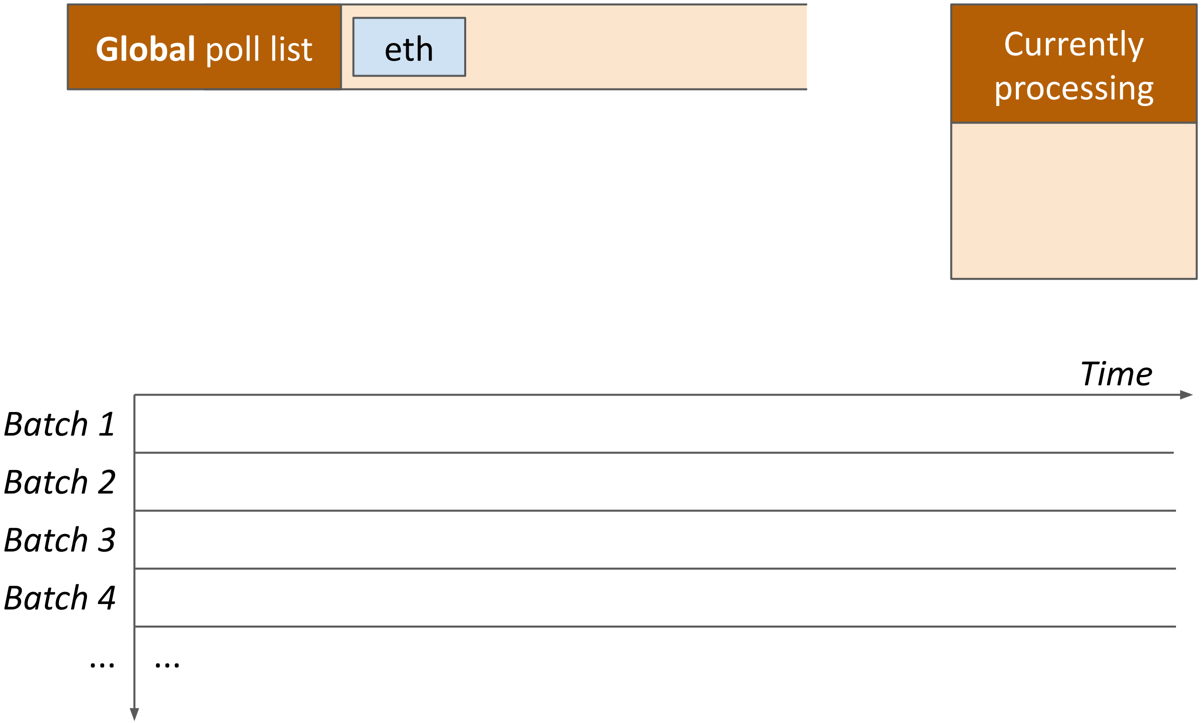
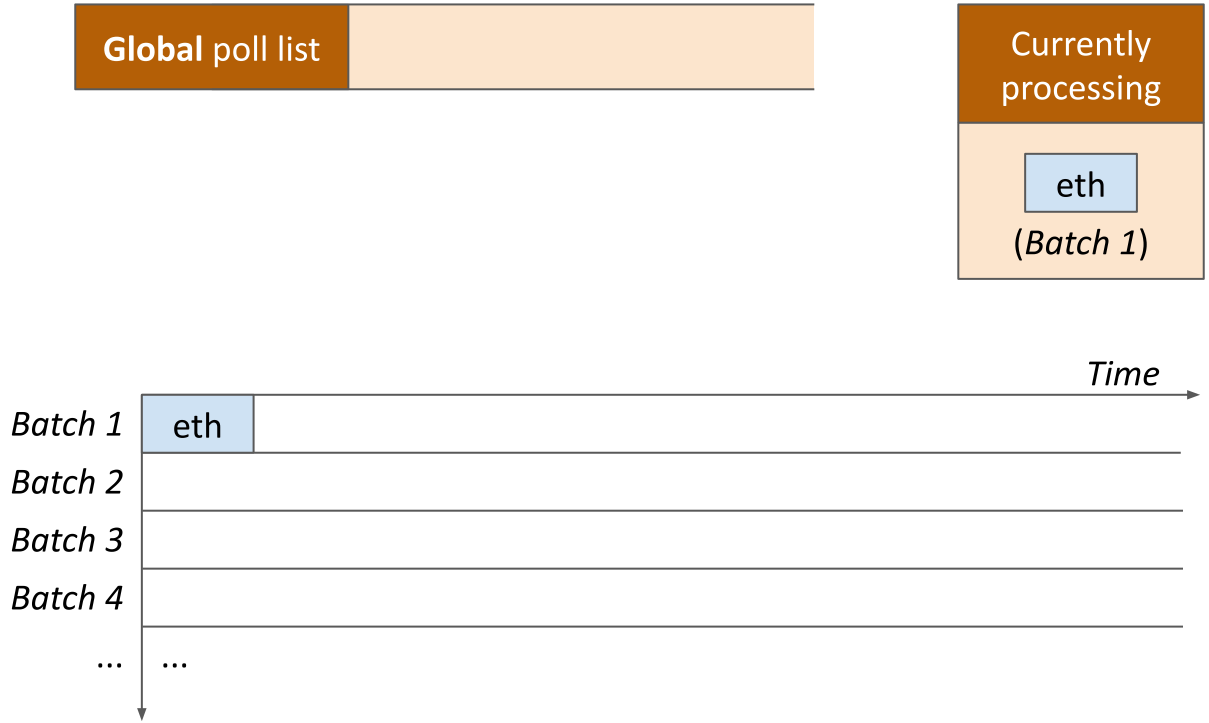

Global poll list
eth
Currently processing
Time
Batch 1
Batch 2
Batch 3
Batch 4
…
…

PRISM-batch



Global poll list

Currently processing

eth

(*Batch 1*)

Time

Batch 1 eth

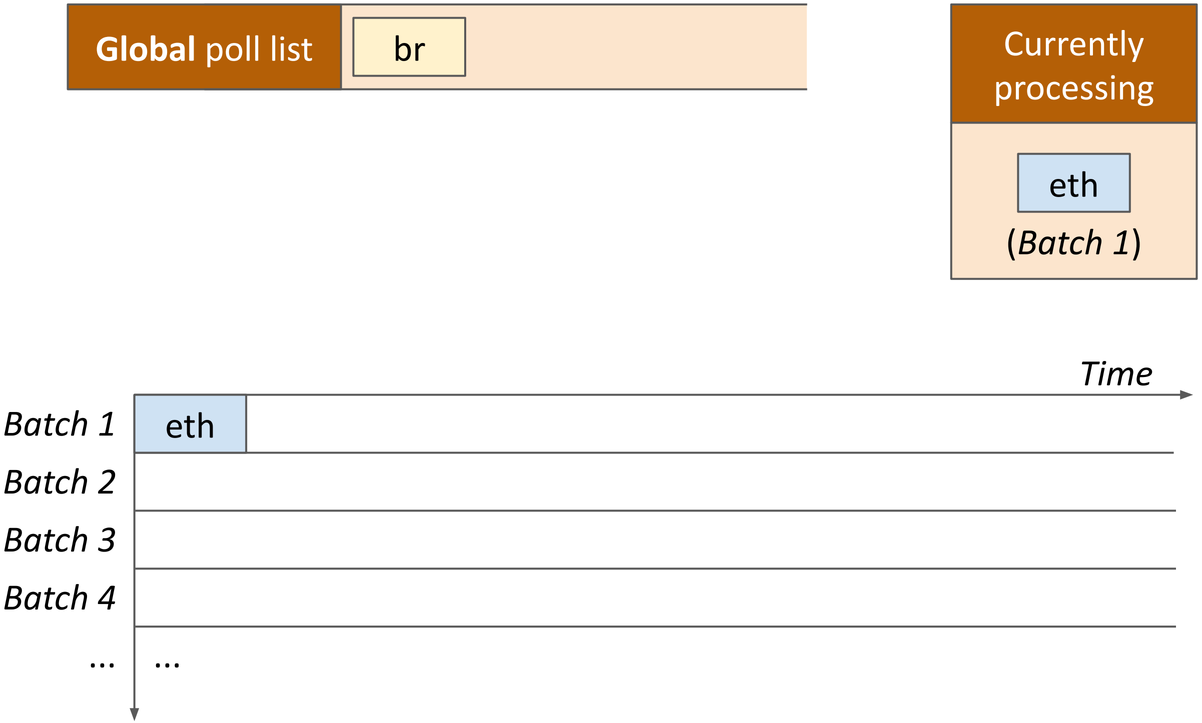
Batch 2

Batch 3

Batch 4

... ...

PRISM-batch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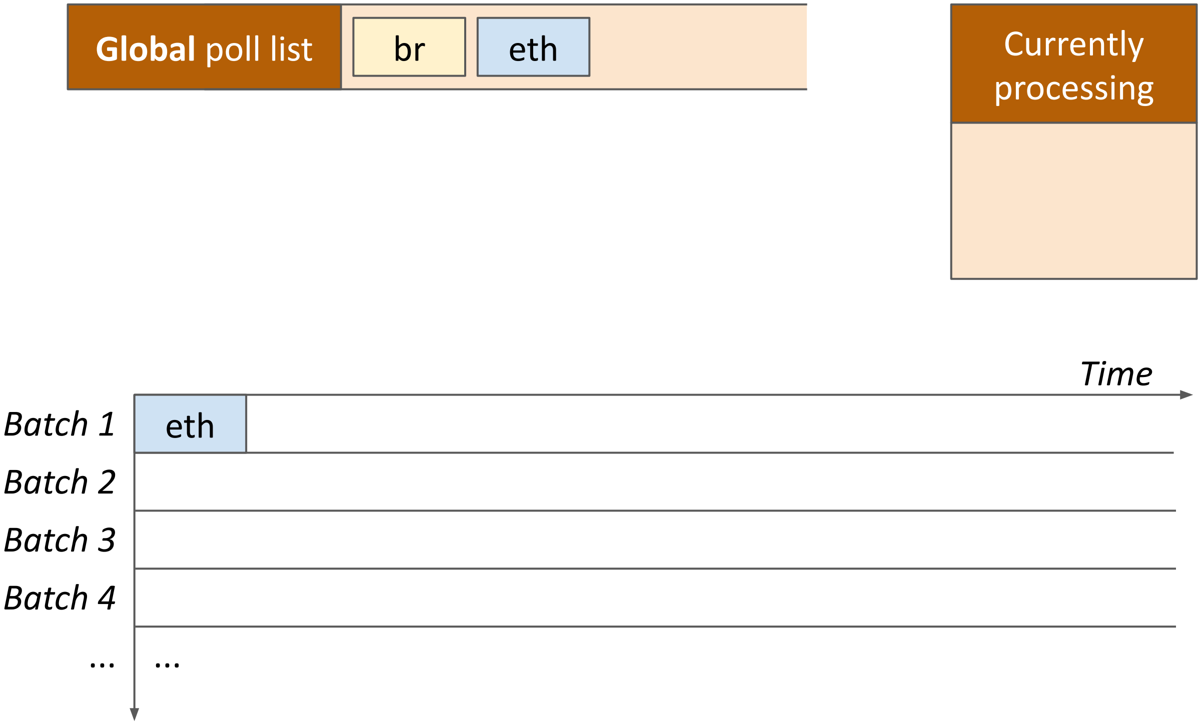
PRISM-batch



Global poll list

br

eth

Currently processing

Time

Batch 1

eth

Batch 2

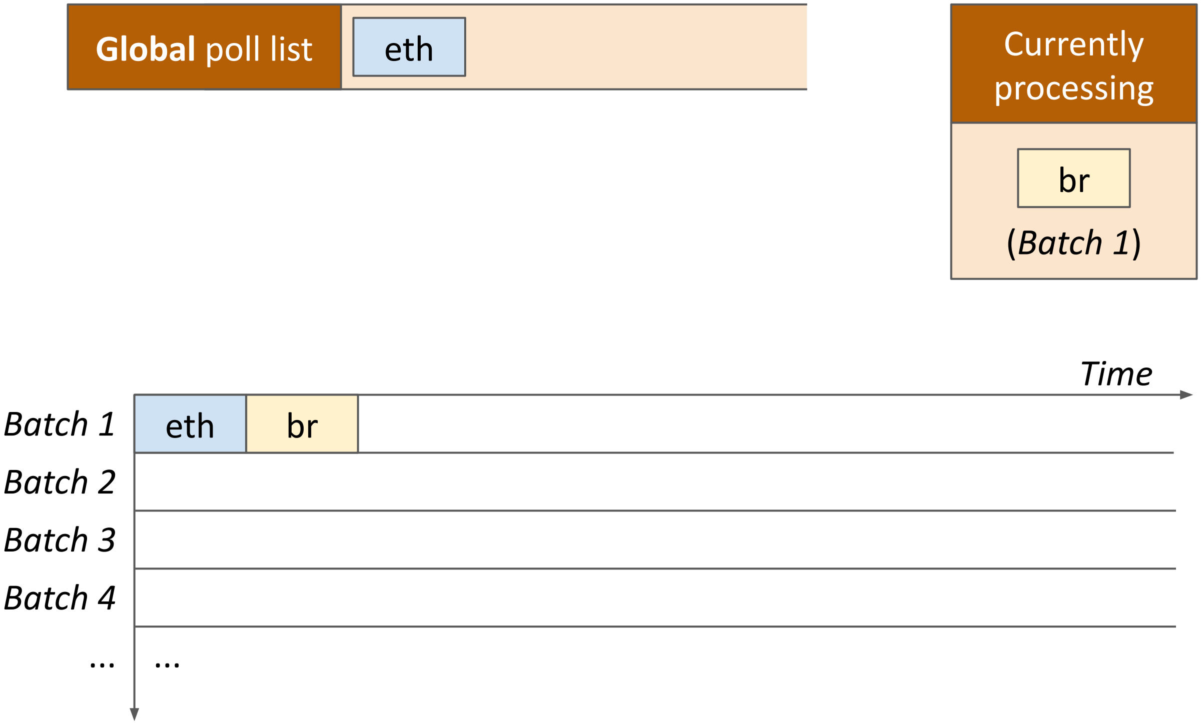
Batch 3

Batch 4

...

...

PRISM-batch



Global poll list
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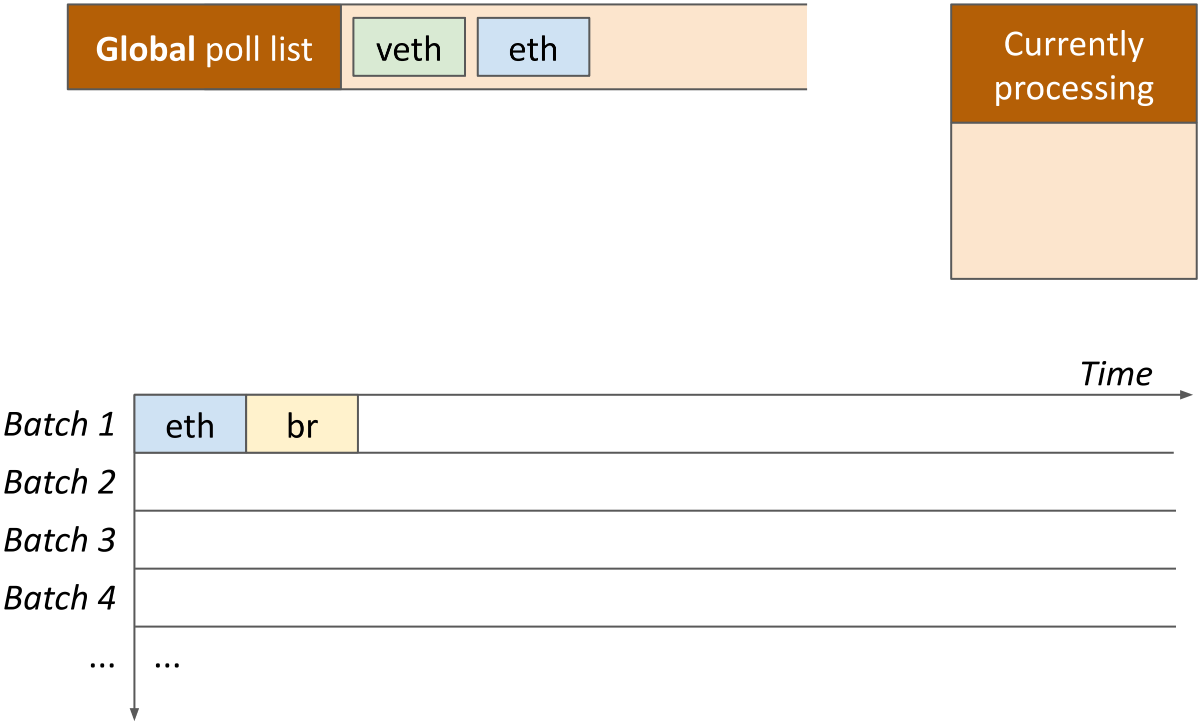
Currently processing
br
(*Batch 1*)
Time
Batch 1
eth
br
Batch 2
Batch 3
Batch 4
...
...

PRISM-batch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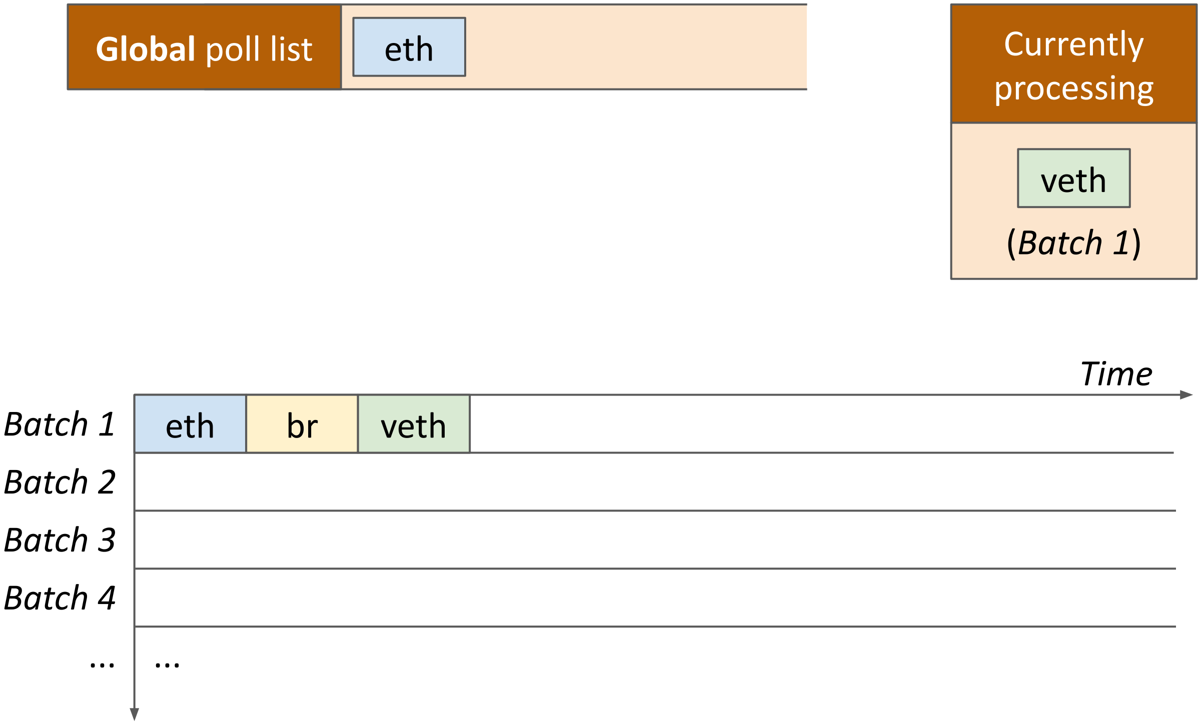
veth
eth
Currently processing
Time
Batch 1
eth
br
Batch 2
Batch 3
Batch 4
...
...

PRISM-batch



Global poll list

eth

Currently processing

veth

(*Batch 1*)

Time

Batch 1 eth br veth

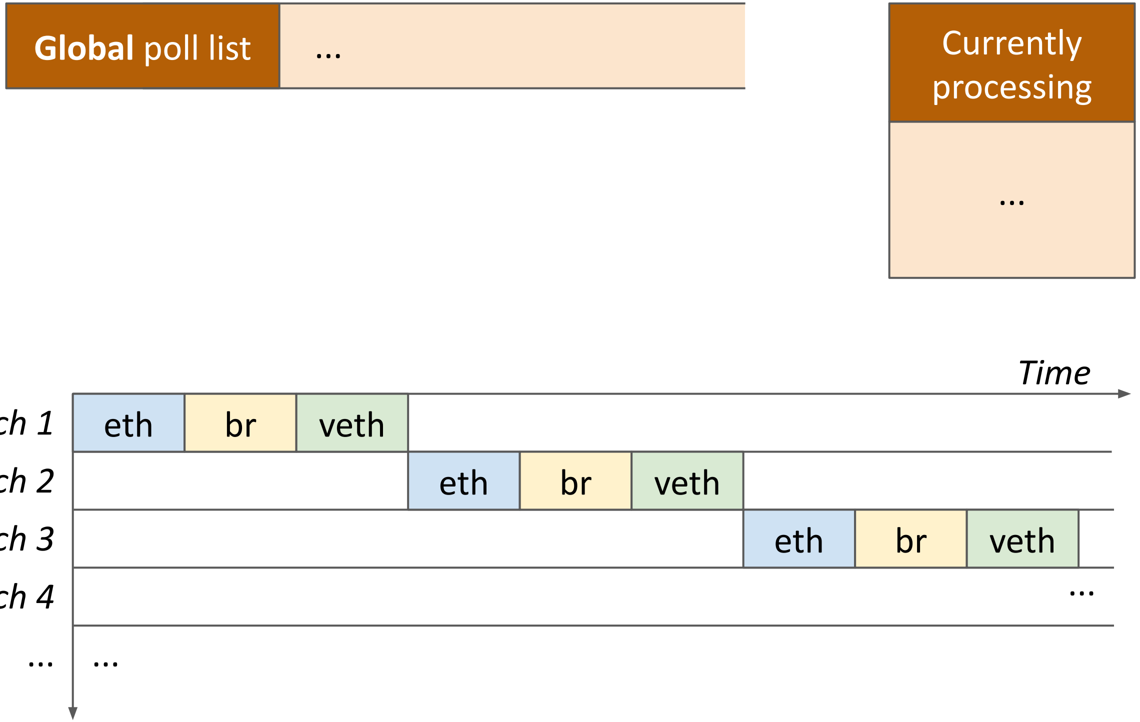
Batch 2

Batch 3

Batch 4

… …

PRISM-batch

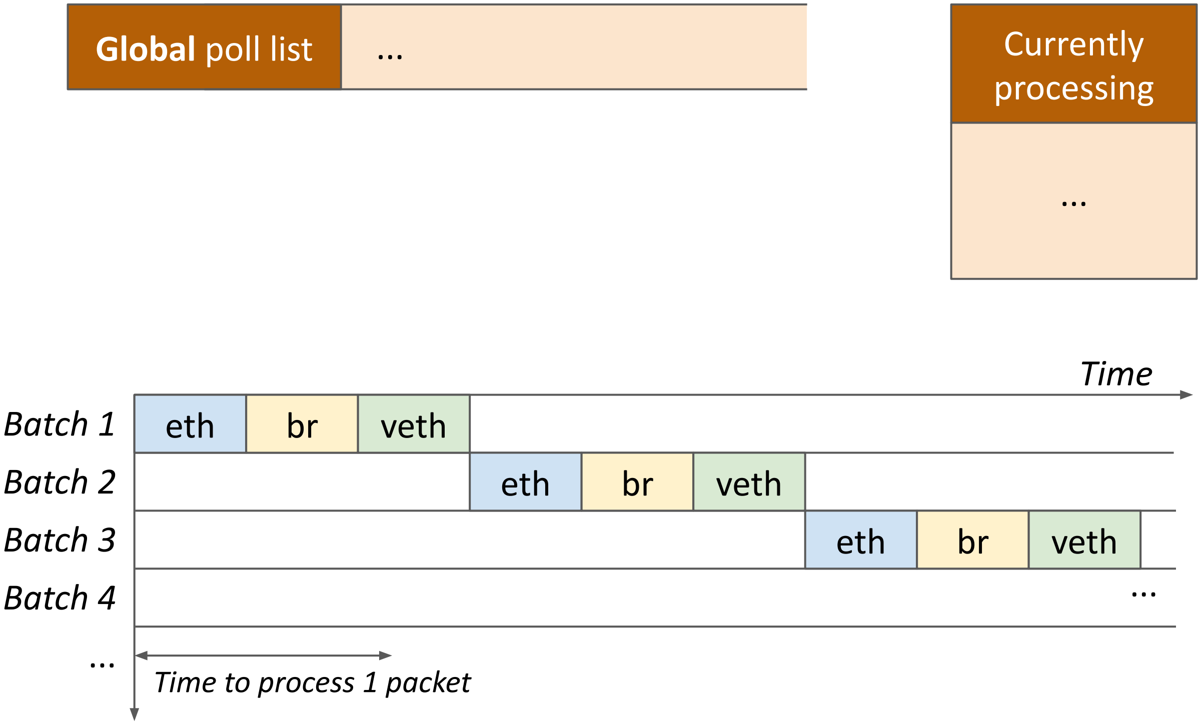


Global poll list	…

Currently processing
…

										Time
Batch 1	eth	br	veth							
Batch 2				eth	br	veth				
Batch 3							eth	br	veth	
Batch 4										…
…	…									

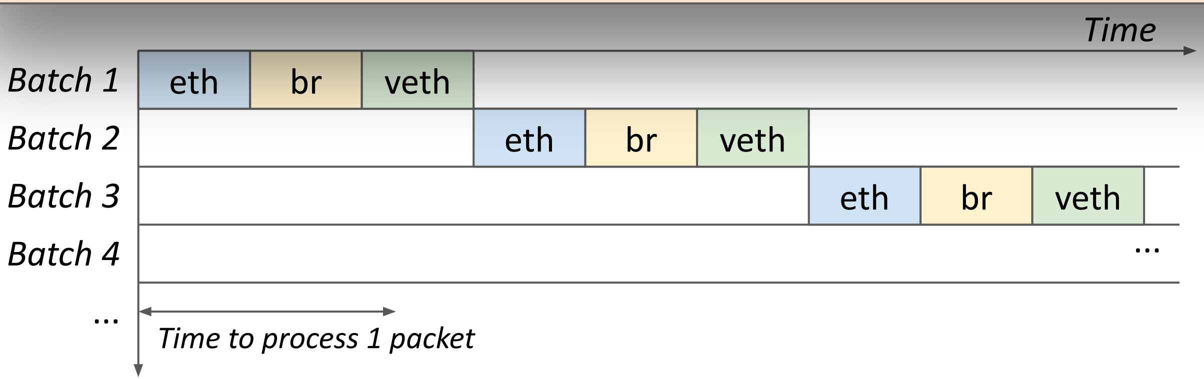
PRISM-batch


Global poll list
...
Currently processing
...
Time
Batch 1
eth
br
veth
Batch 2
eth
br
veth
Batch 3
eth
br
veth
Batch 4
...
...
Time to process 1 packet

PRISM-batch

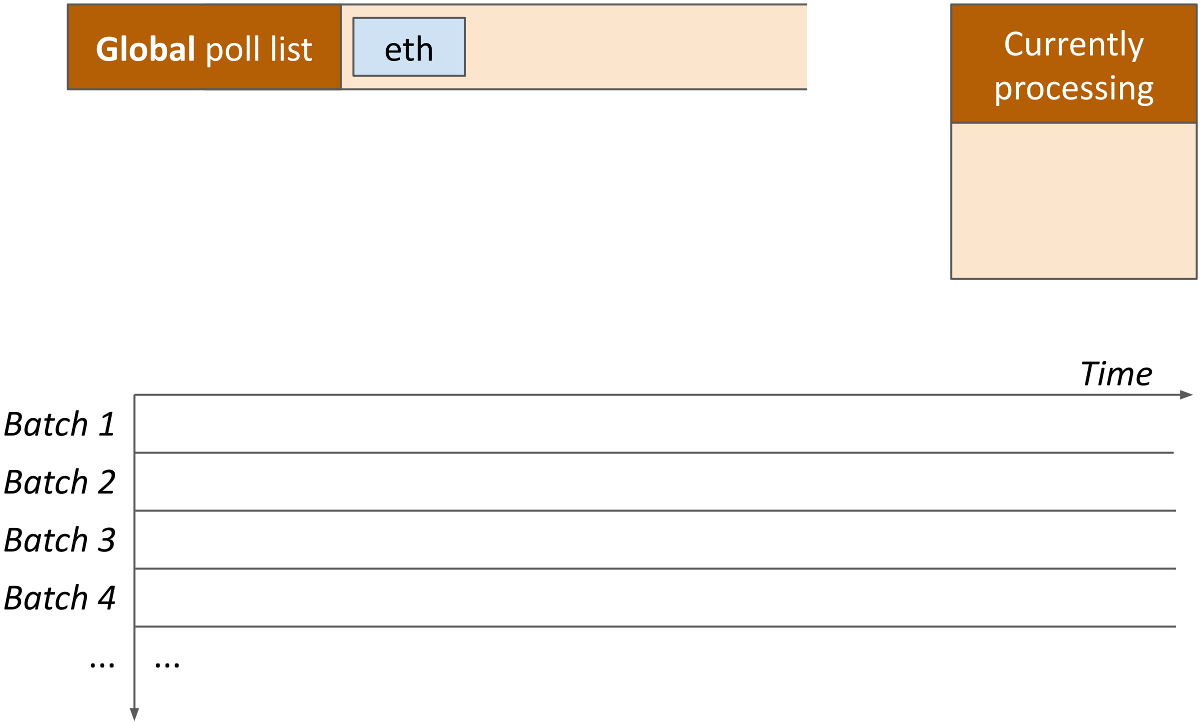
PRISM-batch:

- Improves latency by streamlining processing of batches
- Enables batch-level preemption
- But still maintains batching benefits



PRISM-sync

PRISM-sync



Global poll list

eth

Currently processing

Time

Batch 1

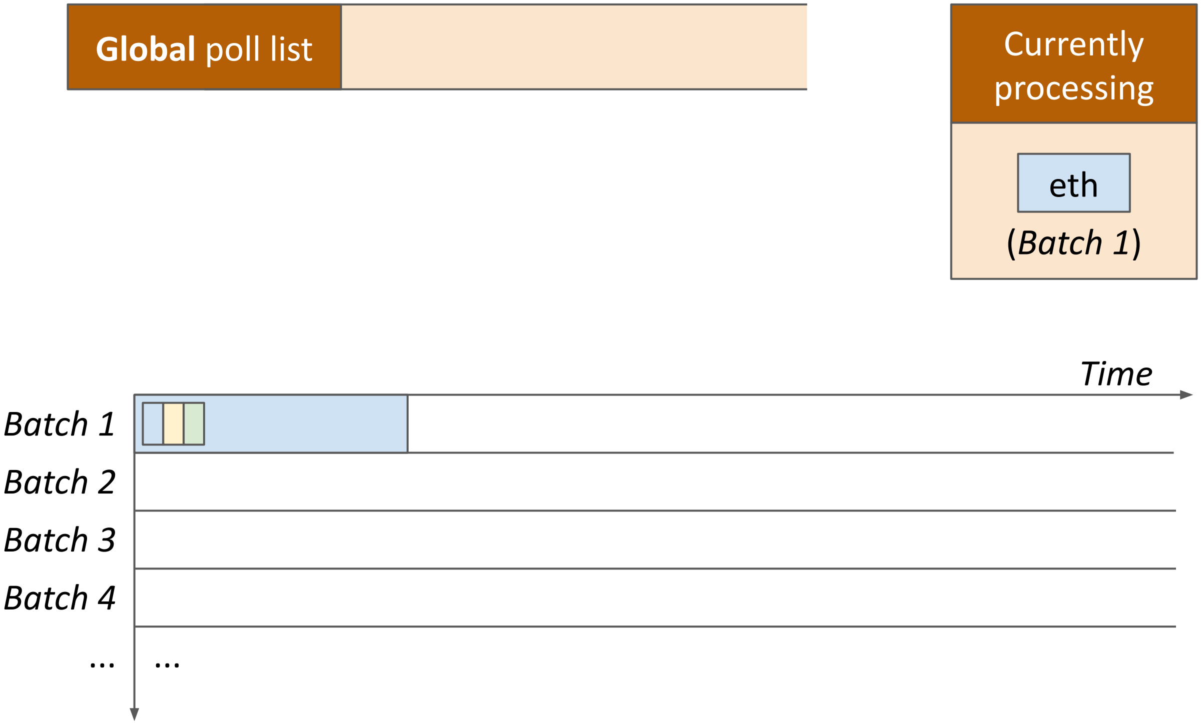
Batch 2

Batch 3

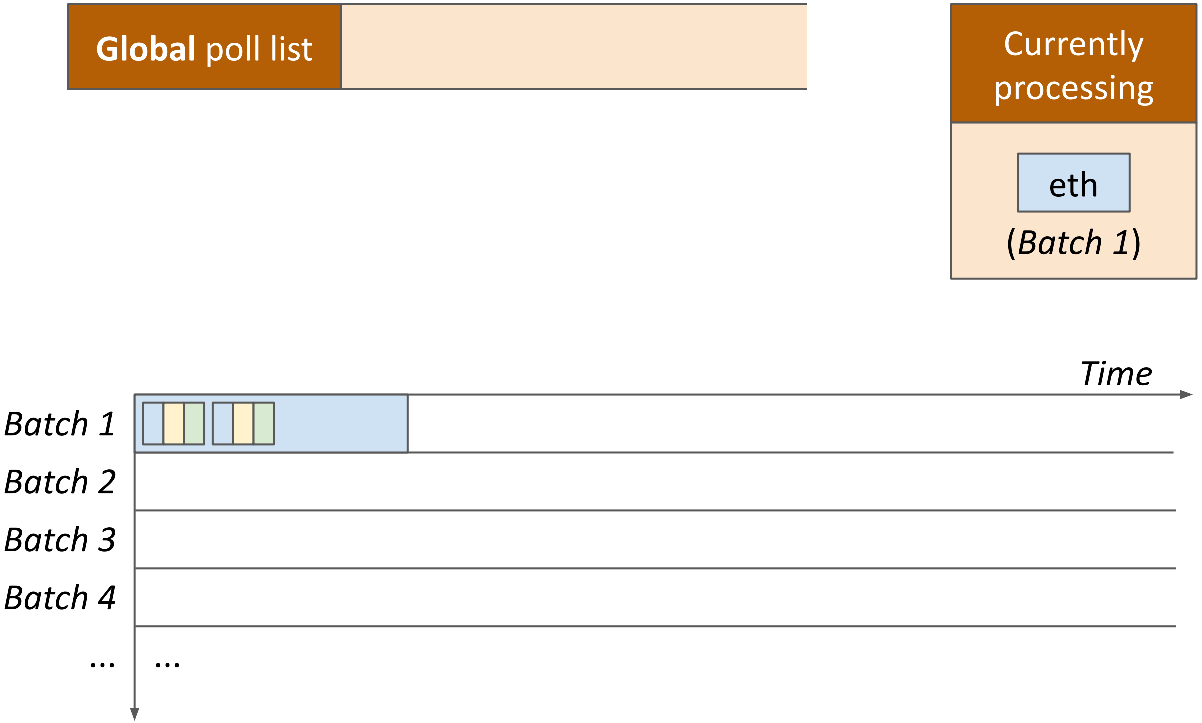
Batch 4

… …

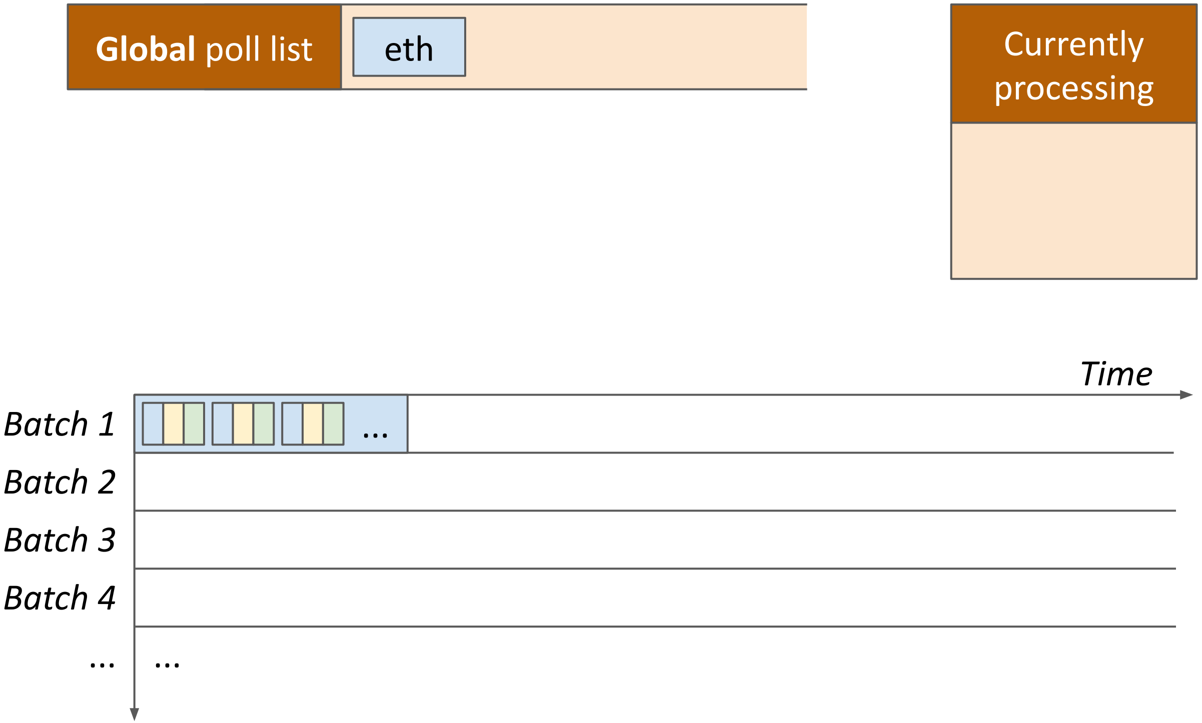
PRISM-sync


Global poll list
Currently processing
eth
(*Batch 1*)
Time
Batch 1
Batch 2
Batch 3
Batch 4
...
...

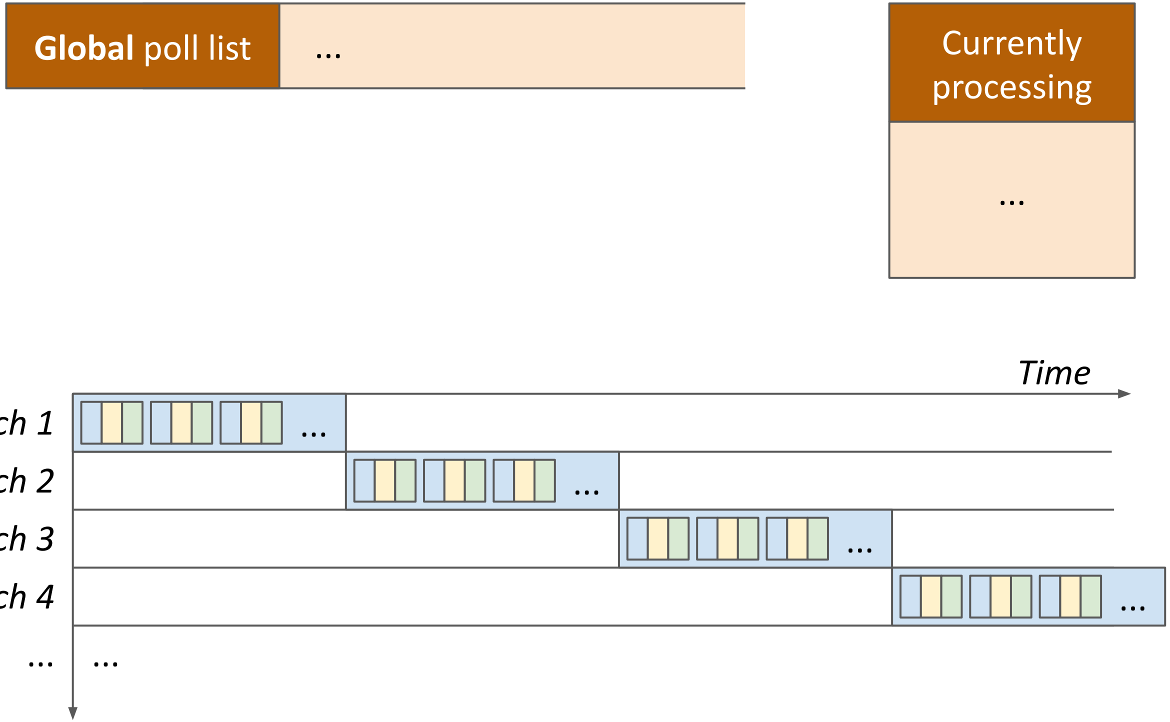
PRISM-sync


Global poll list
Currently processing
eth
(*Batch 1*)
Time
Batch 1
Batch 2
Batch 3
Batch 4
...
...

PRISM-sync


Global poll list
eth
Currently processing
Time
Batch 1
…
Batch 2
Batch 3
Batch 4
…
…

PRISM-sync



Global poll list

...

Currently processing

...

Time

Batch 1

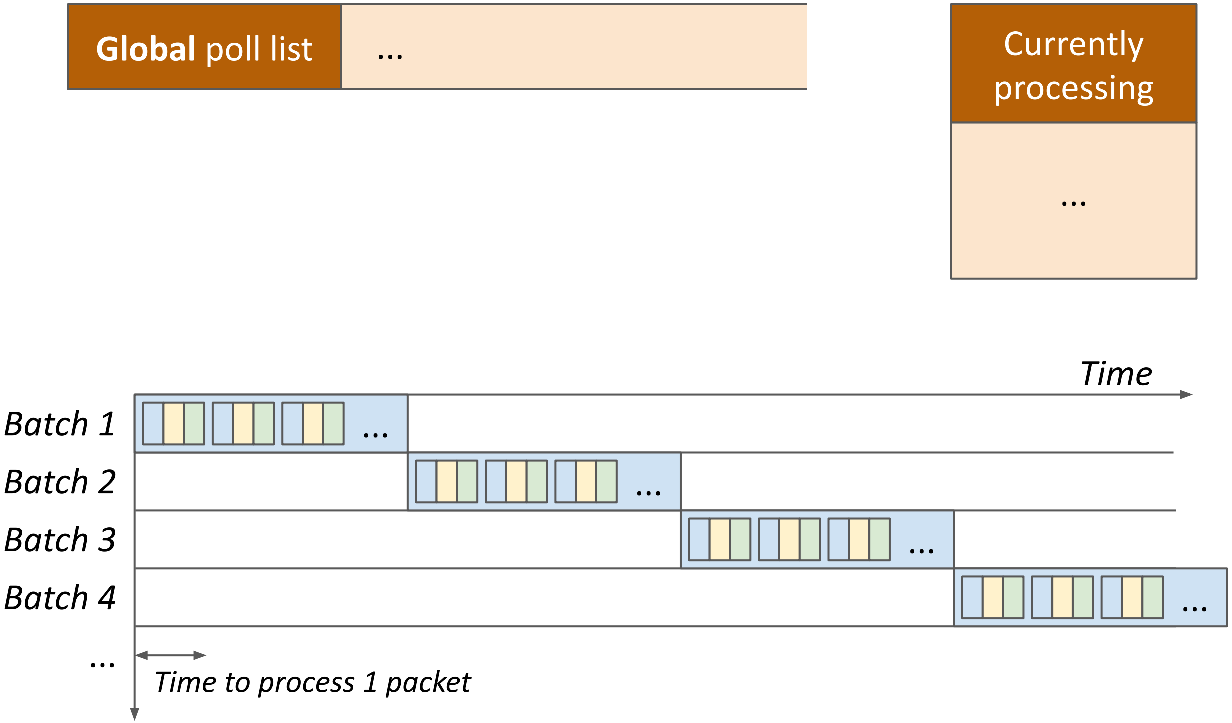
Batch 2

Batch 3

Batch 4

...

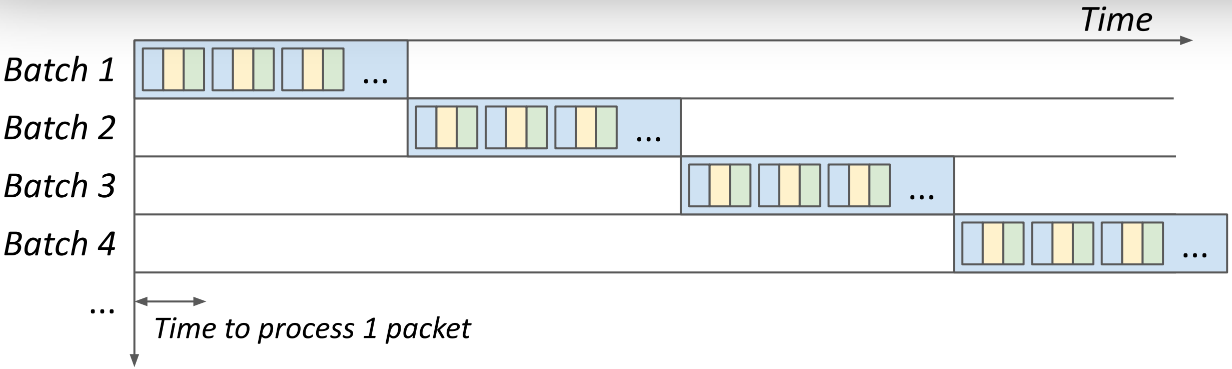
PRISM-sync


Global poll list
…
Currently processing
…
Time
Batch 1
…
Batch 2
…
Batch 3
…
Batch 4
…
…
Time to process 1 packet

PRISM-sync

PRISM-sync:

- minimizes latency by processing each packet to completion
- loses batching benefits



Implementation

- Prototype implemented on top of Linux 5.4
- ~550 lines of code in the kernel network stack
- Publicly available at: github.com/munikarmanish/prism

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Some things to note:

- Priority identification is left to user
- Prioritization in the first stage (NIC)

Evaluation — Setup

Hardware:	Intel Xeon, 40 logical cores @ 2.2GHz, 128GB memory
NIC:	Mellanox ConnectX-5 EN (100GbE)
Software:	Ubuntu 18.04, with Linux kernel 5.4

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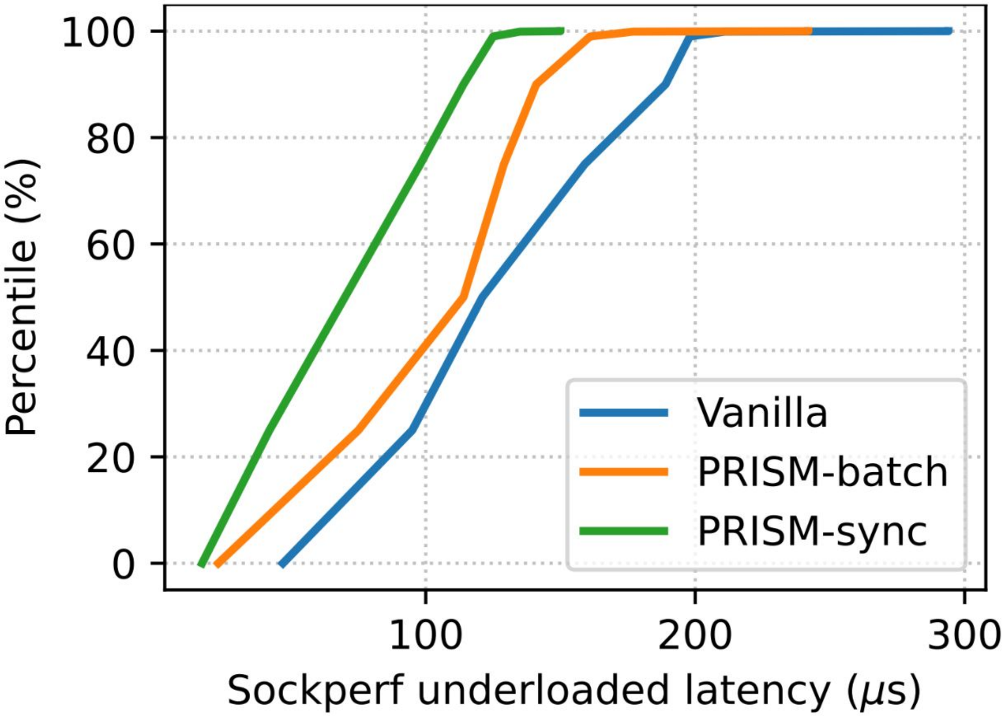
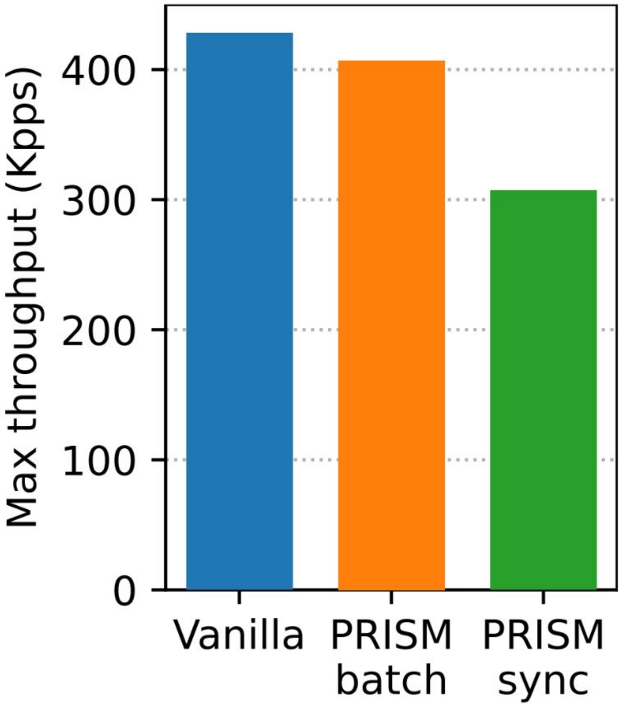
Experiments:

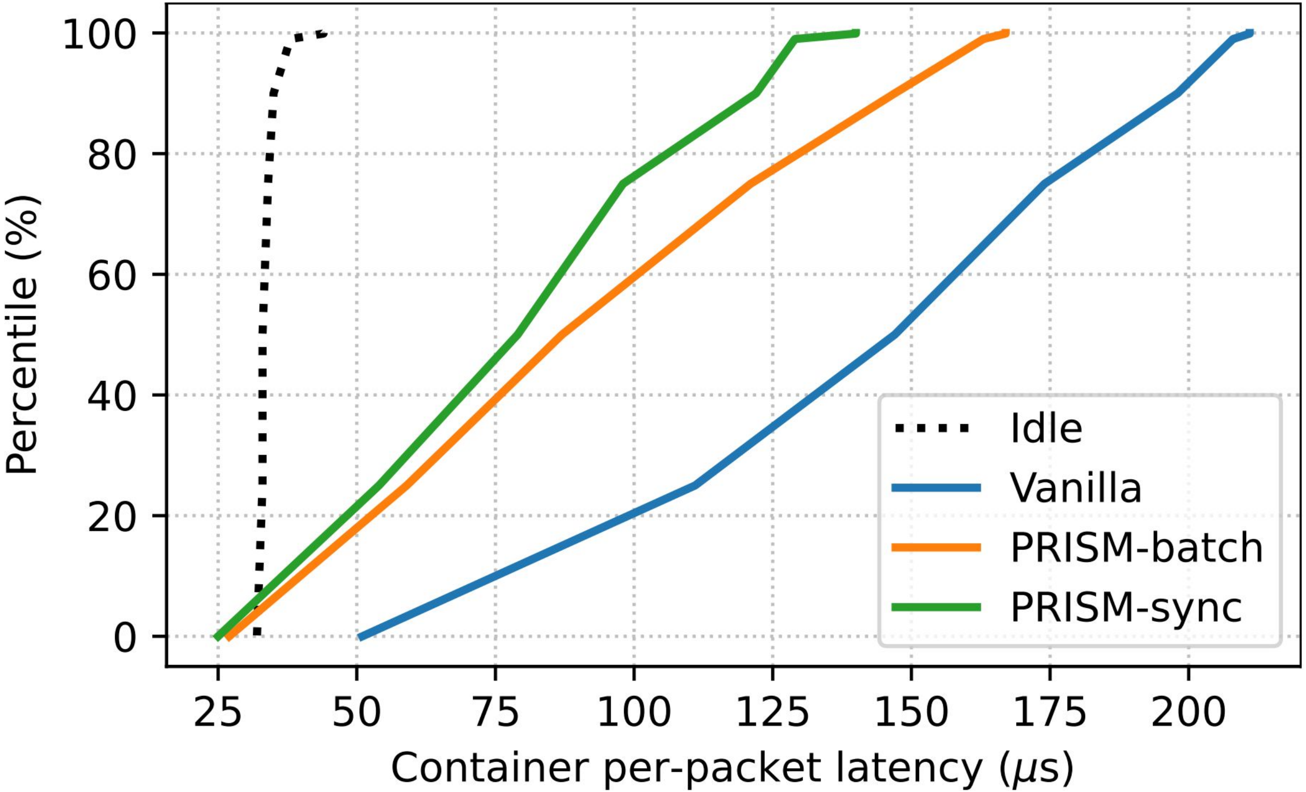
- Microbenchmarks
- Application benchmarks (Memcached, Web serving)
- *[More in the paper]*

Microbenchmark — Streamlined NAPI processing





Microbenchmark — Priority differentiation



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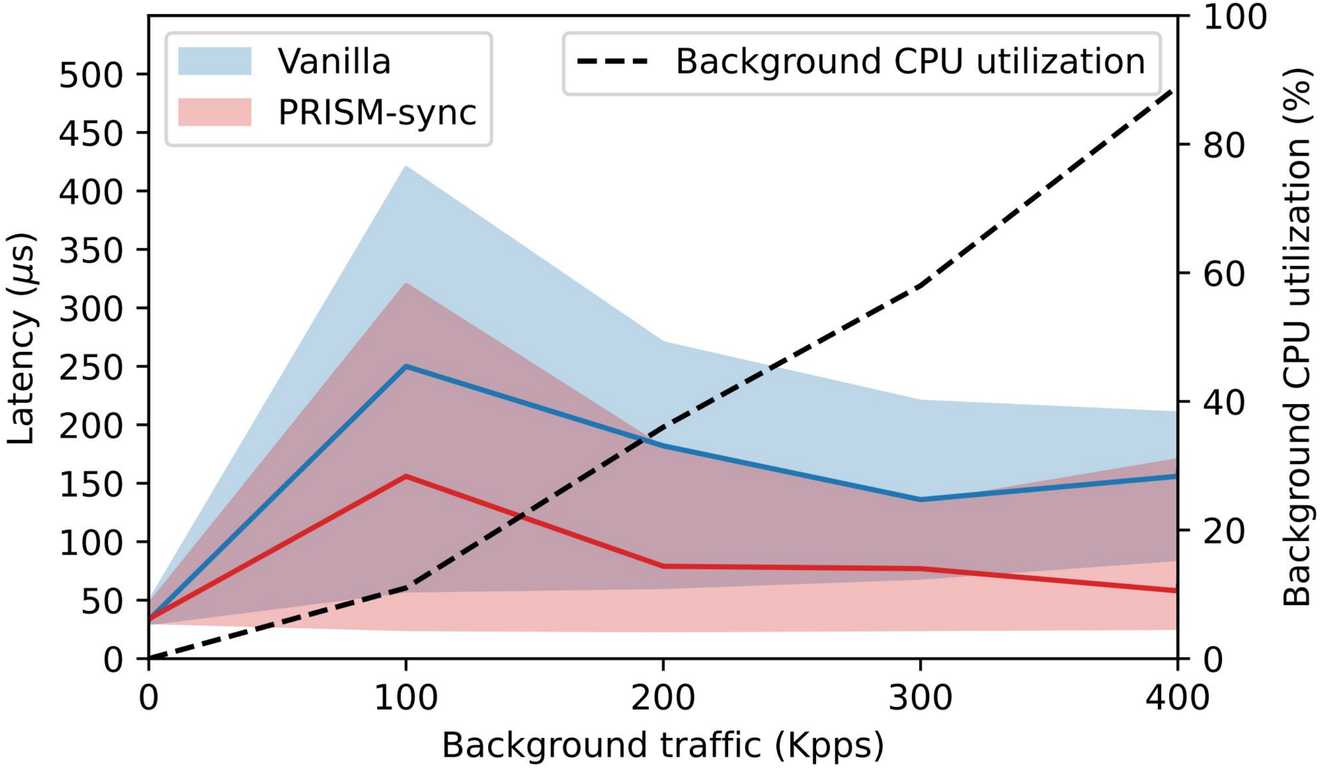
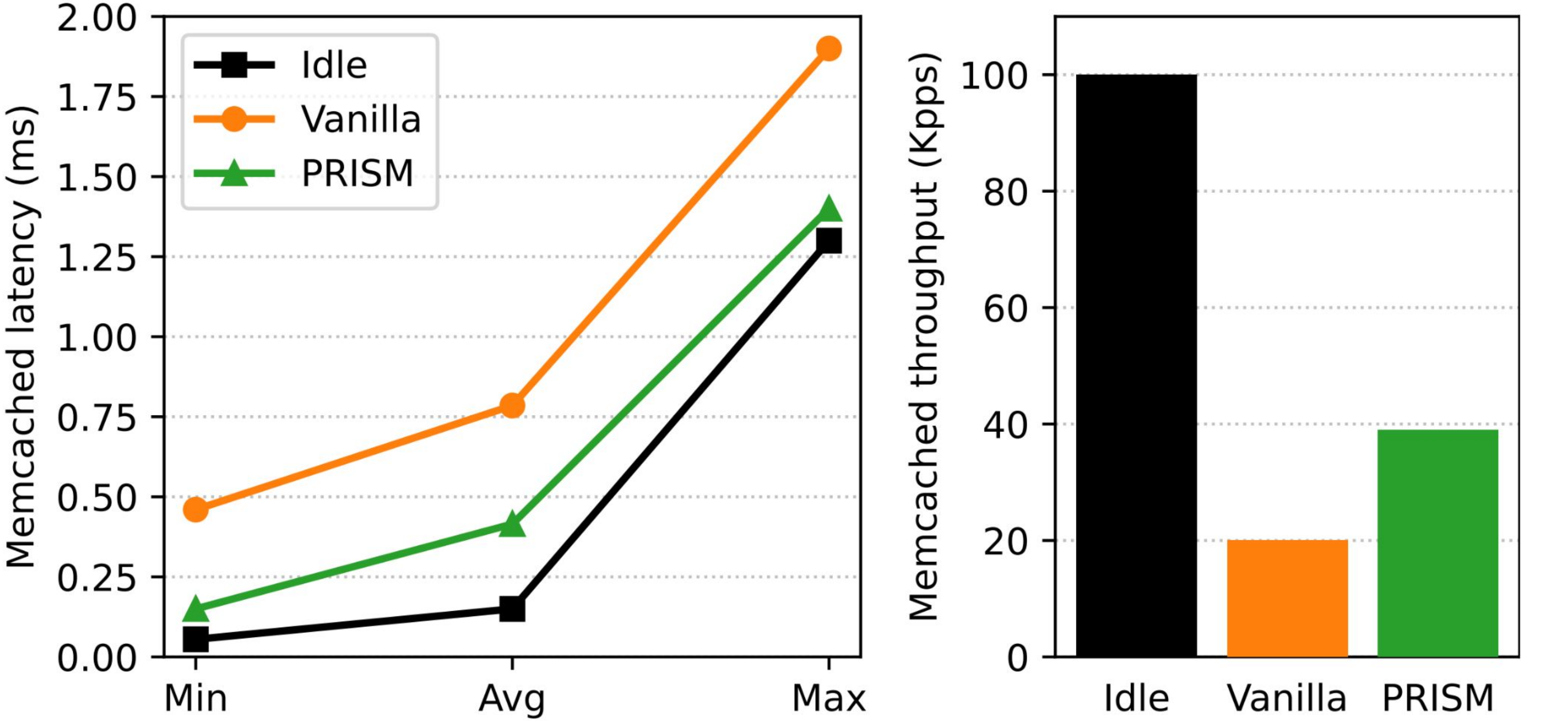
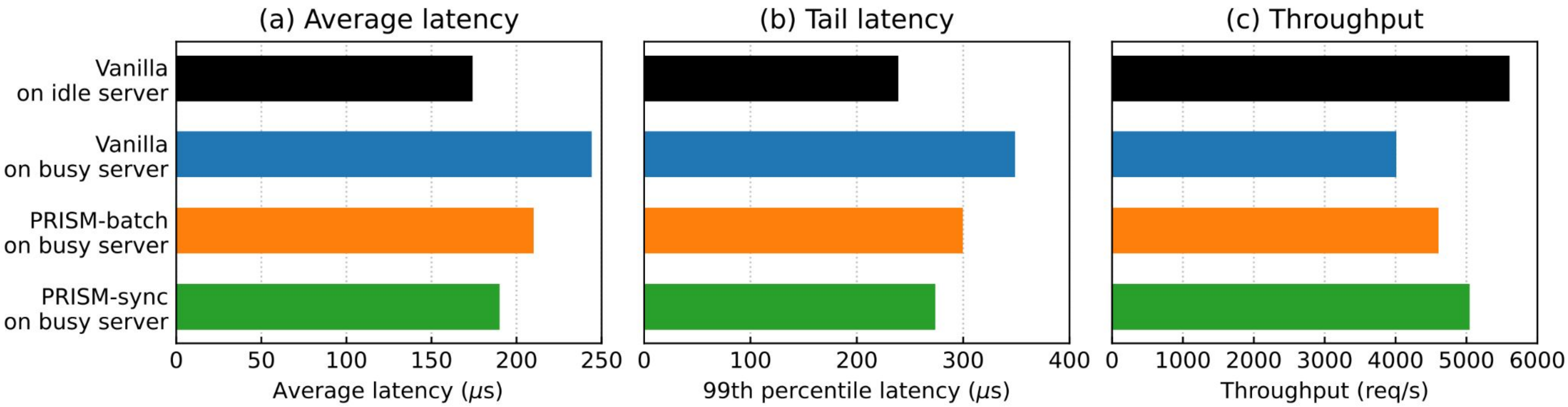


Memcached benchmark



Web serving benchmark



Conclusion

- Linux kernel has many sources of inefficiencies
  - Especially for overlay packet processing
  - Interleaved packet processing logic
  - No support for flow prioritization
- PRISM improves the performance of container flows
  - **Priority-based** packet queue management
  - **Streamlined** multi-stage processing pipeline
  - **Batch-level preemption** or synchronous processing
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For more info, please contact me at manish.munikar@uta.edu.

Backup slides

Background: NAPI

- Interrupt-based packet processing
  - IRQ raised for each packet received by the NIC
  - Good for light load, bad for heavy load
- NAPI
  - Many packets are processed (in batches) after a single interrupt
  - Interrupt-mode for light load
  - Poll-mode for heavy load
- RSS / RPS / RFS
  - Distributes independent flows to separate cores for processing
- Still naive FIFO queueing!
  - High-priority packets can get stuck behind long queues of low-priority packets

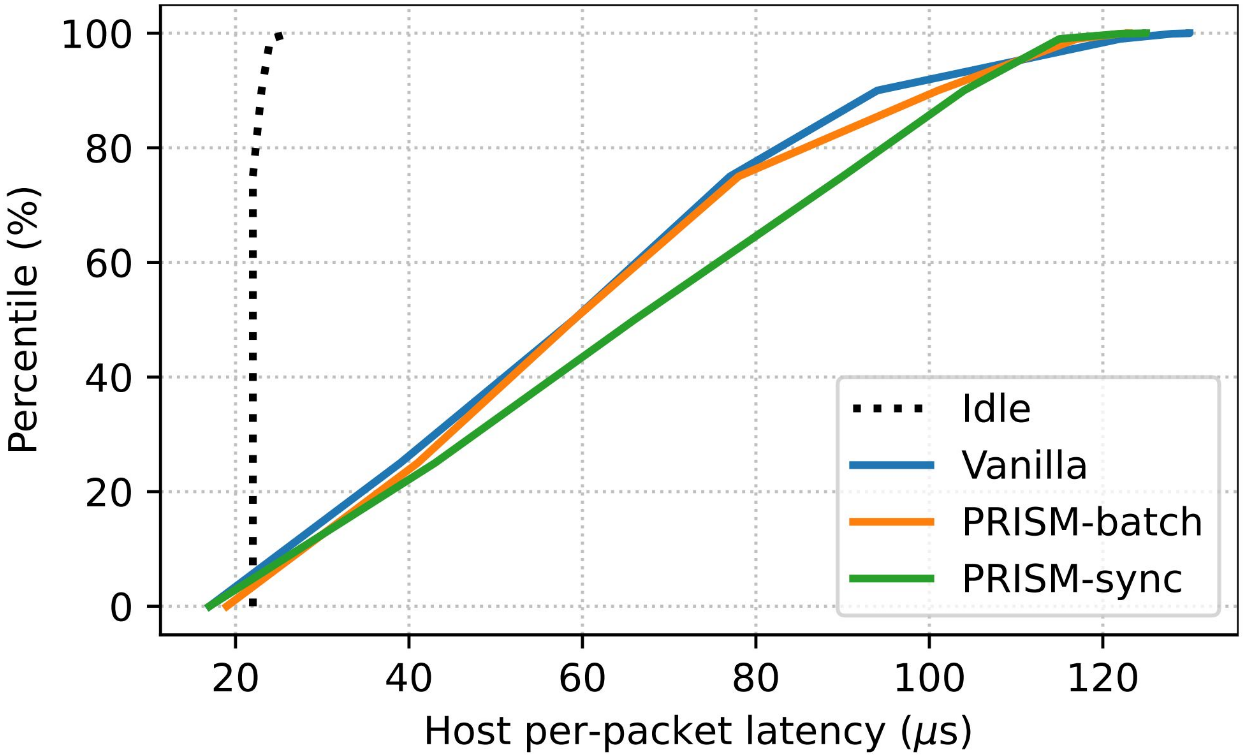
Remaining issues

- Flow prioritization in the NIC queue
- Priority synchronization between user application and network stack
- Multiple priority levels

Why this problem?

- NICs are becoming faster quicker
- CPUs cannot keep up
- OS packet processing logic is becoming performance bottleneck
- Moreover, containers are everywhere
- Containers use container overlay networks
- Container network incurs high overheads
- In a highly utilized system, the high priority messages experience large queueing delays

Microbenchmark — Priority differentiation (host network)


Percentile (%)
Host per-packet latency (μs)
Idle
Vanilla
PRISM-batch
PRISM-sync