SOSP 2024

VPRI: Efficient I/O Page Fault Handling via Software-Hardware Co-Design for IaaS Clouds

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Shared by **Zheng Yang**
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Device pass-through kills memory paging

Pass-through: good I/O performance

But bad for dynamic memory utilization

Software solution: not suitable for IaaS cloud

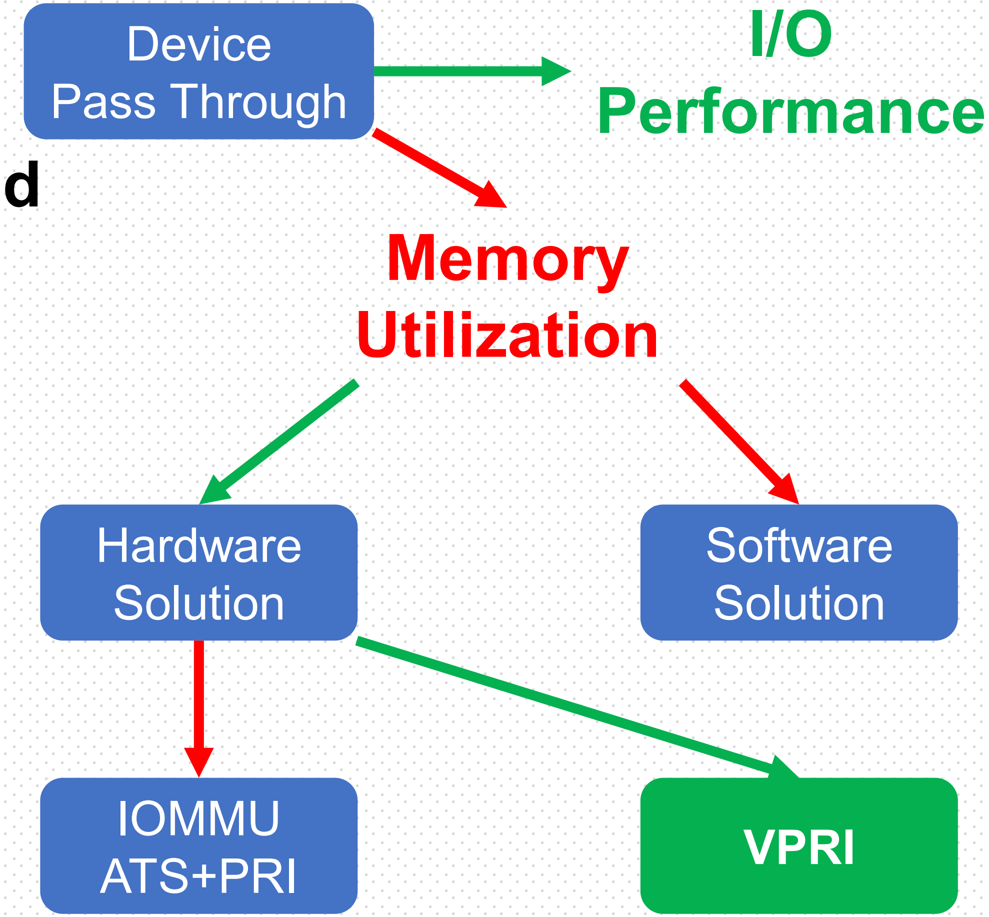
- Para-virtualization
- Guest OS modification and/or performance setback

I/O Page Fault (IOPF): difficult to popularize

- ATS: Address Translation Service
- PRI: Page Request Interface

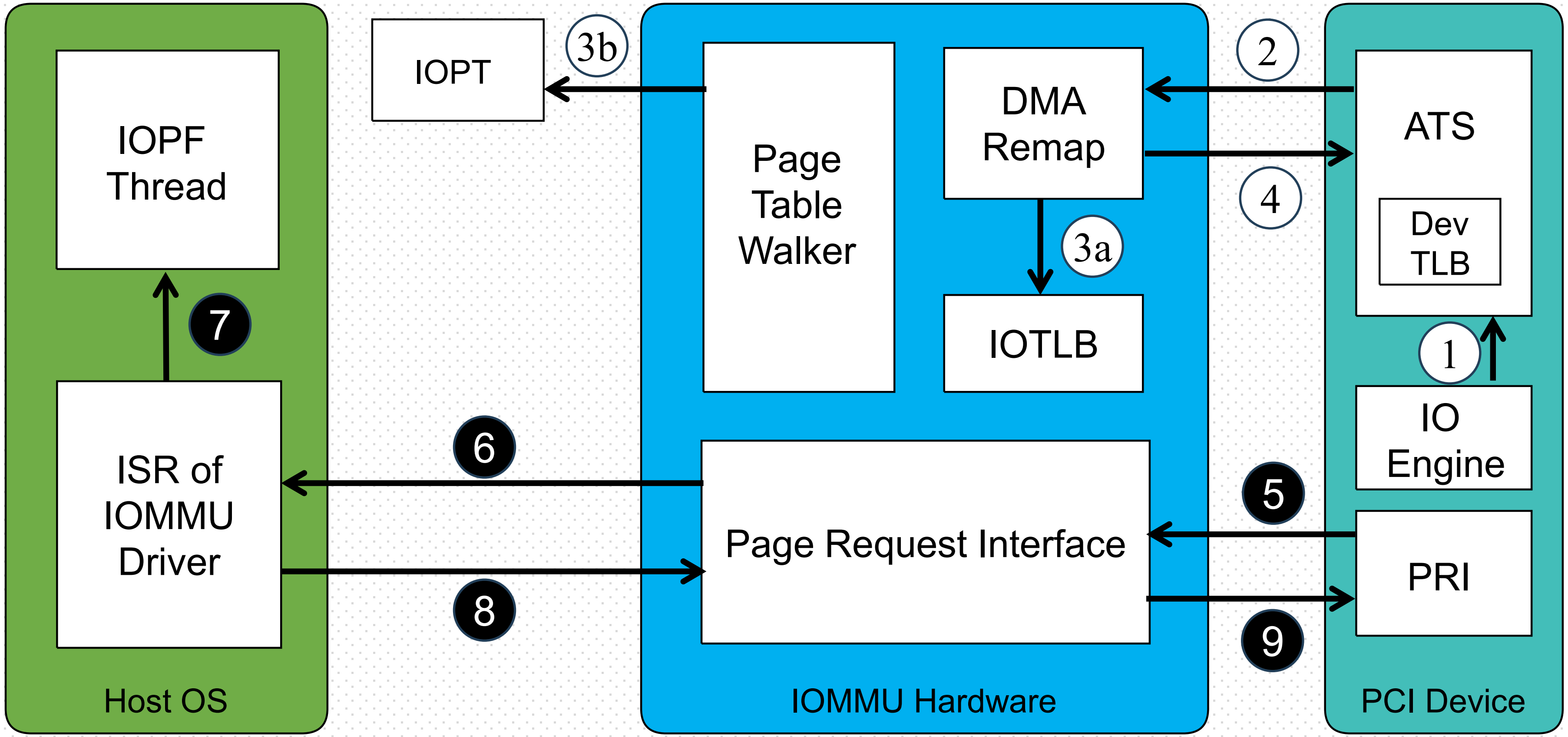
VPRI: Virtualized Page Request Interface

- **Low cost/complexity**
- **Works with existing platforms**
- **Up to 99% reduced IOPFs**



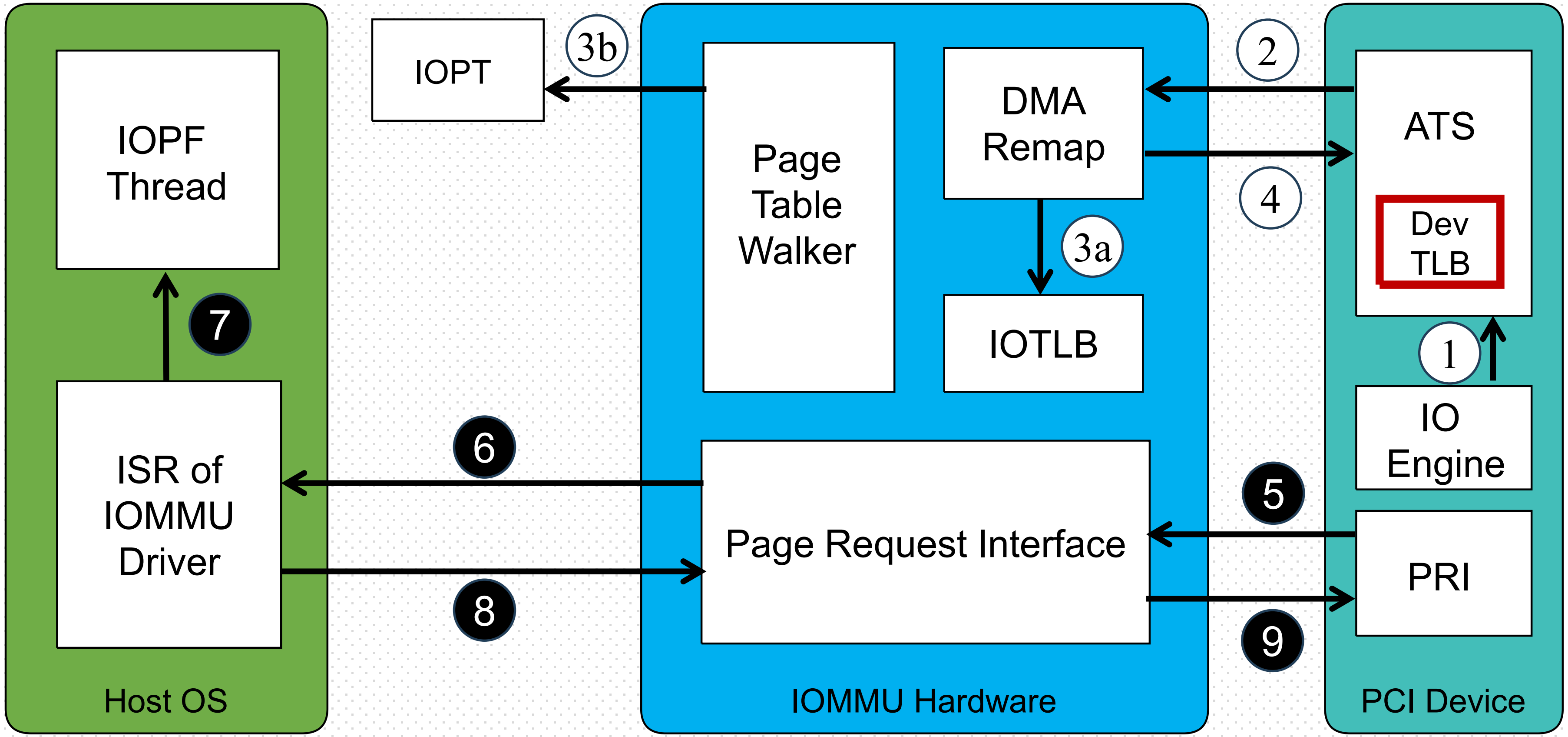
IOPF: IOMMU ATS+PRI

○ Address Translation Service (ATS)   ● Page Request Interface (PRI)



Limitations of IOPF: Standard IOMMU ATS+PRI

1. Device TLB



Limitations of IOPF: Standard IOMMU ATS+PRI

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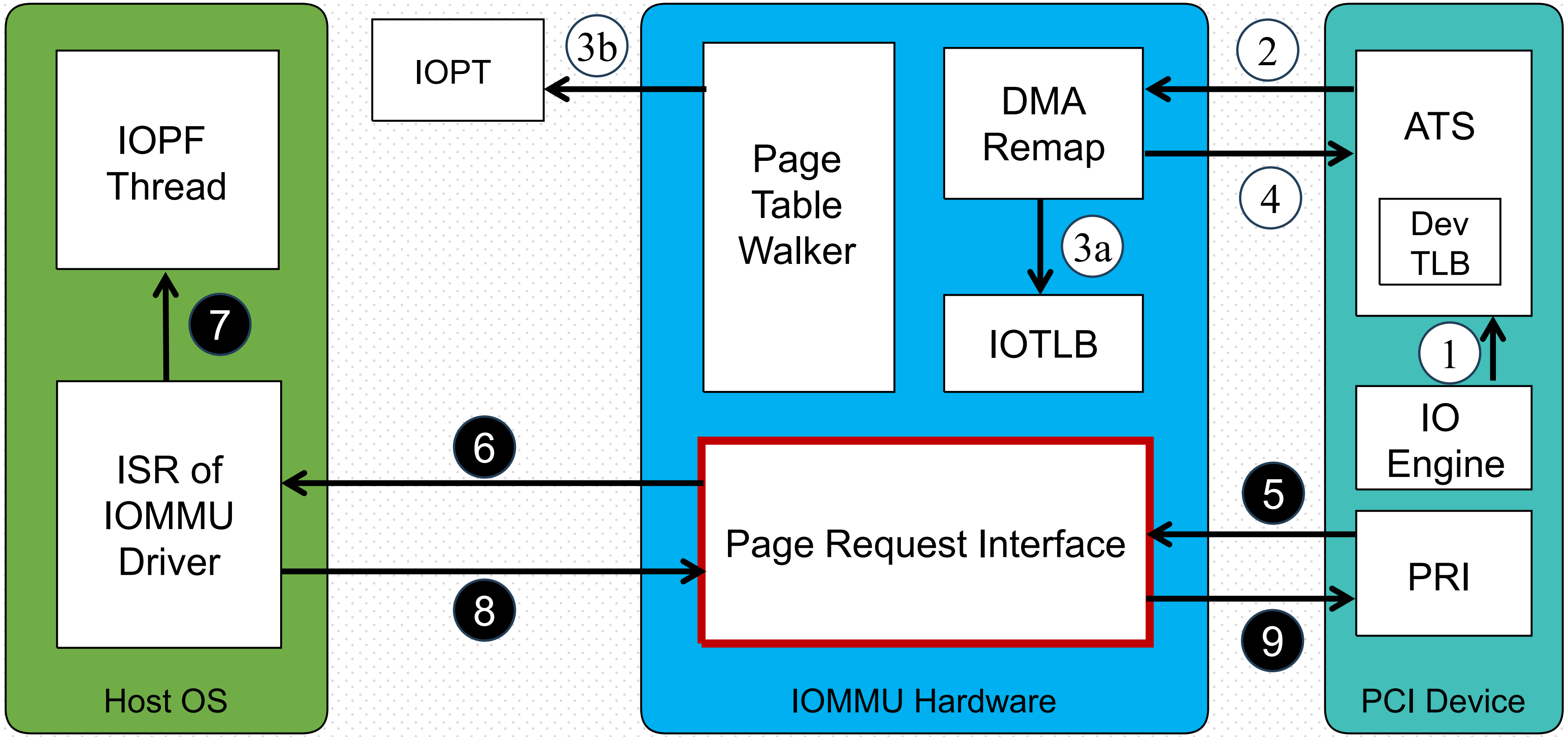
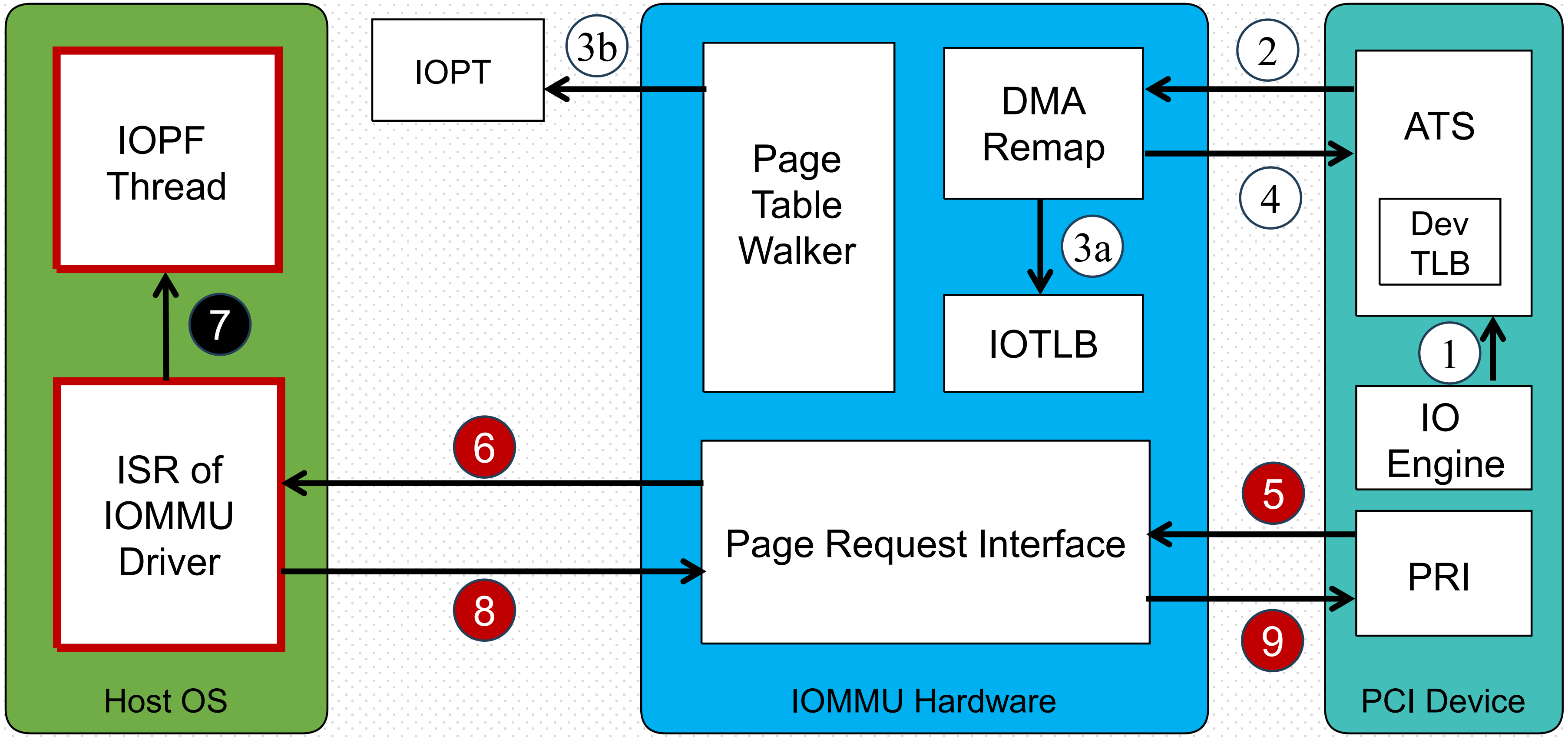
2. Compatibility

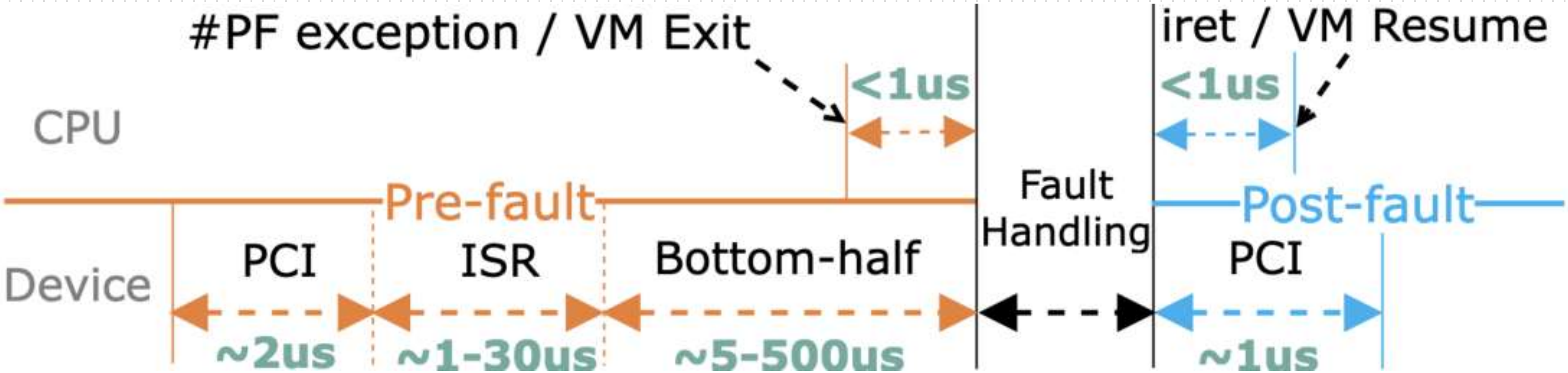


Limitations of IOPF: Standard IOMMU ATS+PRI

1. Device TLB 2. Compatibility 3. Performance



Breakdown of I/O fault v.s. CPU fault



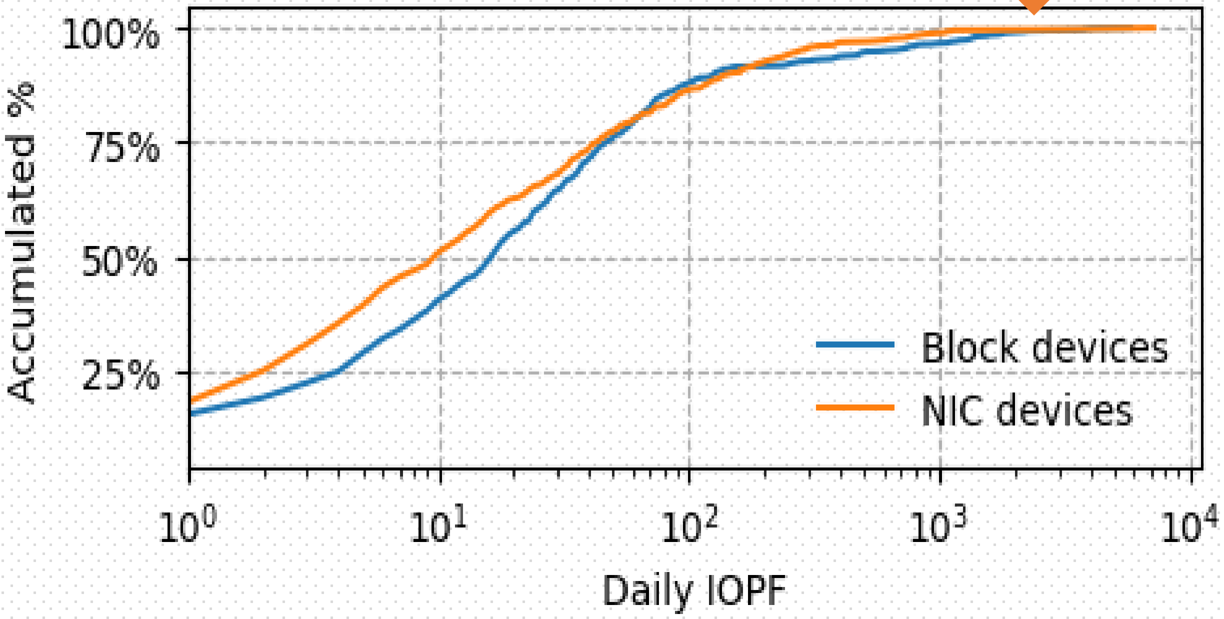
Pre-fault Latency:

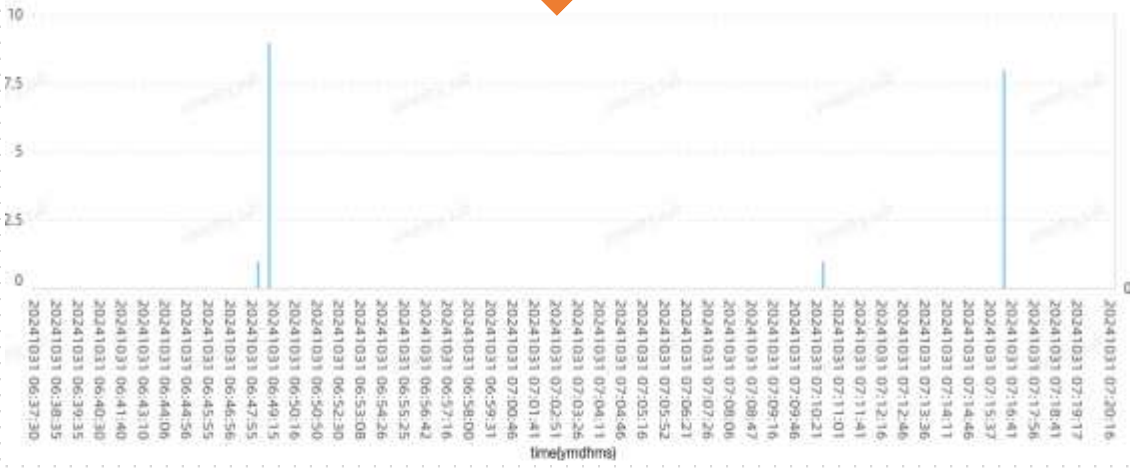
- CPU: < 1us
- I/O: ~10-500 us

Observation of IOPF counts in production

- Block : NIC = 2 : 1
- Variation across VM/devices
- Max count ~3000 per day

- Burst with workloads
- Peak burst IOPF rate > 20/s



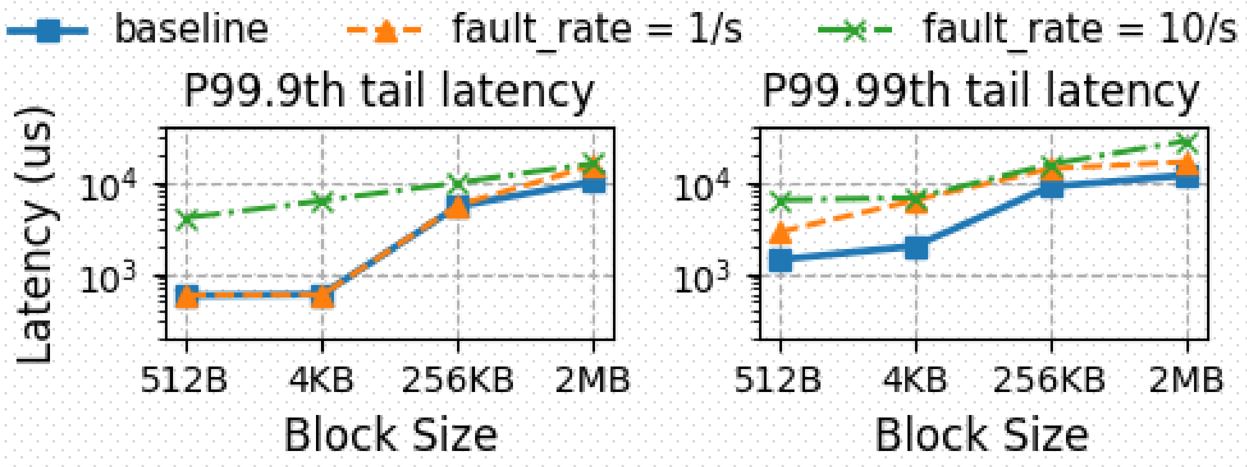


IOPF of a device in 40 minutes

Queue blocked during IOPF handling

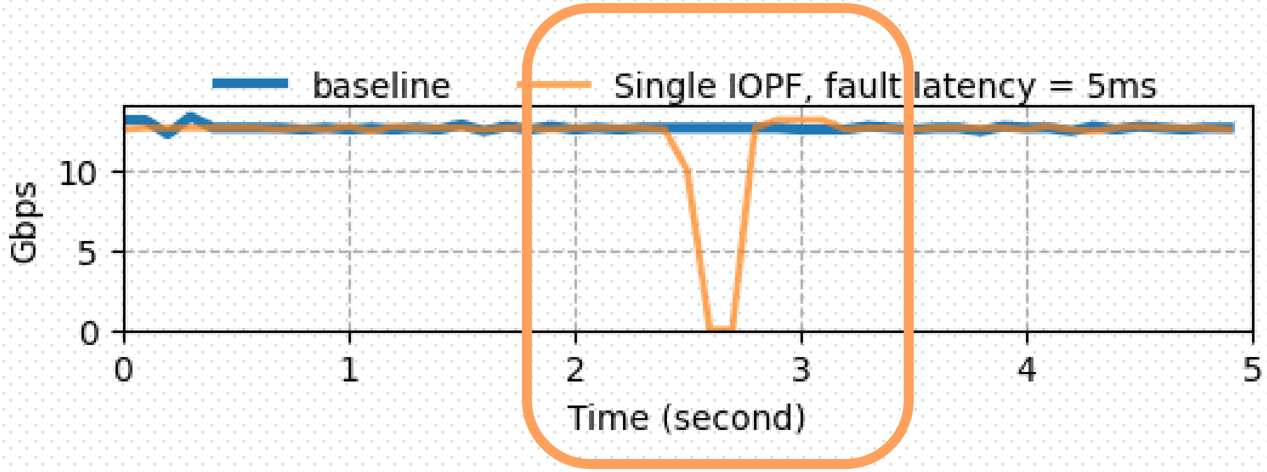
Block devices:

- Hike of long tail I/O
- P99.9TH: hike @ fault rate of 10/s
- P99.99th: hike @ fault rate of 1/s



NIC devices:

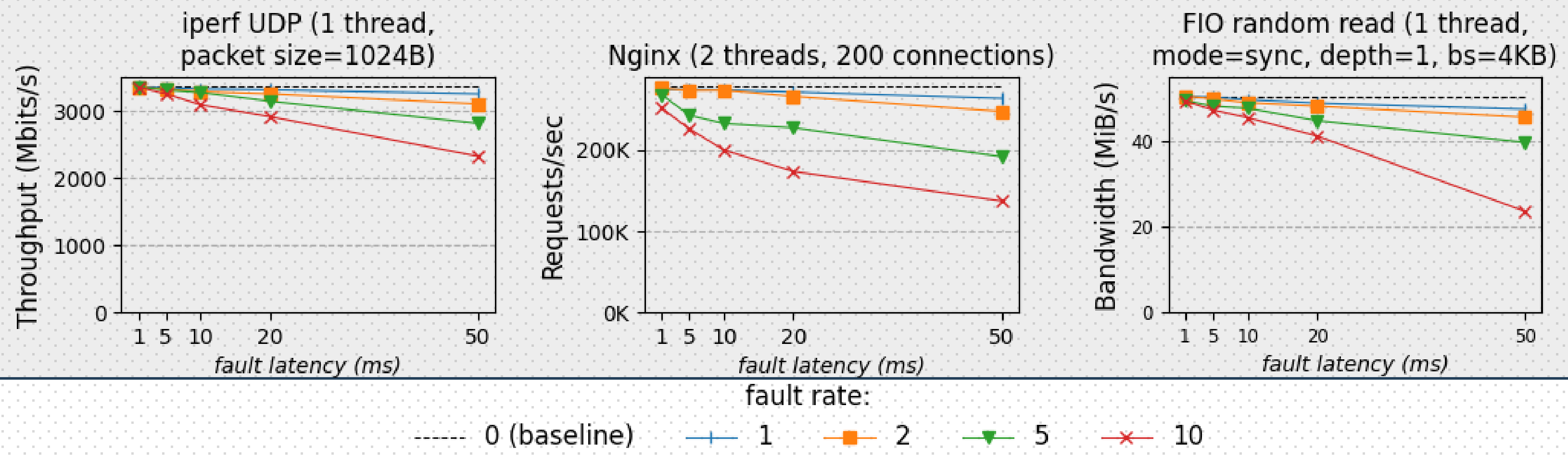
- Packet drop
- Retransmission
- Service interruption



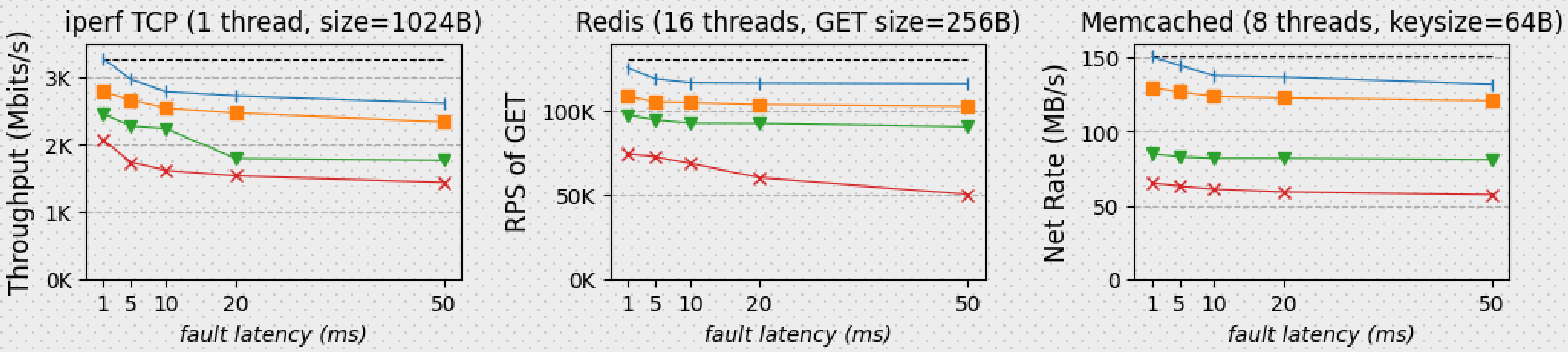
300 ms!

Evaluation: impact to workloads

Non-TCP Workloads



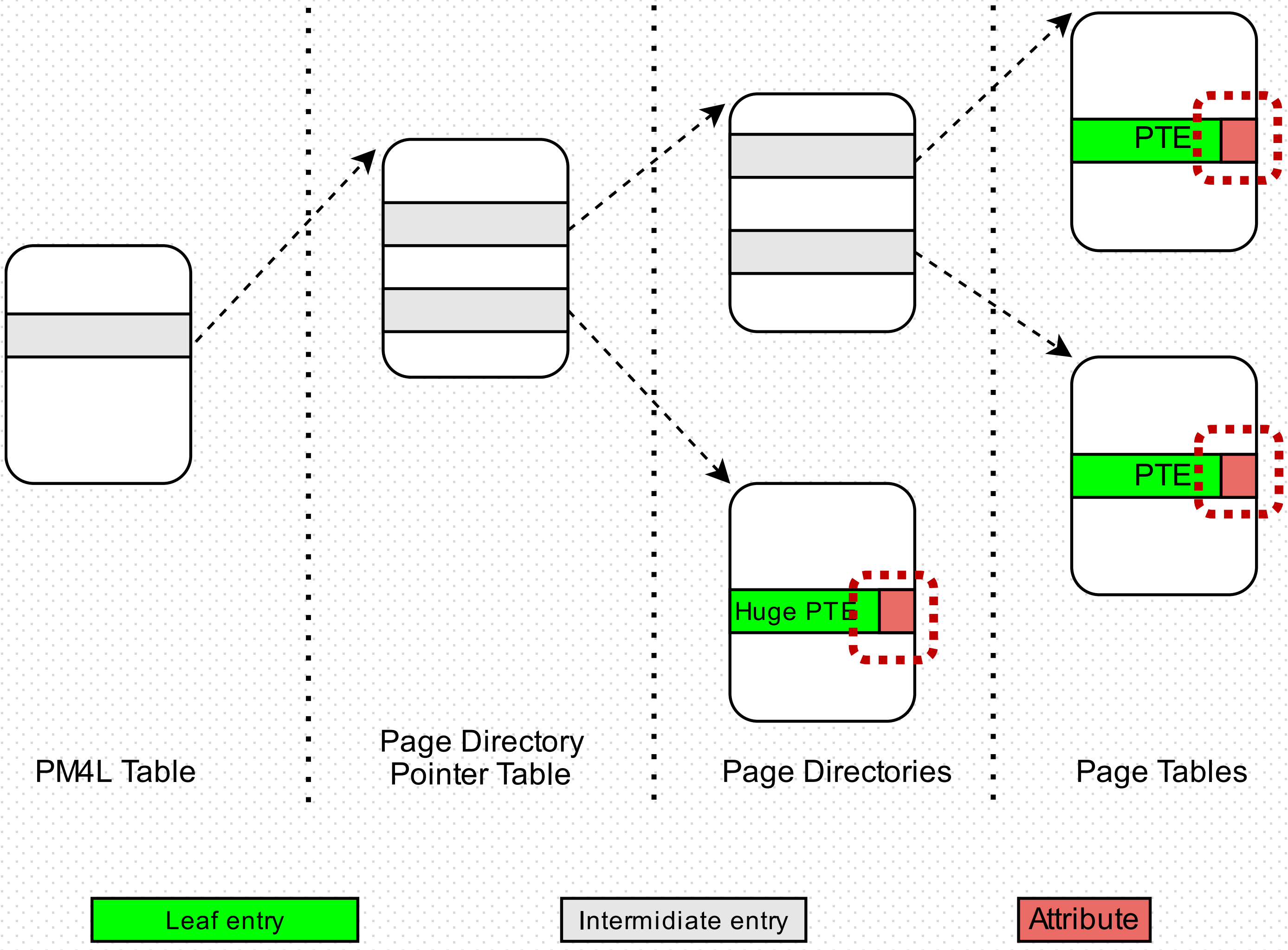
TCP Workloads



Design Goal

Problem	Design Goal	Solution
Fault detection needs ATS	No ATS/MMU in detecting faults	???
Fault reporting needs PRI	No PRI in reporting faults	???
Performance impact of IOPF	Reduce the rate	???

Challenge #1: fault detection



- Page tables are huge
- But attributes are small (2 bits)

- Page walk is costly
- But fault detection can be simple

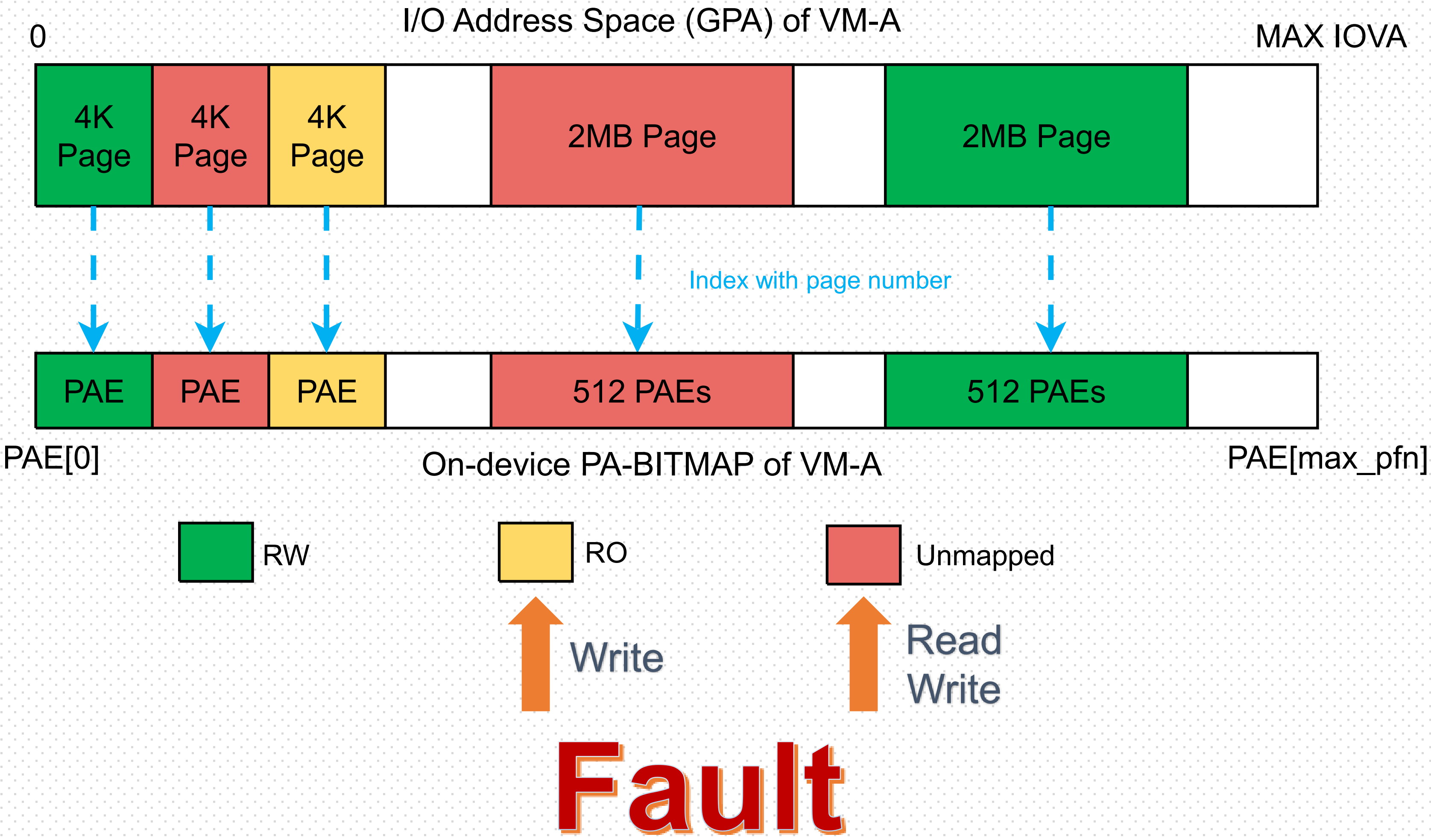
PA-BITMAP: Coherent on-device page attributes bitmap

Page Attribute Entry (PAE):

❑2 bits per PAE

❑4KB GPA/IOVA per PAE

❑On-device memory



I/O Address Space (GPA) of VM-A

0

MAX IOVA

4K Page

4K Page

4K Page

2MB Page

2MB Page

Index with page number

PAE

PAE

PAE

512 PAEs

512 PAEs

PAE[0]

On-device PA-BITMAP of VM-A

PAE[max_pfn]

🟩 RW

🟨 RO

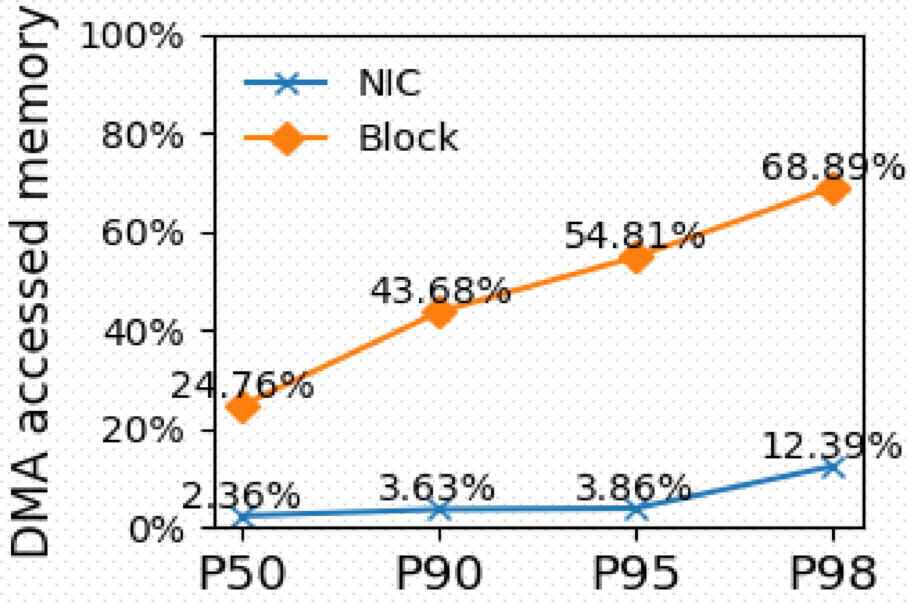
🟥 Unmapped

Write

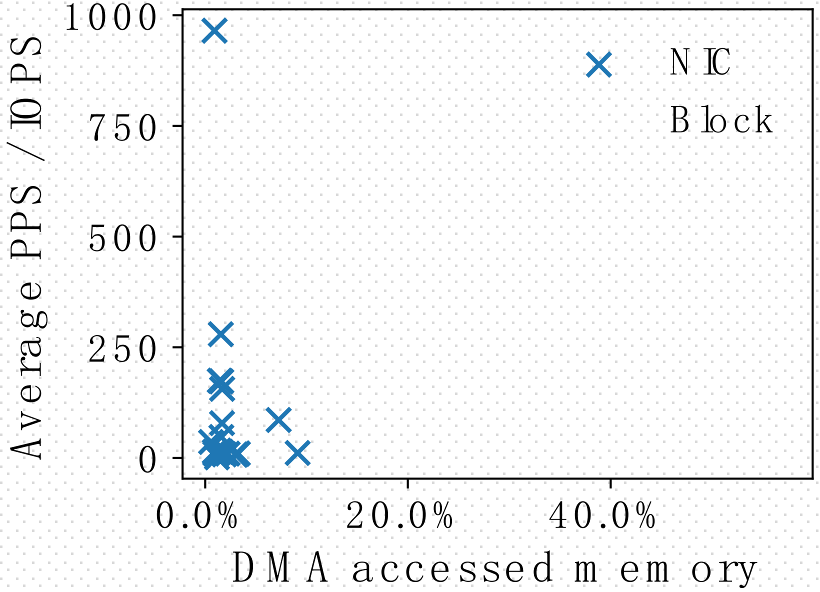
Read
Write

Fault

Challenge #2: reduce IOPF rates



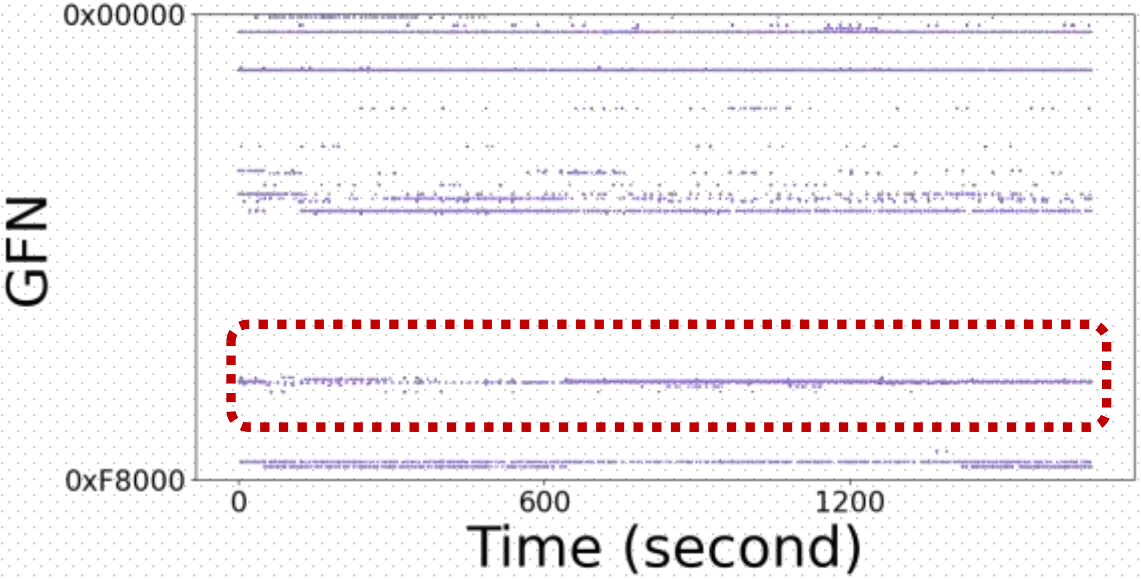
Footprints distribution in 30 minutes

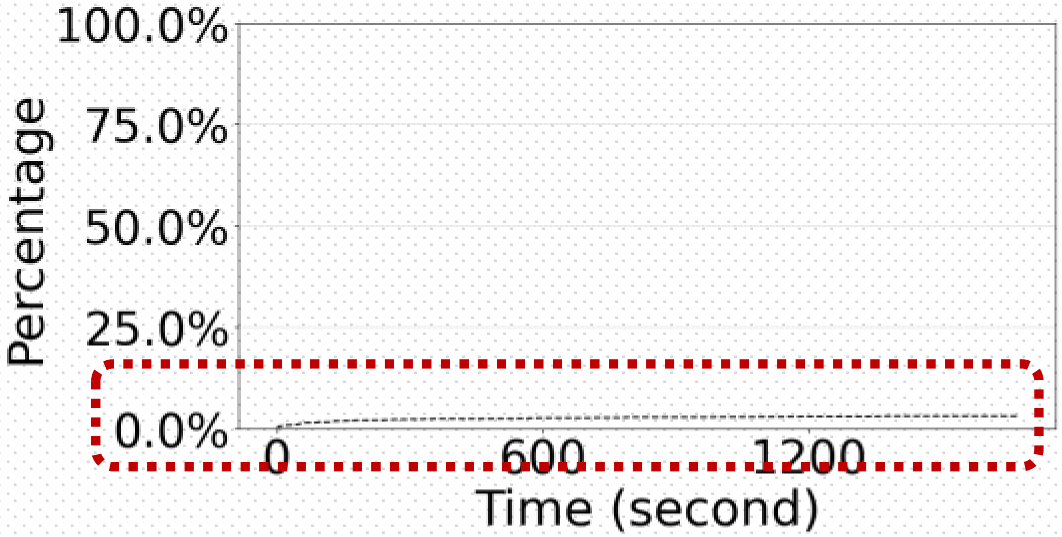


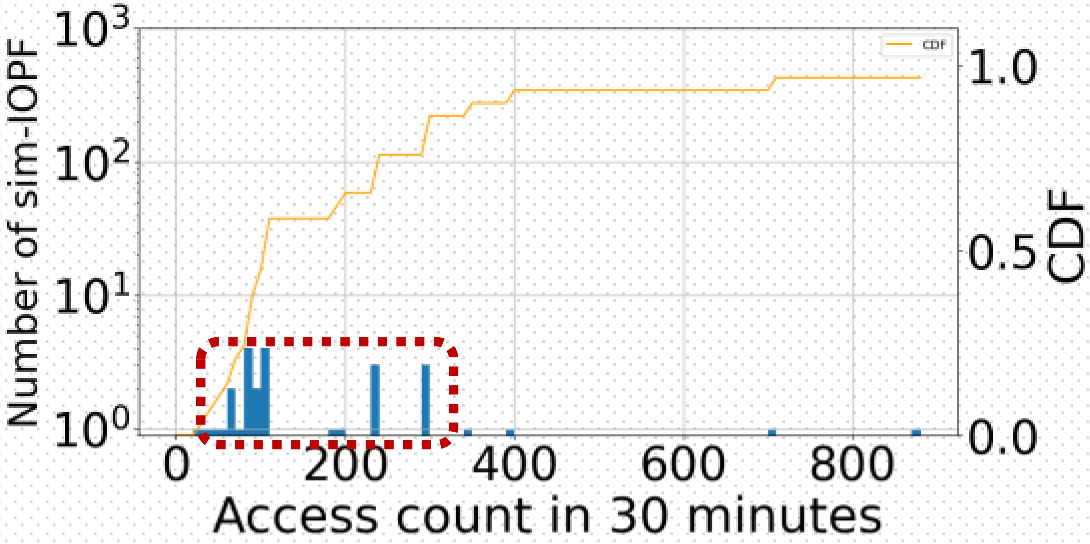
Footprints distribution in 30 minutes

Challenge #2: NIC characterization

- (Almost) bounded buffer
- Very strong temporal locality
- High return by pinning with LRU

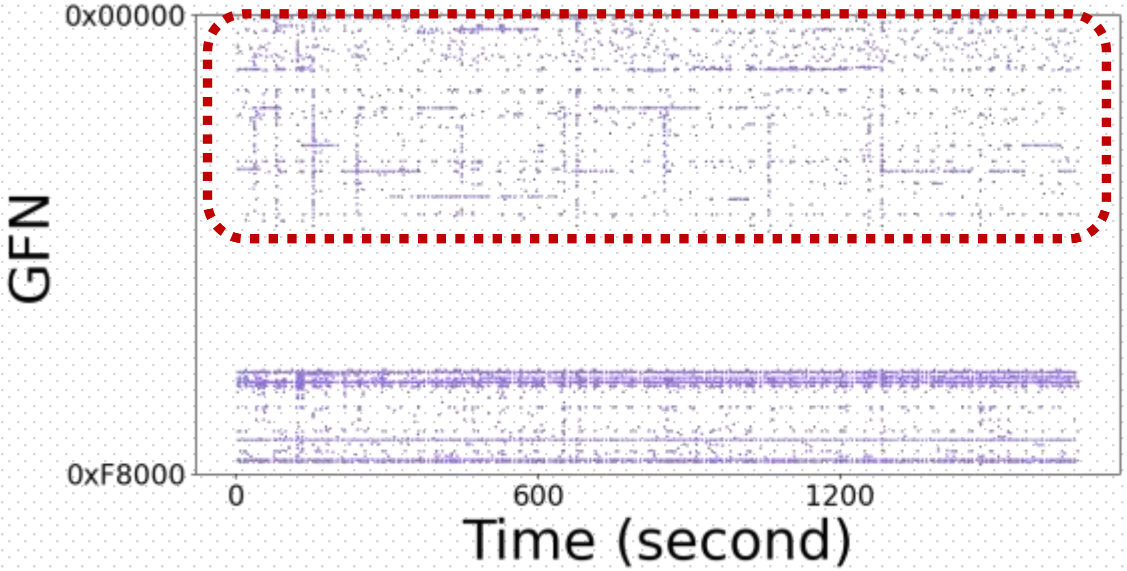


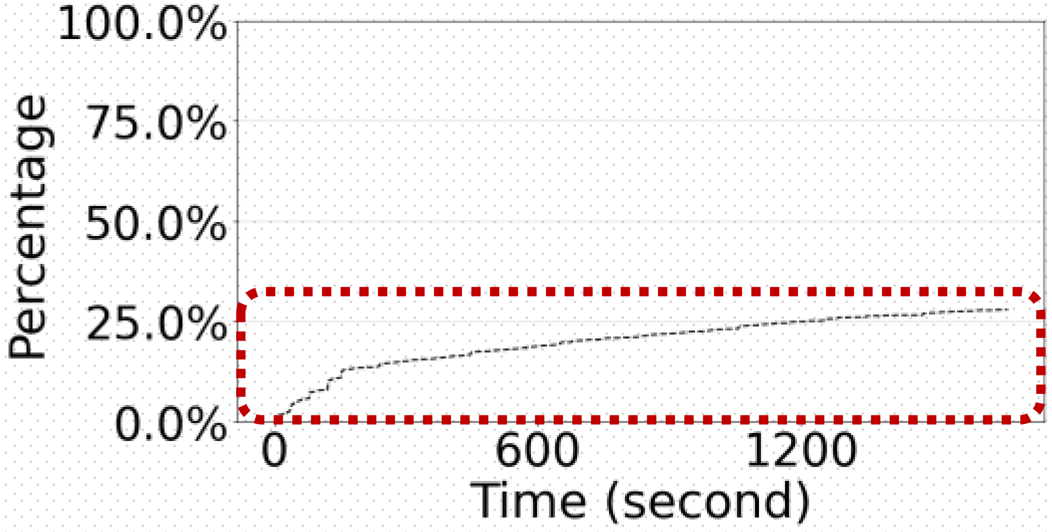


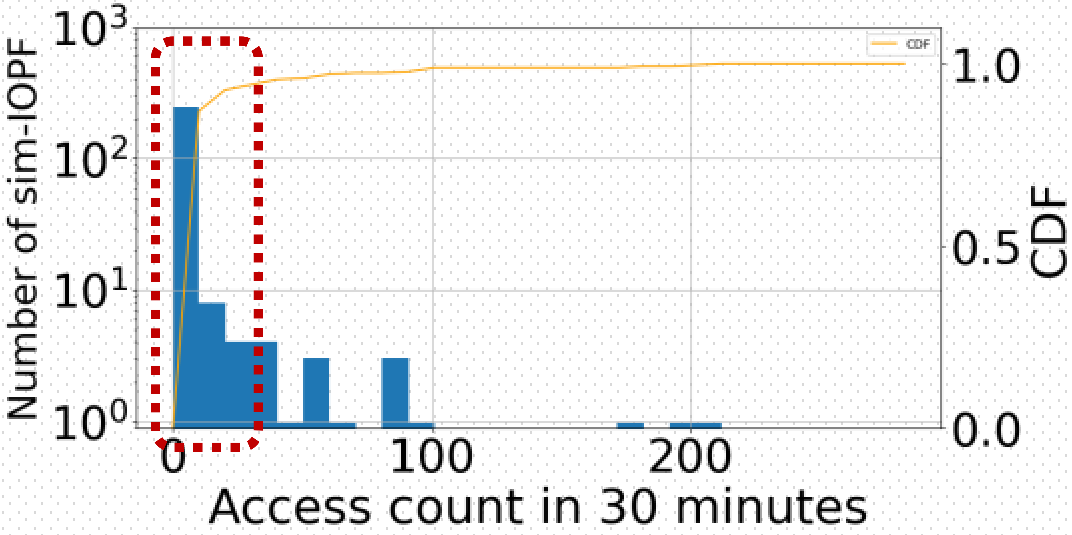


Challenge #2: Storage characterization

- Unbounded buffer (page cache)
- Weaker temporal locality
- >70% page will be visited > twice
- Long access distance







Key Takeaways

PA-BITMAP:

Break dependency on ATS

Customized PCIe interface:

Break dependency on PRI

DMA access tracking:

Device level

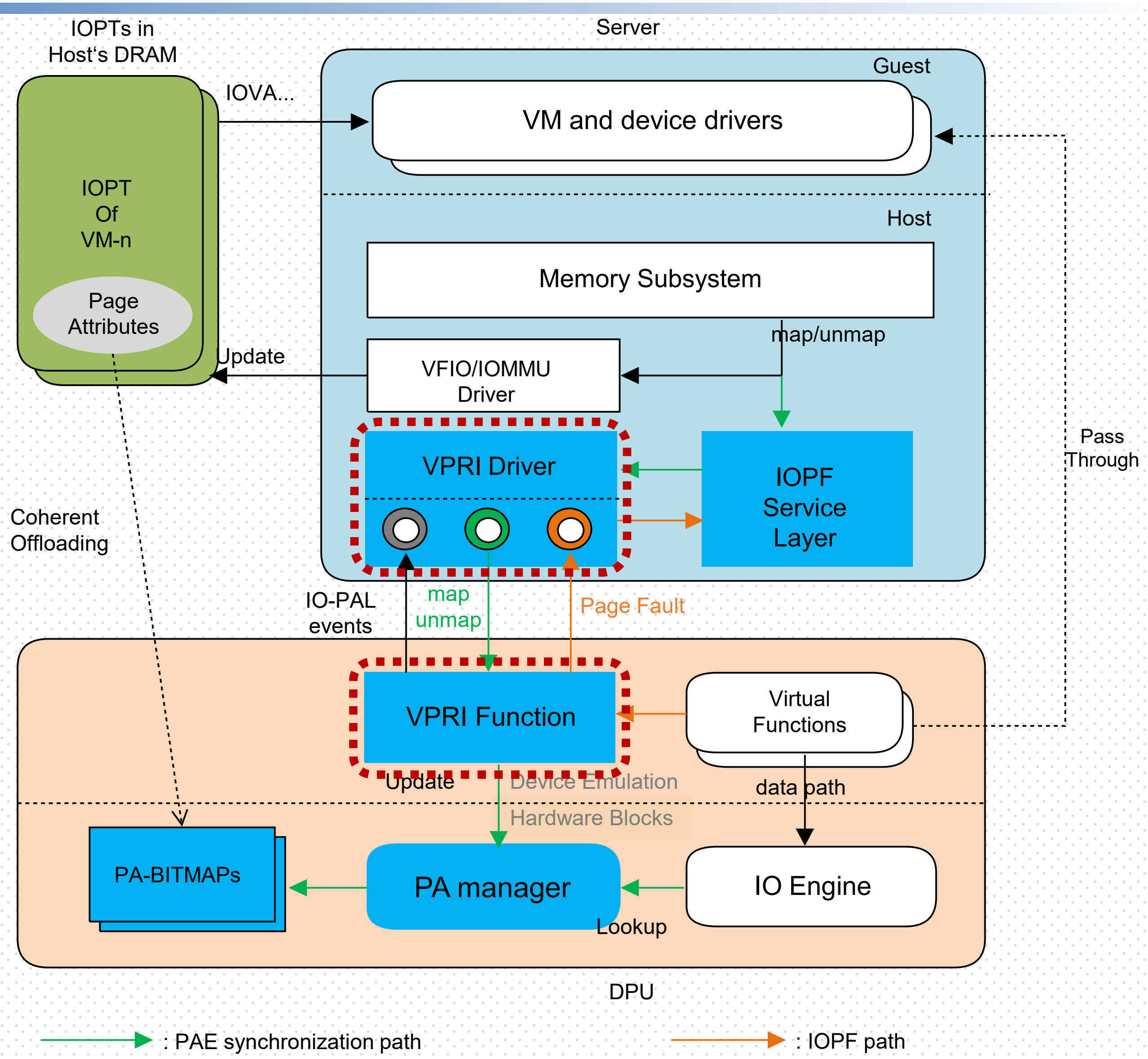
Gap in today’s hardware

Software pinning policy:

Minimum pin ratio

Maximum IOPF reduction ratio

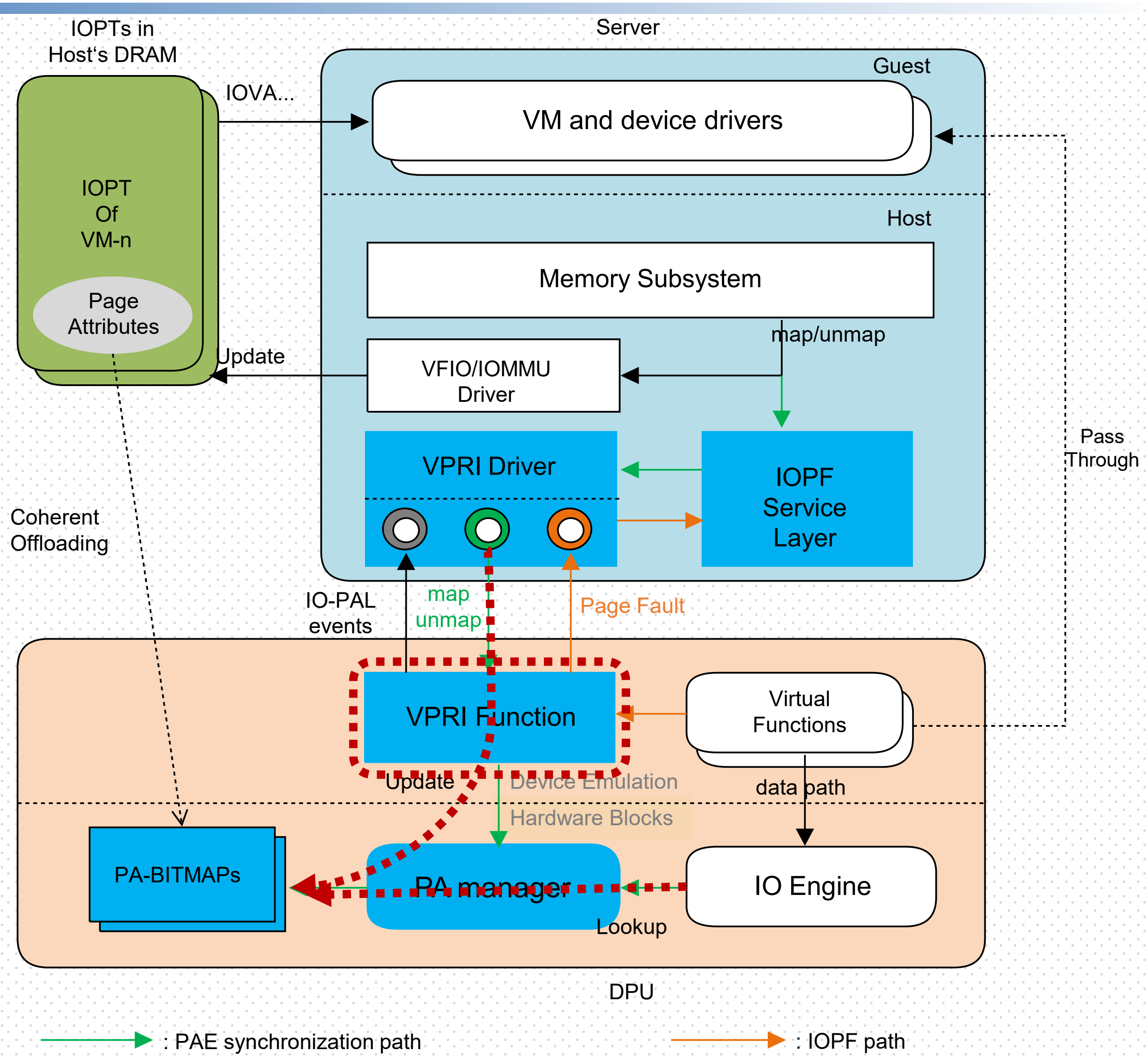
VPRI Hardware Overview



VPRI Hardware Overview

Fault detection:

- On-device PA-BITMAP
- Free from ATS



VPRI Hardware Overview

Fault detection:

- On-device PA-BITMAP
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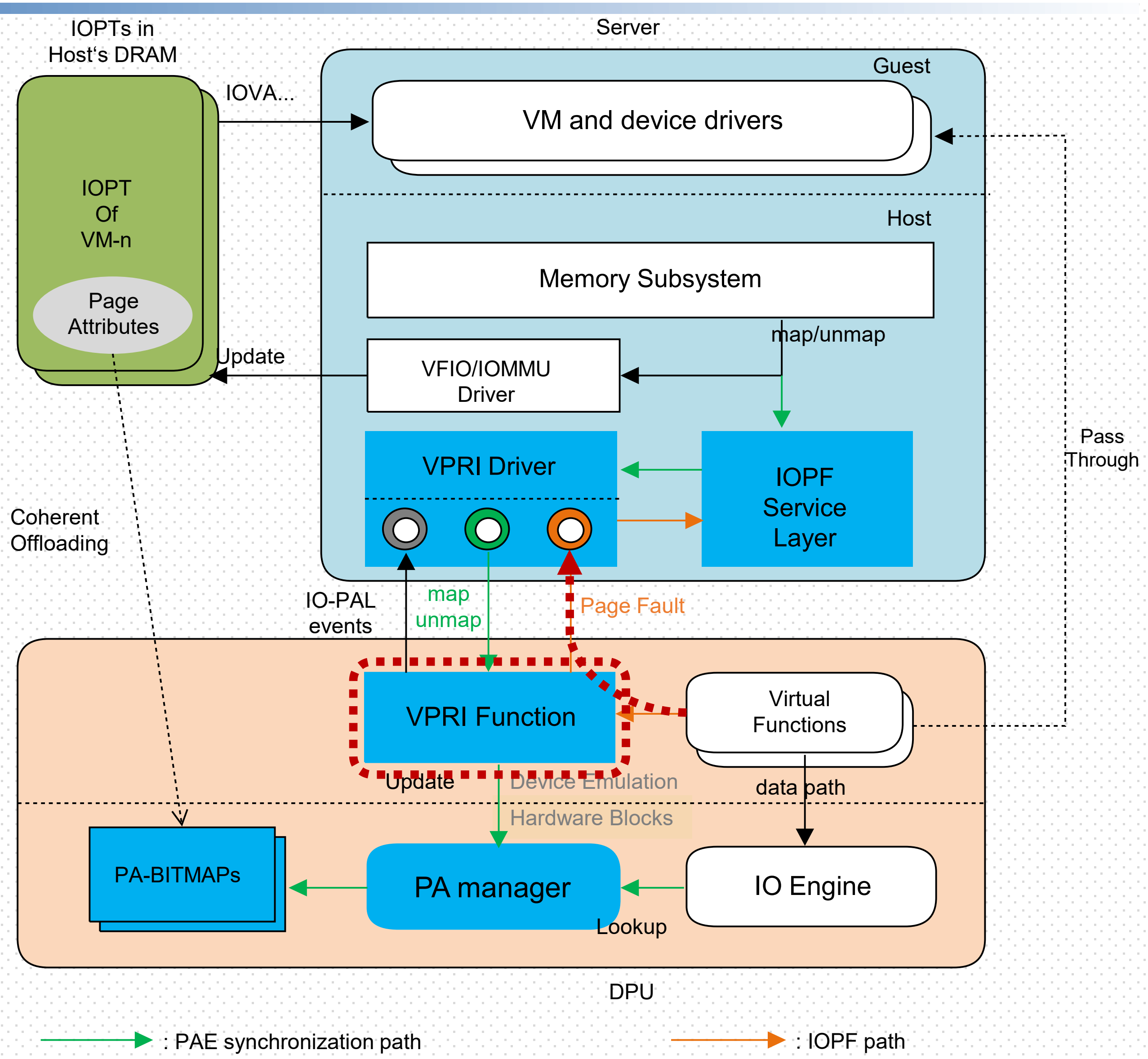
Fault reporting:

- Sideband channel
- Free from PRI



VPRI Hardware Overview

Fault detection:

- On-device PA-BITMAP
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Fault reporting:

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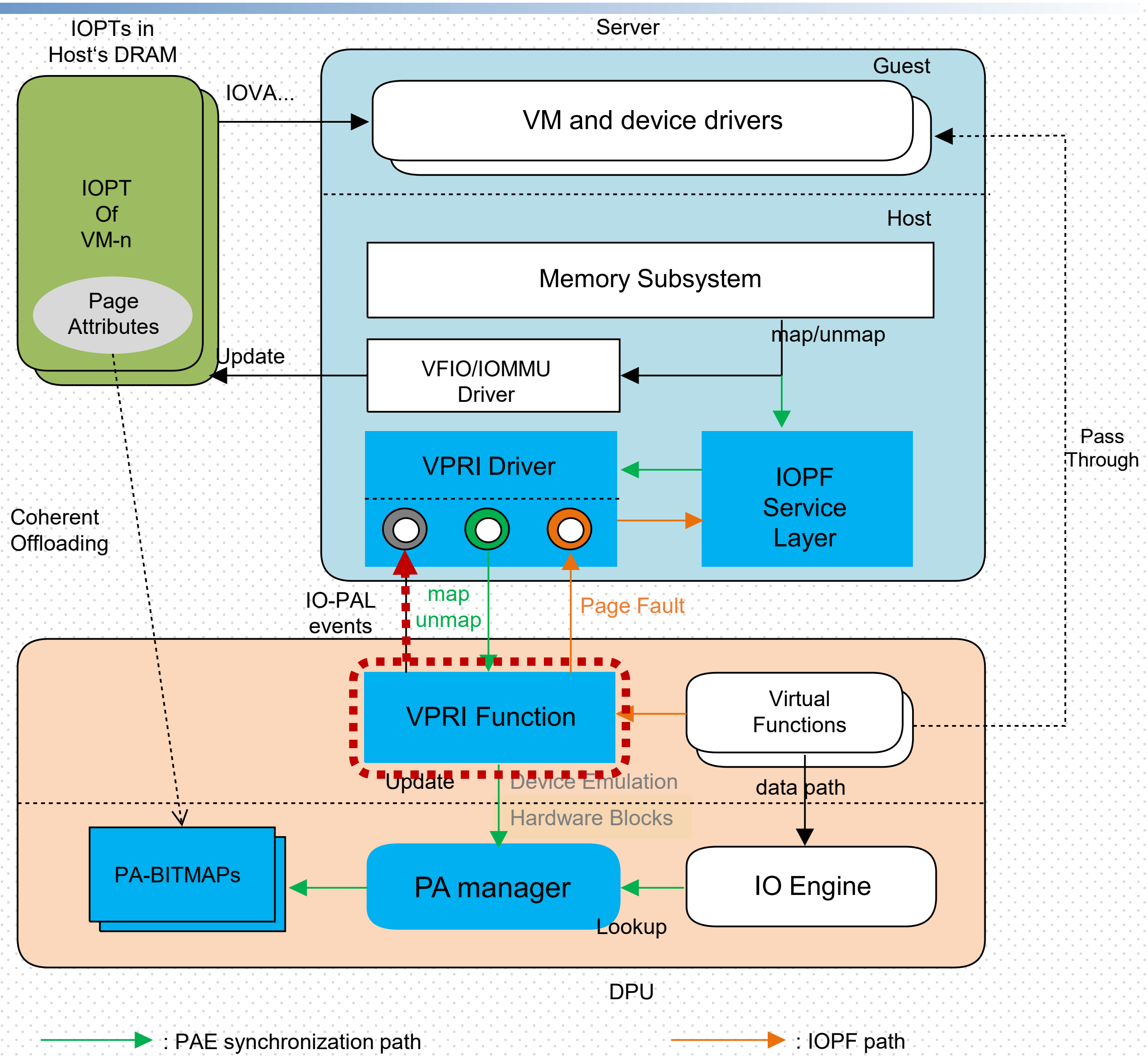
- Free from PRI

Performance opt:

- NIC: > 95% reduction
- Block: > 50% reduction



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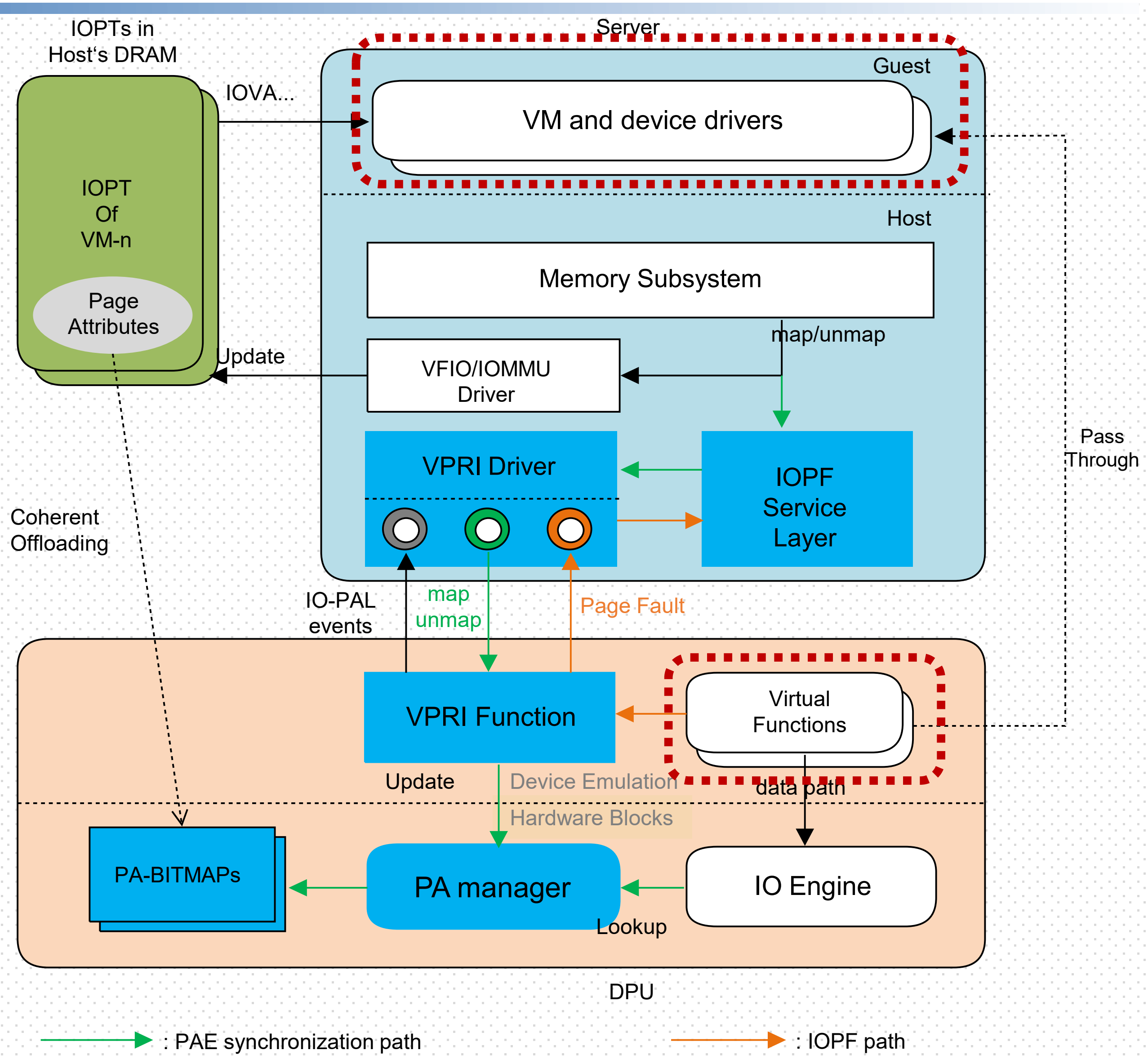
Zero changes to VM:

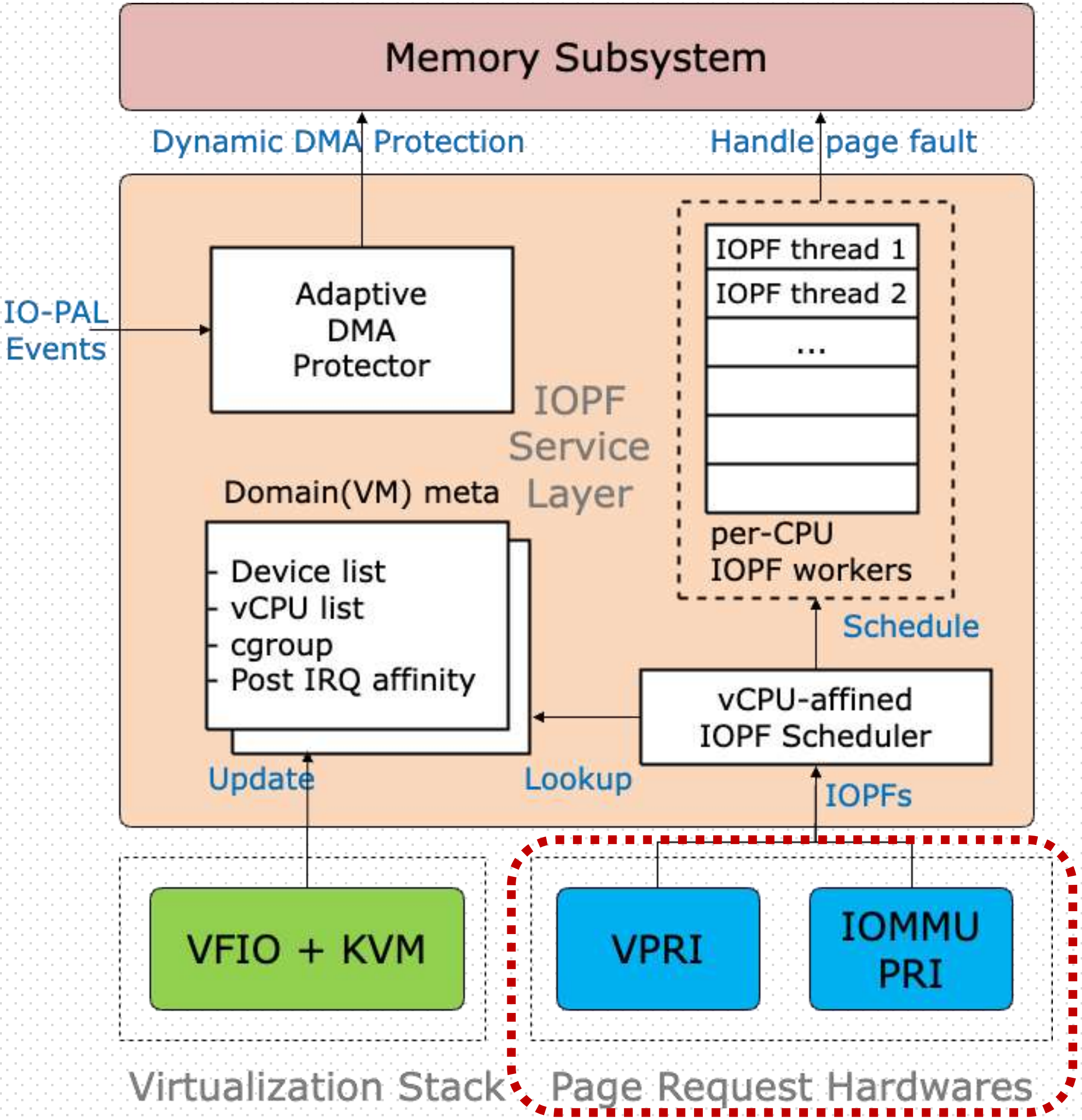
- Device
- Driver



VPRI Software Overview

IOPF HW Abstraction Layer:

- VPRI driver
- IOMMU PRI driver



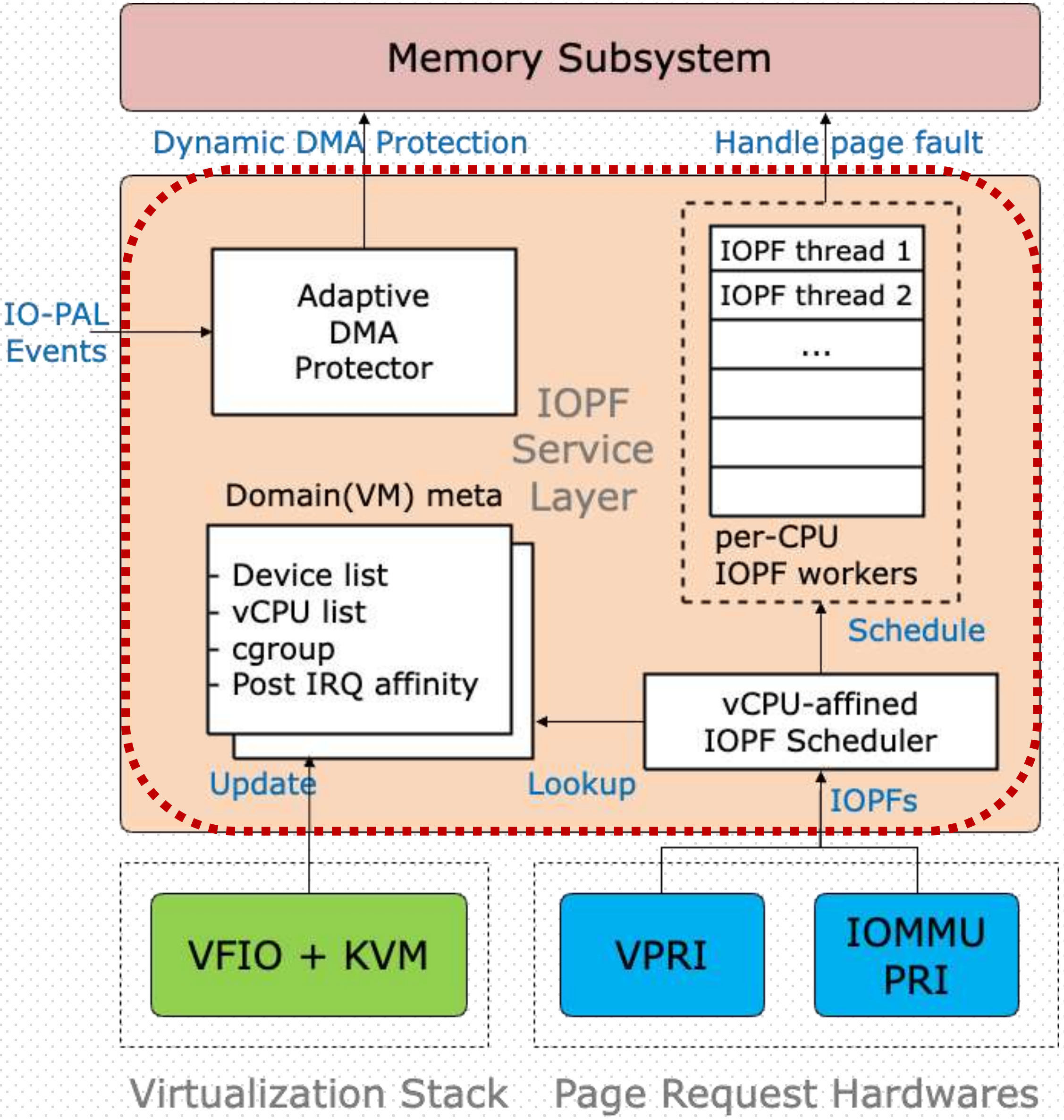
VPRI Software Overview

IOPF HW Abstraction Layer:

- VPRI driver
- IOMMU PRI driver

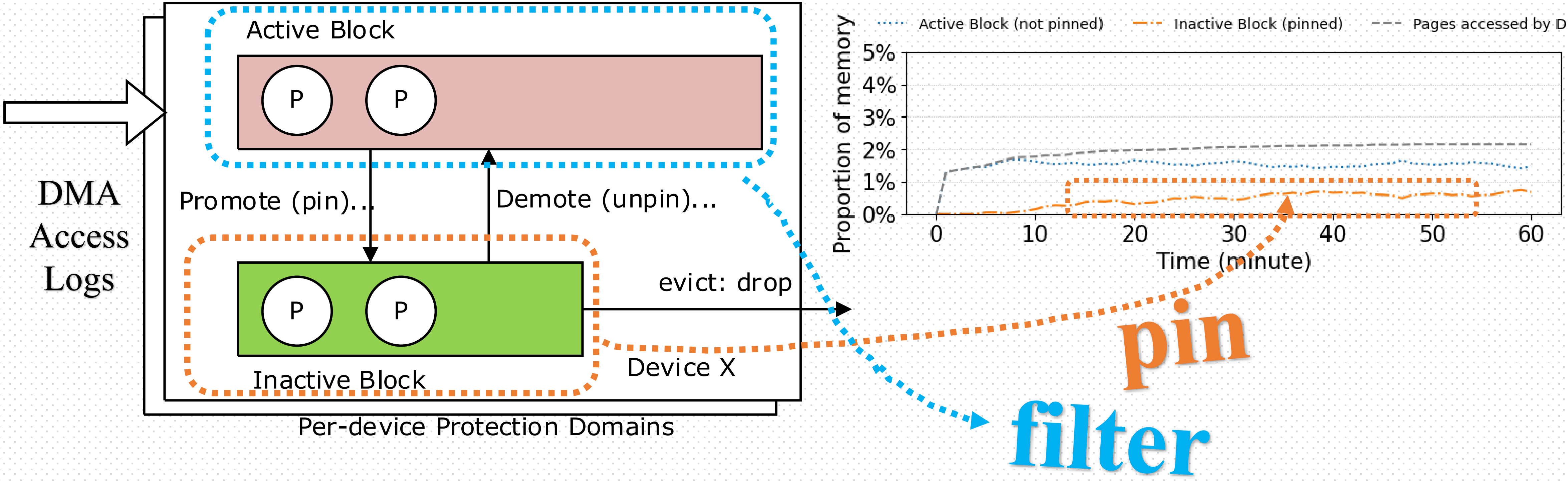
IOPF Service Layer:

- Device-domain mapping
- vCPU-affined IOPF scheduling
- Fault handling
- Adaptive DMA Protector



ADP: Adaptive DMA Protector

- **Active DMA pages are not likely to be swapped out.**



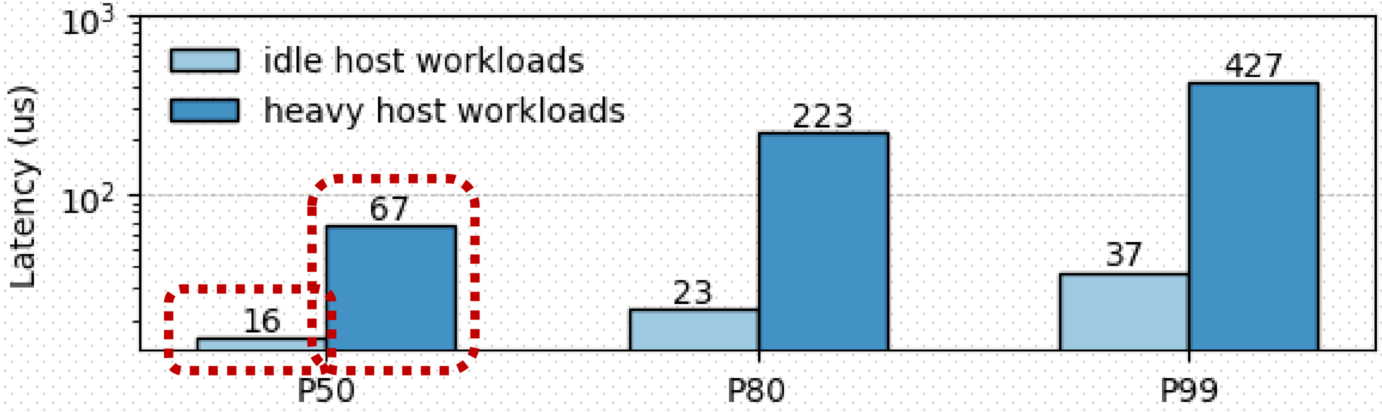
- **(Temporarily) Inactive DMA pages are more prone to IOPF**

Evaluation: Hardware

Bitmap

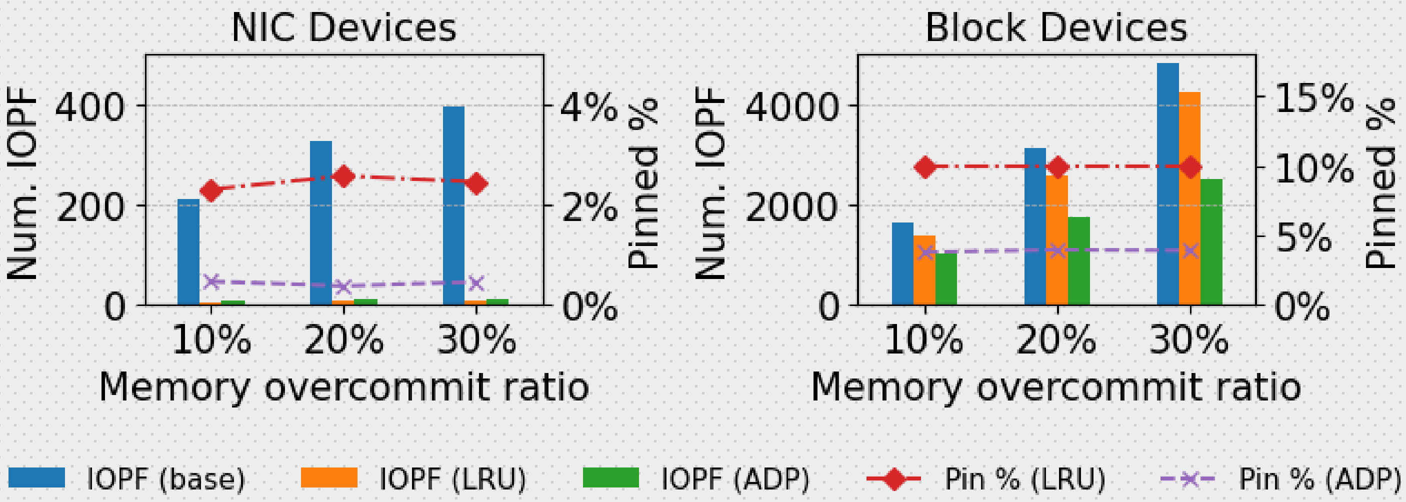
Metric	On-device lookup (ns)	Host update (ns)
Avg.	69	1,742
P99th	92	2,341

Page Fault RTT

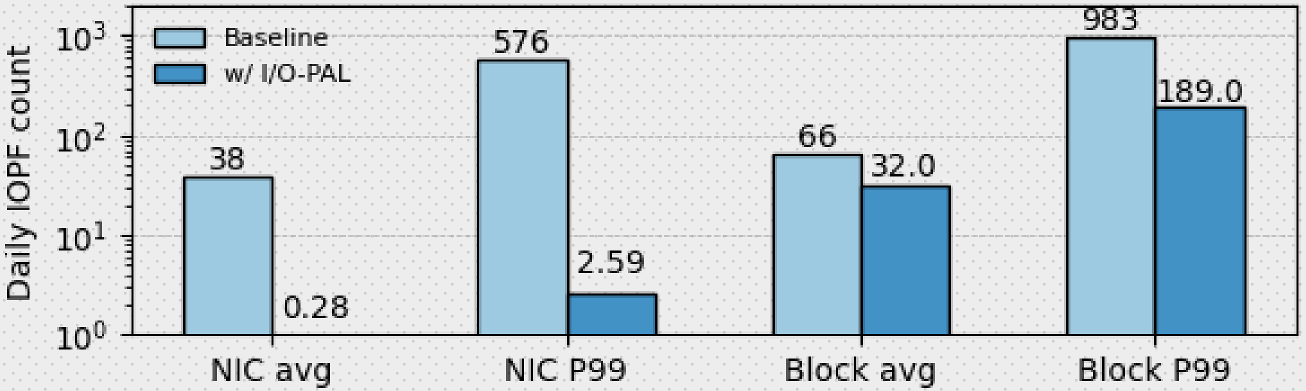


Evaluation: IOPF Reduction

- **Memory overcommit:**
  - 10%-30%
- **Mixed workloads:**
  - Network
  - Storage
- **Result (cmp w/ LRU):**
  - NIC: 6.28x
  - Block: 10.56x



- **In Production**
  - NIC: > 99% reduction
  - Block > 50% reduction
  - 5.2% pinning per VM



Summary

- ❑Deployed in Alibaba Cloud
  - ❖Negligible HW cost
  - ❖Compatible with all x86 platforms
  - ❖Landed in production in just 6 months
- ❑Facilitates memory overcommitment
- ❑Other use cases:
  - ❖Post-copy opt.
  - ❖Page migration
  - ❖Fast boot
  - ❖Etc.

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Thank you for you attention!