TeRM: Extending RDMA-Attached Memory with SSD

Zhe Yang[1], Qing Wang[1], Xiaojian Liao[1], Keji Huang[2], Jiwu Shu[1]

[1]Tsinghua University

[2]Huawei Technologies Co., Ltd

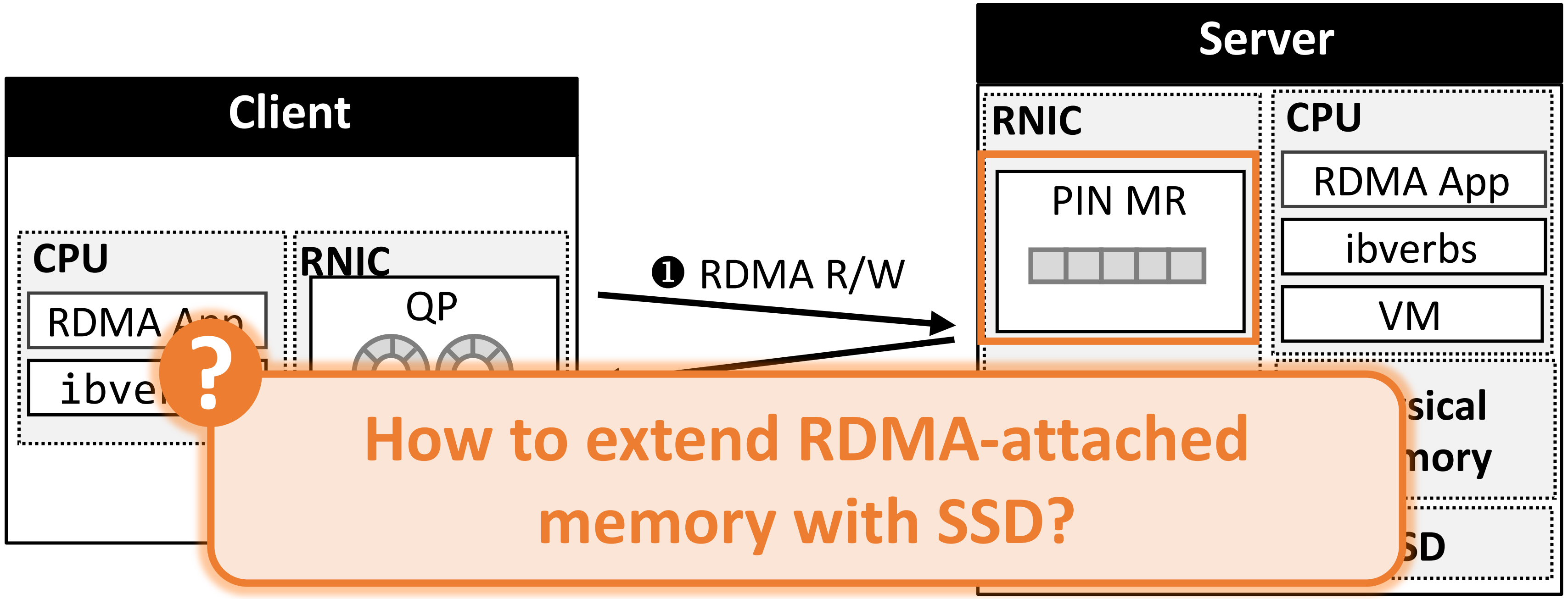
RDMA-based Storage System

- **RDMA catalyzes in-memory storage systems**
  - File systems, key-value stores, transactional databases, …

Assise [OSDI'20]
Pilaf [ATC'13]
FaRM [NSDI'14]
Aurogon [FAST'22]
Octopus [ATC'17]
Cell [ATC'16]
Sherman [SIGMOD'22]
TH-DPMS [TOS'20]
Rowan [OSDI'23]
Orion [FAST'19]
XStore [OSDI'20]
FileMR [NSDI'20]
DrTM+H [OSDI'18]
RACE [ATC'21]
FORD [FAST'22]
ROLEX [FAST'23]
FUSEE [FAST'23]

RDMA-attached Memory

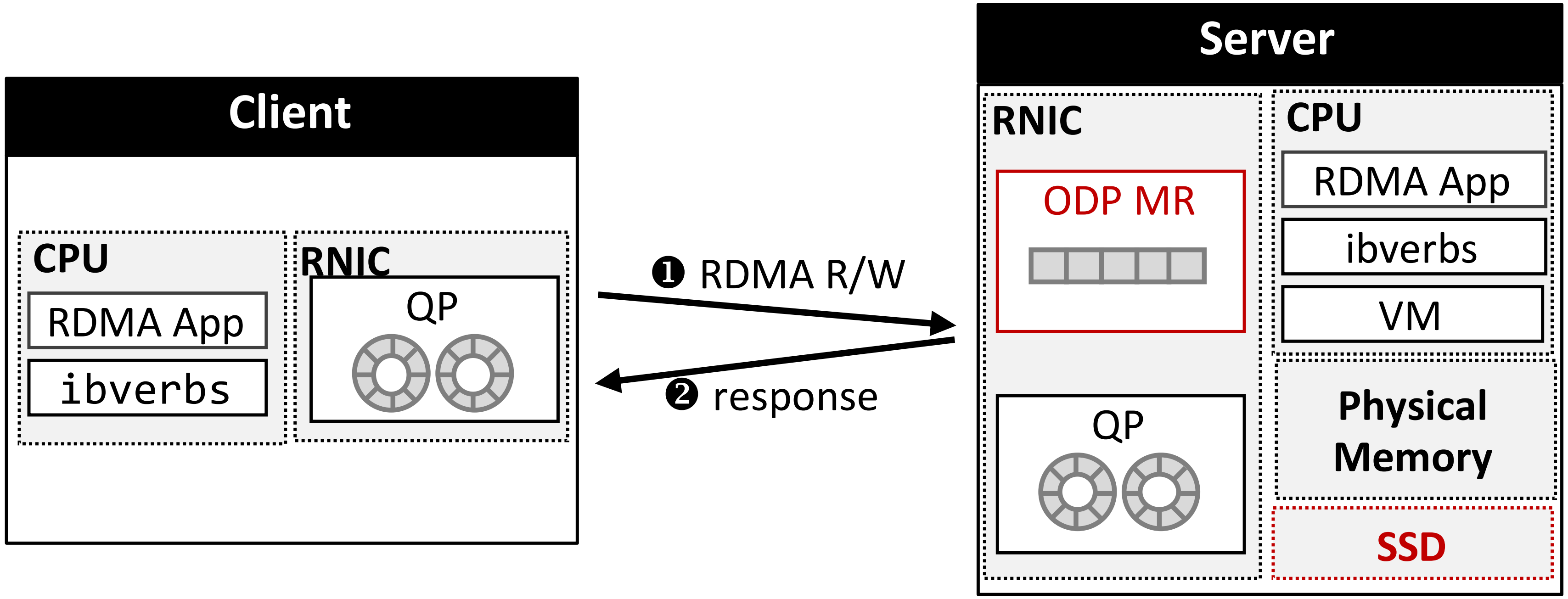
- **Server**
  - Expose virtual memory via **RDMA MR (RDMA-attached Memory)**
  - RNIC accesses the virtual memory via DMA, bypassing the CPU
  - Pin pages in the physical memory; build the RNIC page table
- **Client**
  - Access the MR by one-sided RDMA READ/WRITE



How to extend RDMA-attached memory with SSD?

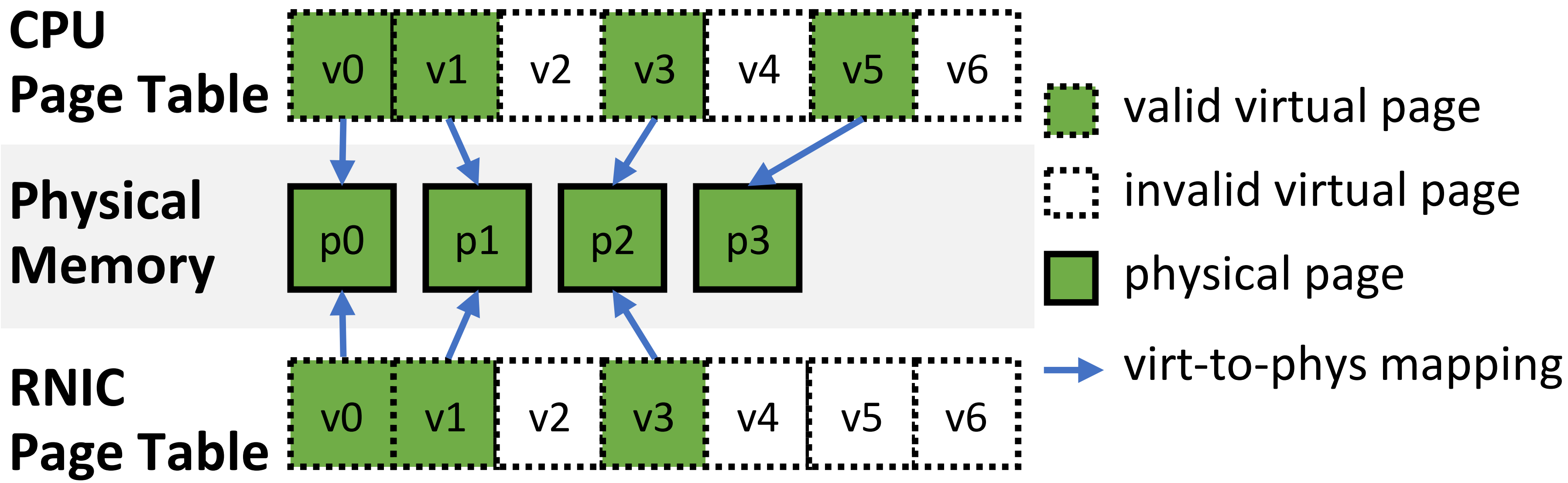
ODP MR

- **On-demand Paging MR**
  - Hardware solution by Mellanox [ASPLOS'17]
  - mmap an SSD and register as an ODP MR
  - The client submits normal RDMA READ/WRITE



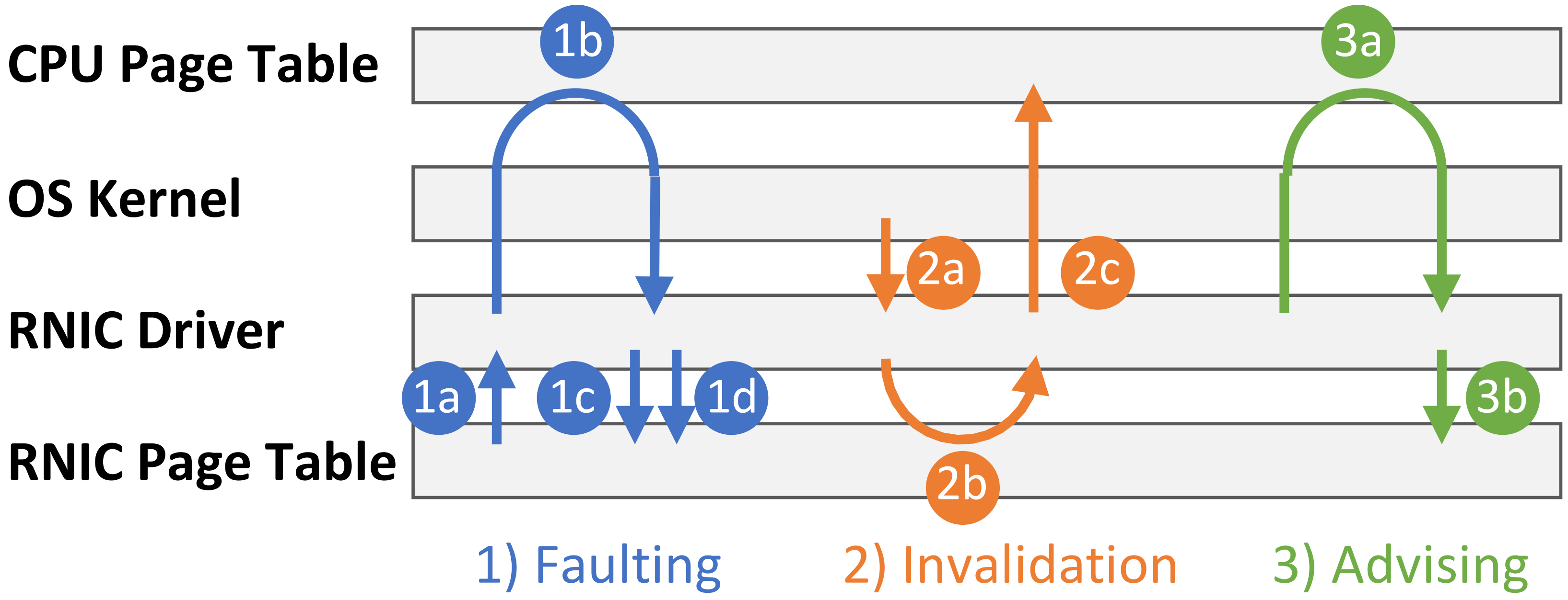
ODP MR

- Not all pages are mapped
- Trigger an **RNIC page fault** when accessing an invalid virtual page



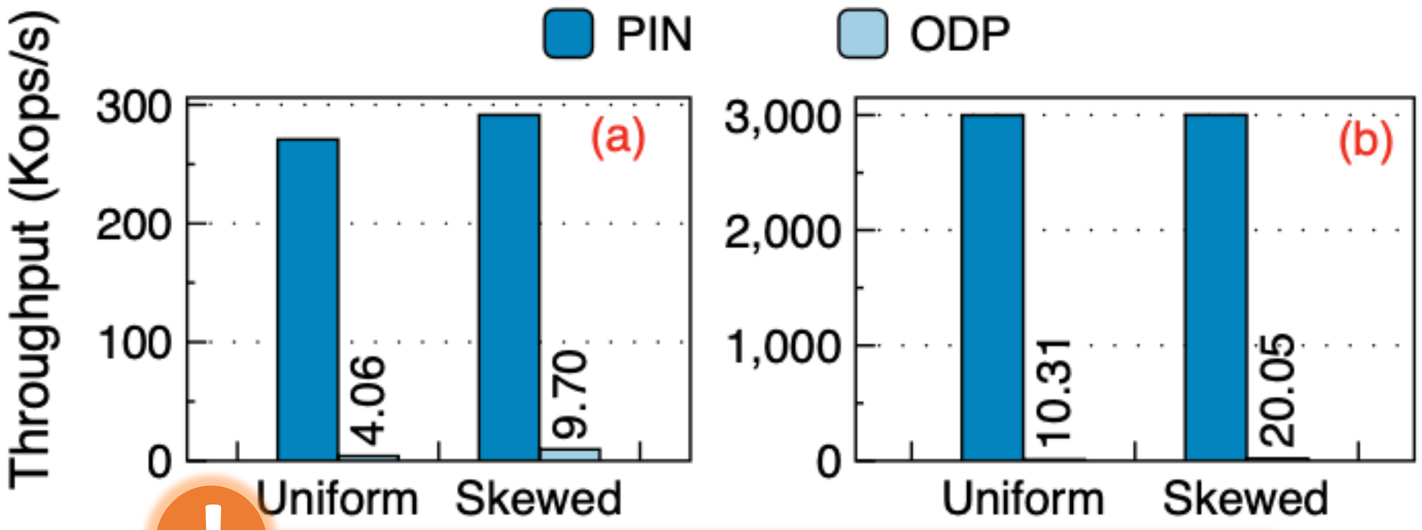
ODP MR

- **Synchronizing between CPU and RNIC page tables**
  - Three flows: faulting, invalidation, advising



ODP MR is not the silver bullet

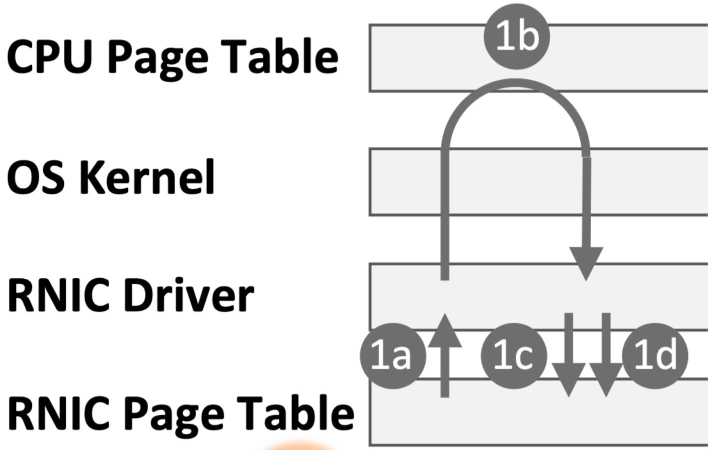
- **Read 4KB performance**
  - 64GB virtual memory , 32GB physical memory
  - mmap() Intel Optane P5800X SSD
  - (a) 1 client thread
  - (b) 64 client threads

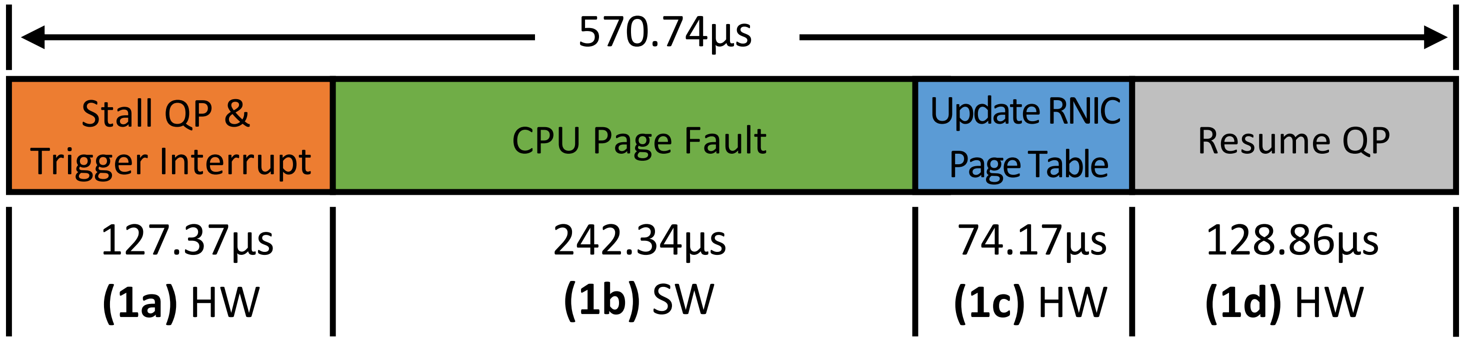


66.64x – 290.76x slowdown!

ODP MR is not the silver bullet

- **Two sources of overhead**
  - A normal read consumes 4µs
  - Hardware: stall & resume QP, trigger interrupt, update RNIC page table
  - Software: CPU page fault

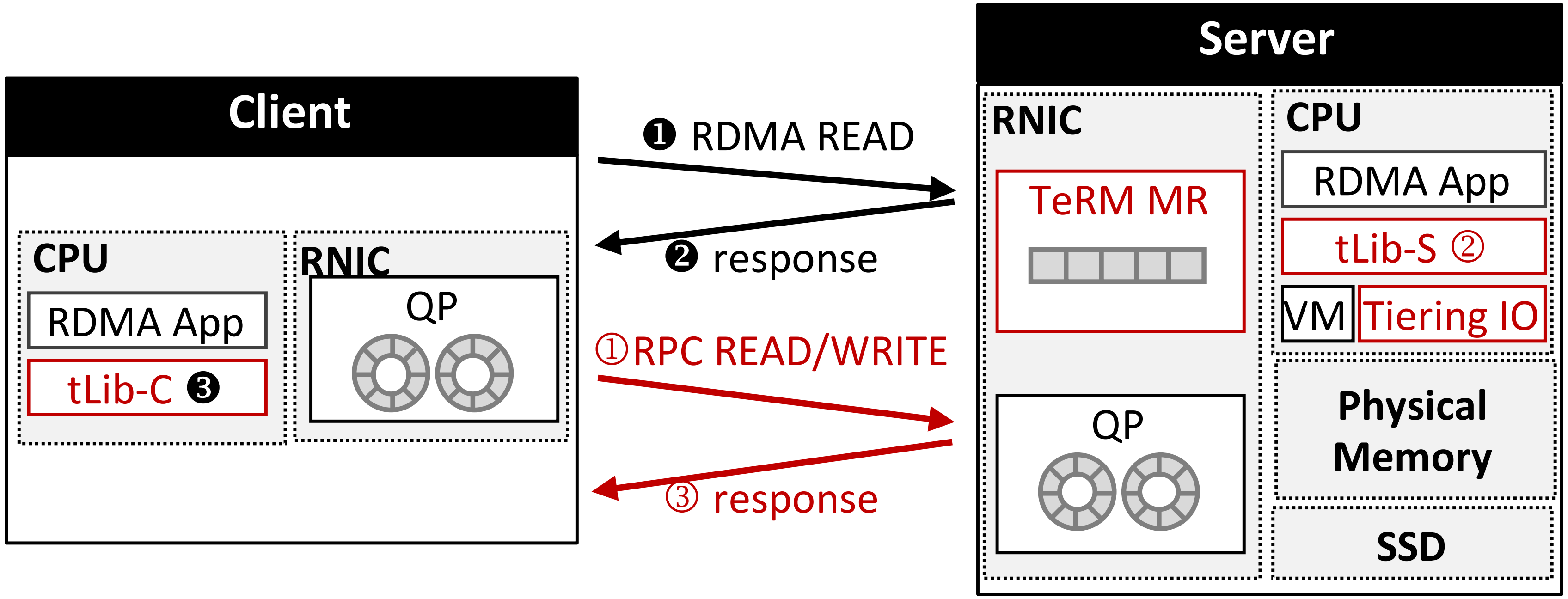




1. **Onload exception handling from HW to SW.**
2. **Eliminate CPU page faults from the critical path.**

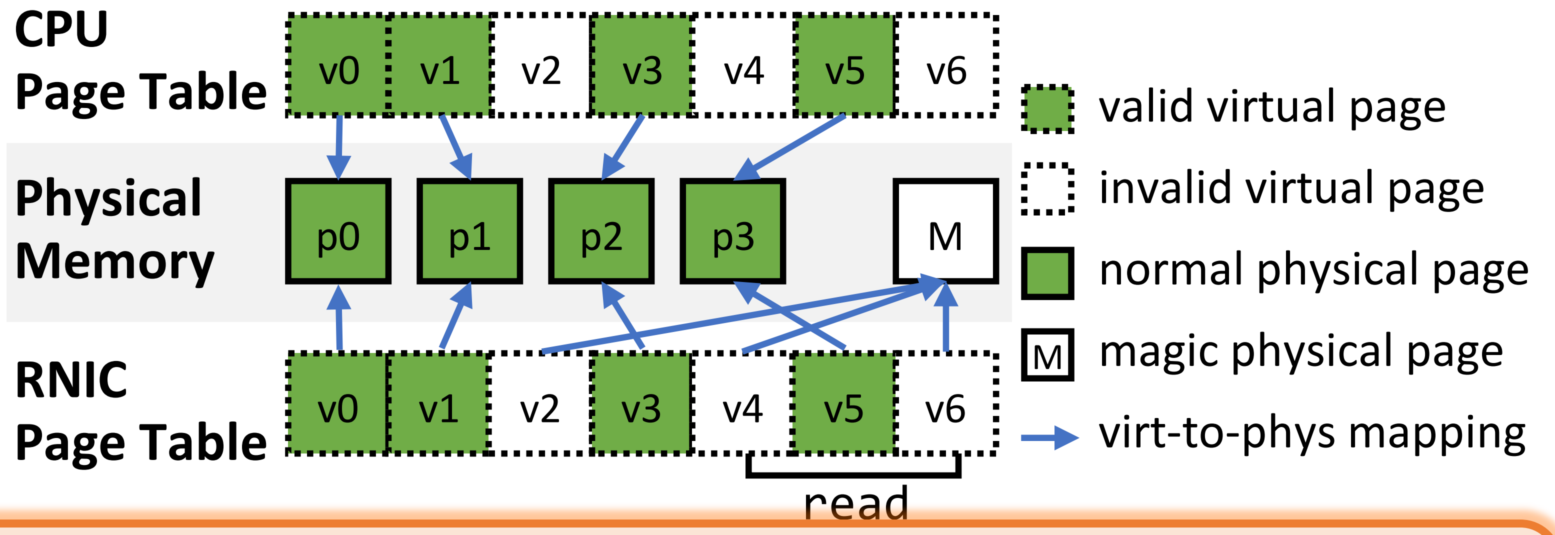
TeRM overview

- **CPU VM**
  - mmap; Serves local access (load/store) from the server-side application.
- **TeRM MR**
  - Serves remote access (memory read/write) from the client-side application.
- **tLib-S/tLib-C**
  - Server-side/client-side shared library; replaces libibverbs using LD_PRELOAD



TeRM MR

- **Magic physical page**
  - Invalid virtual pages are mapped to this one.
  - Filled with magic pattern.



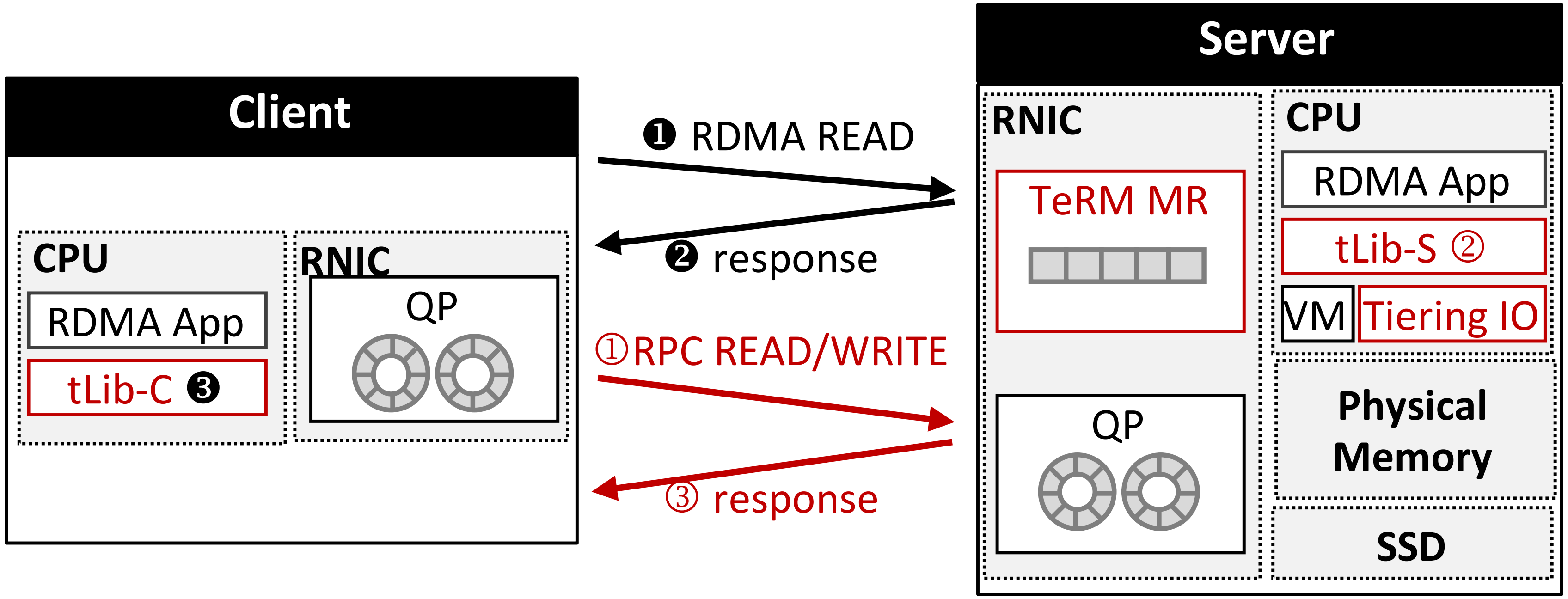
RDMA READ on invalid virtual pages returns with magic pattern.

Read workflow

- **RDMA READ first**
  - ❶ submit an RDMA READ request
  - ❷ receive the response
  - ❸ check whether the data contains magic pattern

  If no magic pattern is found, the read request completes.

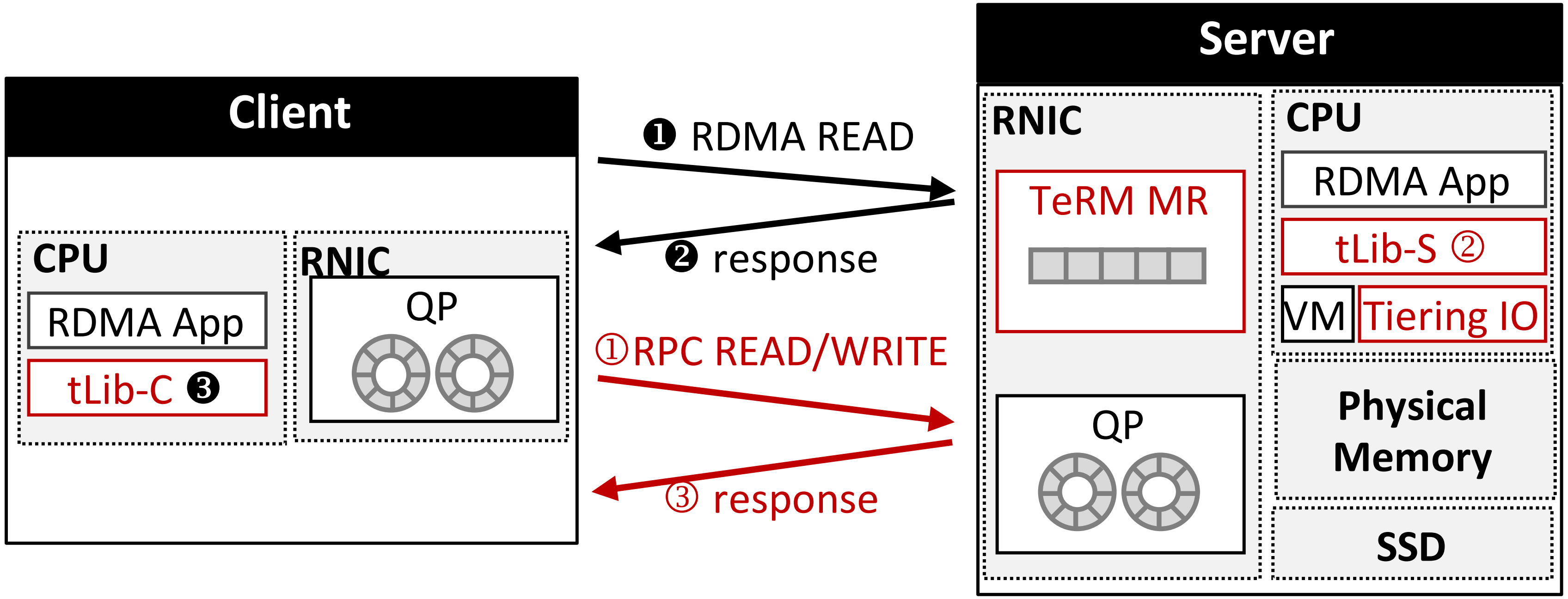
  Otherwise, …



Read workflow

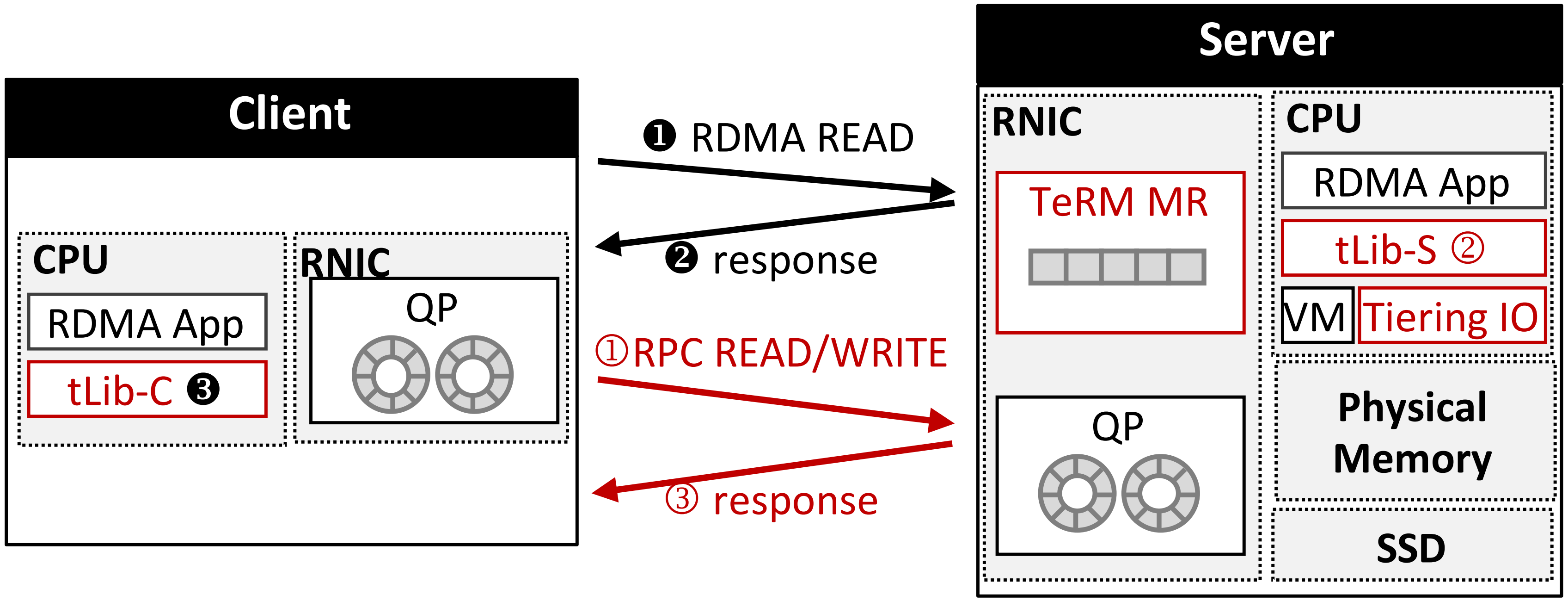
- **RPC READ if necessary**
  - ① submit an RPC READ request
  - ② tLib-S reads data
  - ③ tLib-C receives data and completes the read

"principle 1: onload exception handling from HW to SW"



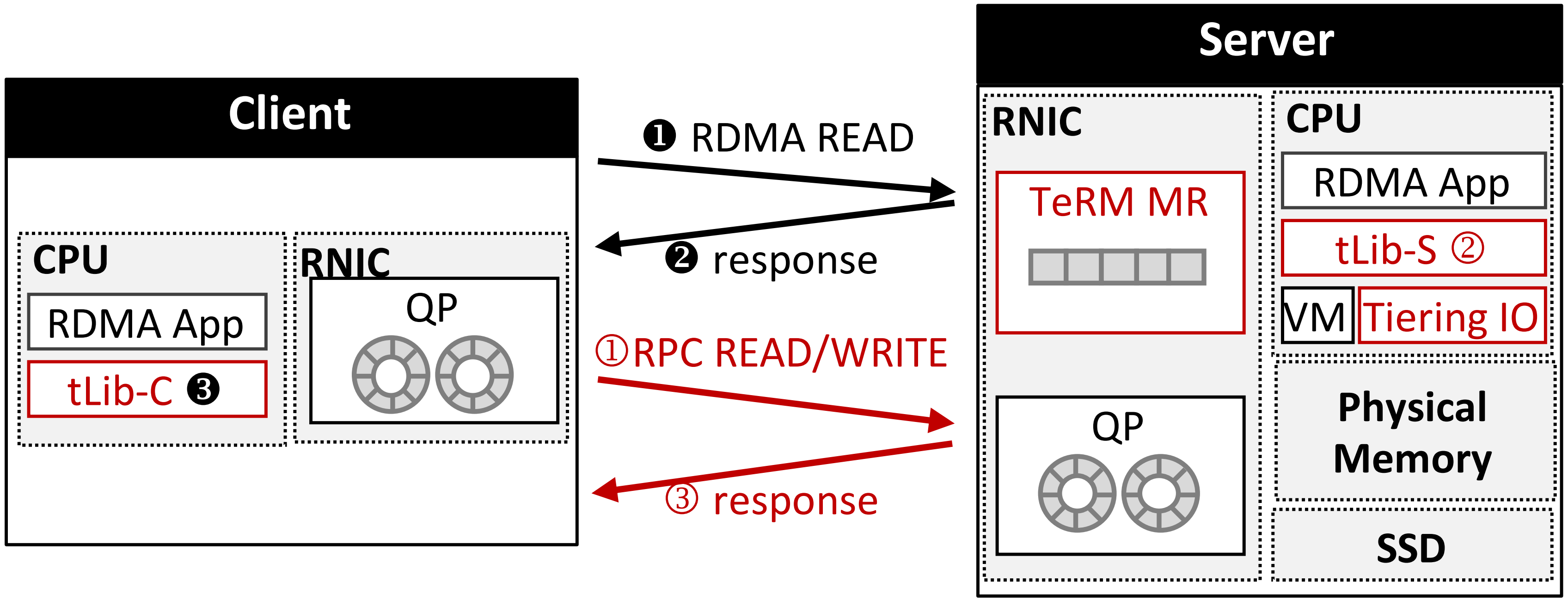
Write workflow

- **RPC WRITE for all**
  - ① submit an RPC WRITE request
  - ② tLib-S writes data
  - ③ tLib-C receives notification and completes the write



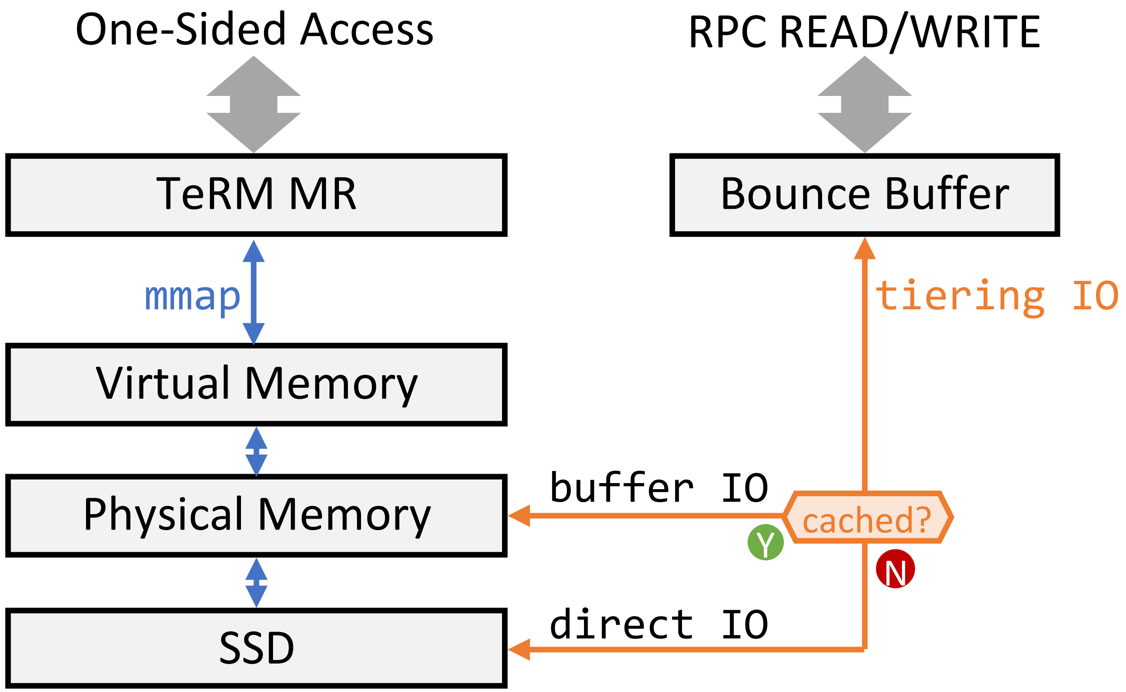
How can RPC access data efficiently?

- **Load/store the CPU VM?**
  - Still triggers CPU page faults!
- **Convert memory load/store to file I/O**
  - Read/write the SSD
  - “Principle 2: eliminate CPU page faults from the critical path”



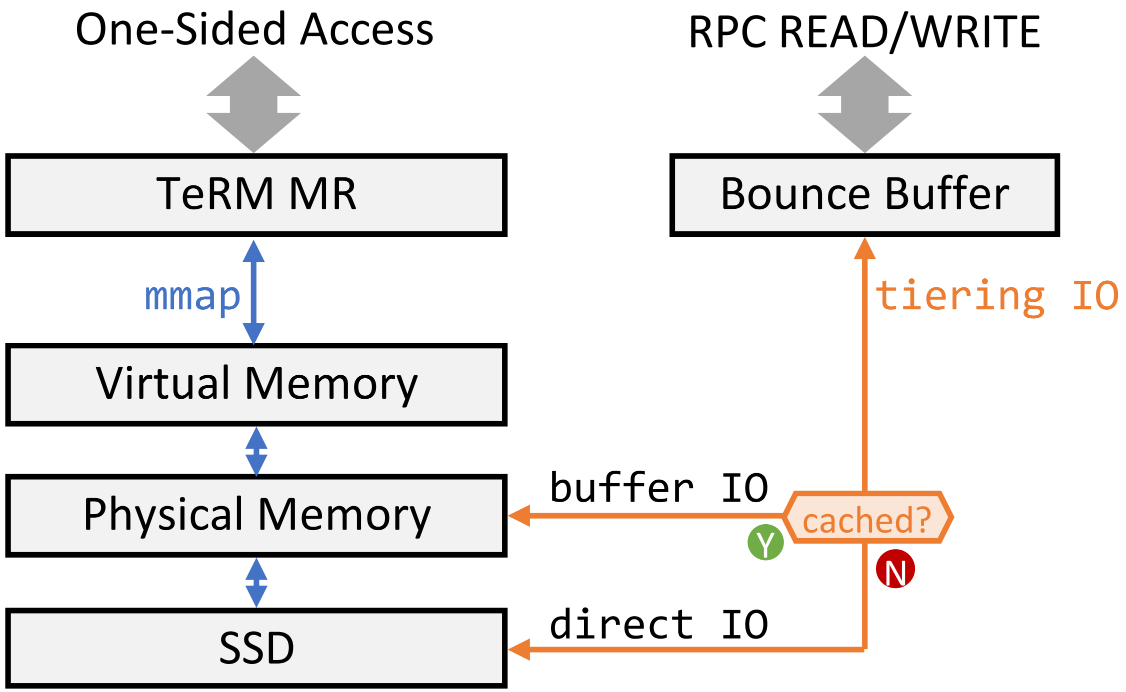
How can RPC access data efficiently?

- **Convert memory load/store to file I/O**
  - SSD LBA range: [slba, slba + length)
  - Virtual address range: [saddr, saddr + length)
  - lba = addr – saddr + slba



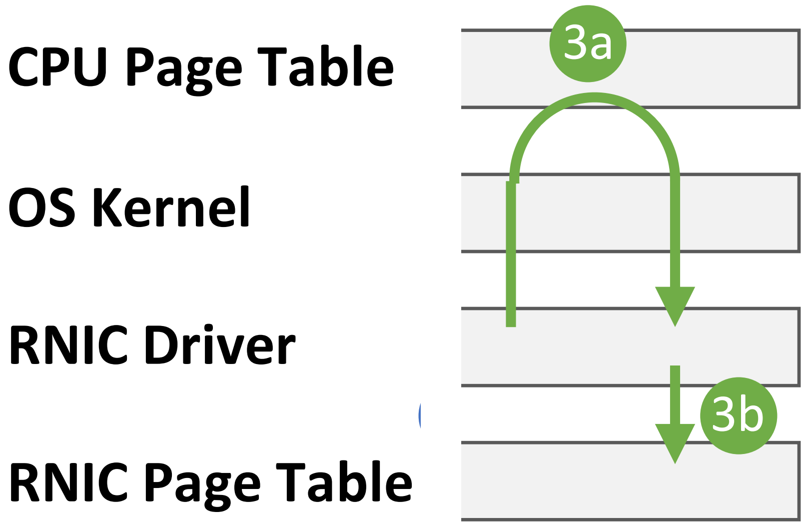
Tiering IO

- **Read/write data via two interfaces**
  - Check the page cache
  - Buffer IO for cached data, using page cache
  - Direct IO for uncached data, bypassing page cache



Promoting Hotspots

- **Client-side**
  - Count accesses on each unit
- **Server-side**
  - Aggregate counters from all clients
  - Find most-accessed units as hotspots
  - Promote via `ibv_advise_mr()`



3) Advising

Evaluation

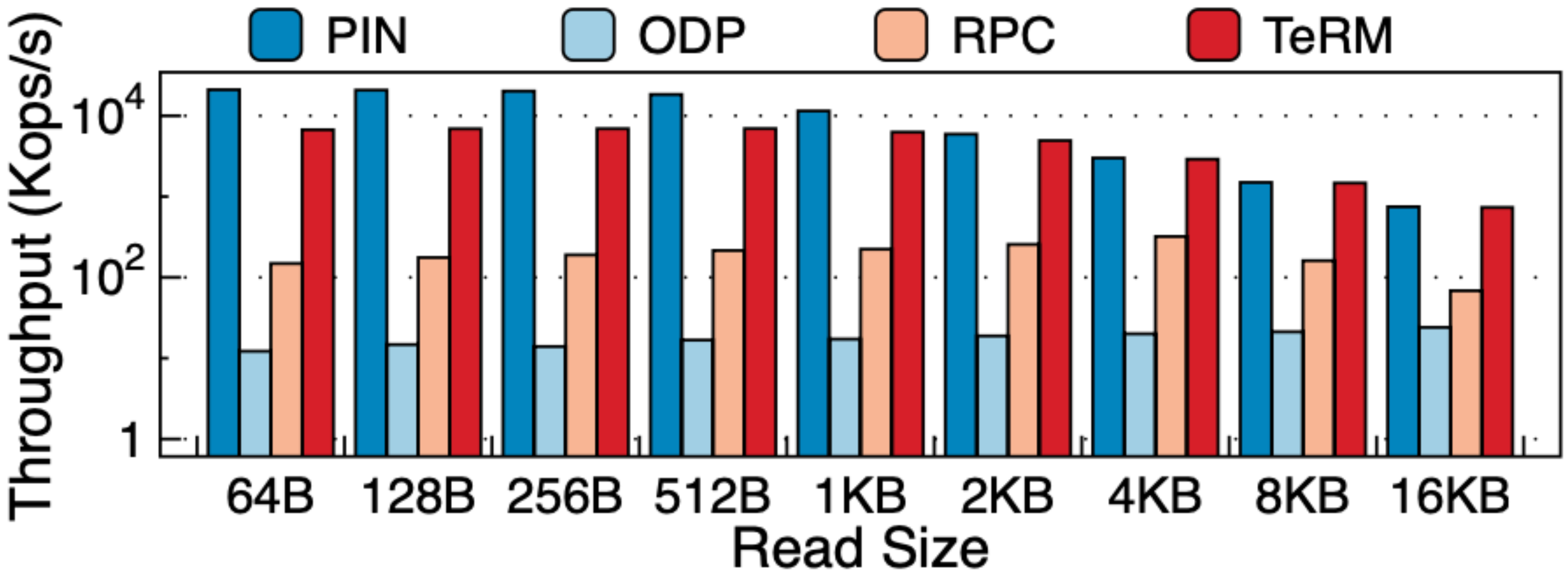
- **Testbed**
  - RDMA Cluster: server machine * 1, client machine * 2
  - SSD: Intel Optane P5800X 400GB
  - RNIC: ConnectX-5 100Gbps
  - Switch: IB 100Gbps
- **Settings**
  - Virtual memory: 64GB, physical memory: 32GB
  - 64 Client threads, 16 server threads

Evaluation

- **Comparing Targets**
  - **PIN:** ideal upper bound, all pages in the physical memory
  - **ODP:** hardware solution, ODP MR
  - **RPC:** software solution, all requests via RPC, access data via memcpy
  - **TeRM:** our solution.

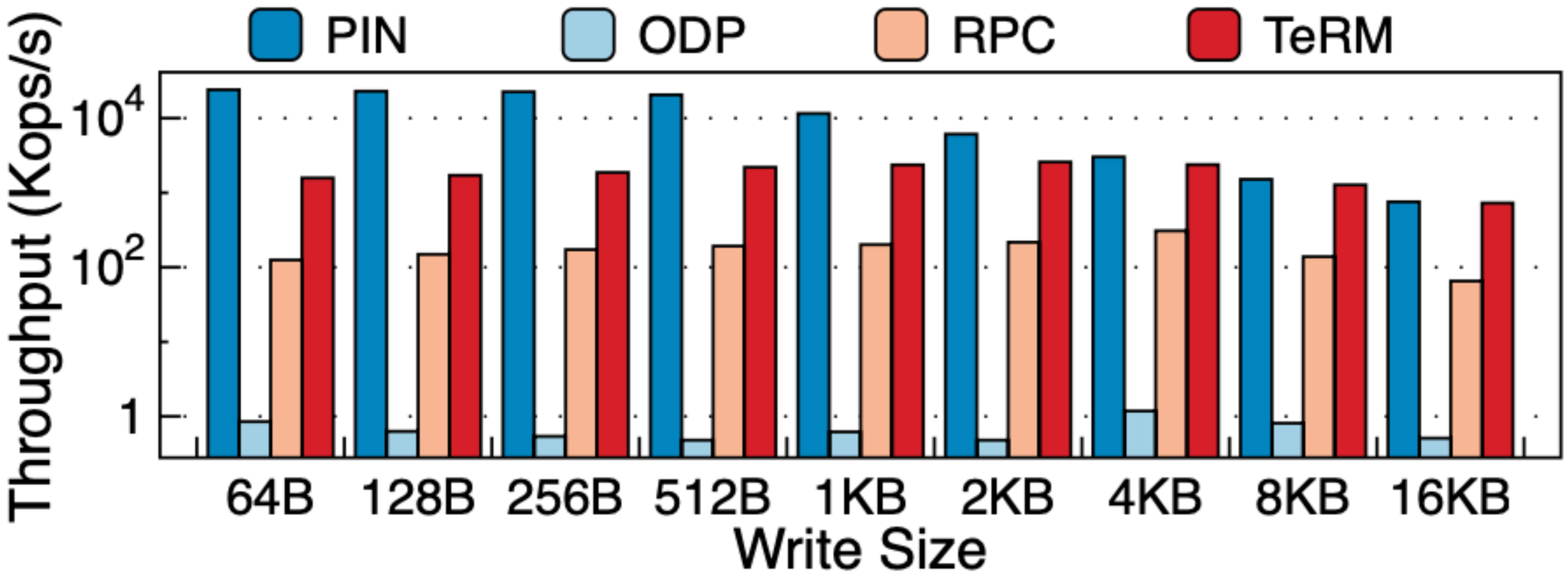
Evaluation: Overall Performance

- **Read**
  - **vs. ODP:** 30.46x – 549.63x
  - **vs. RPC:** 9.05x – 45.19x
  - **vs. PIN:** 37.79% – 96.71%



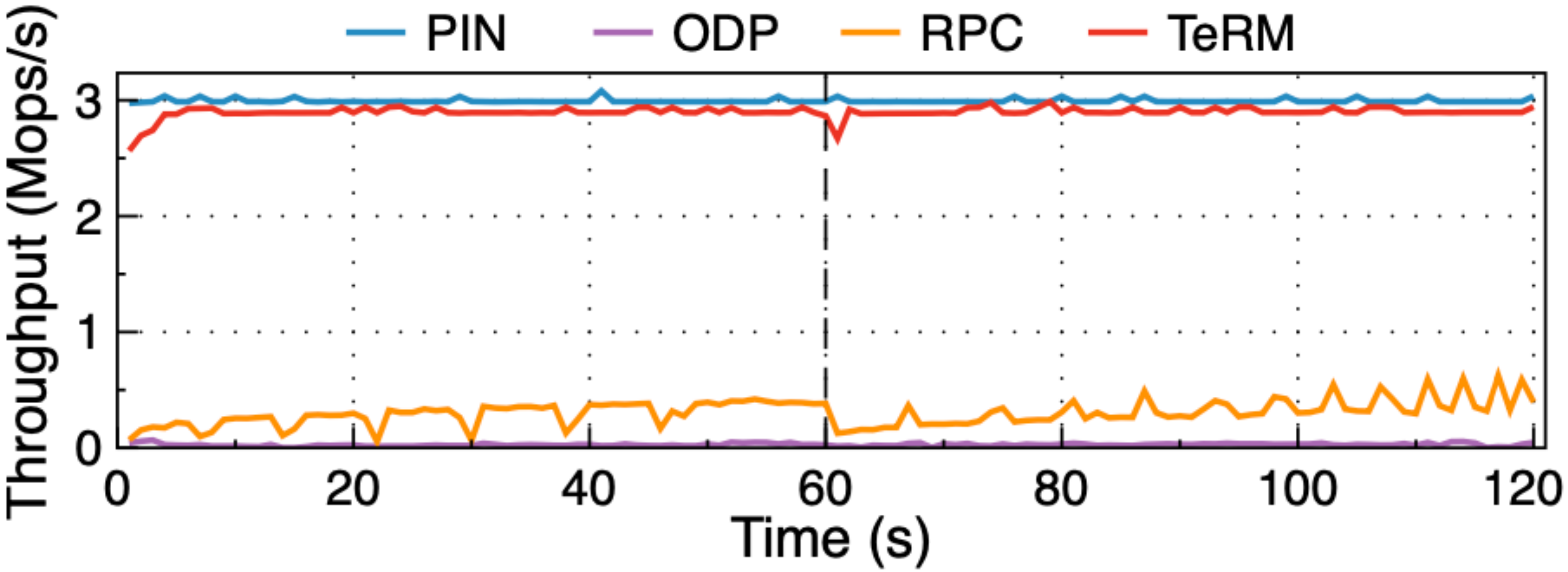
Evaluation: Overall Performance

- **Write**
  - **vs. ODP:** ~ 1000x (ODP write is very unstable and jitters sharply)
  - **vs. RPC:** 7.73x – 12.60x
  - **vs. PIN:** 6.55% – 96.32%



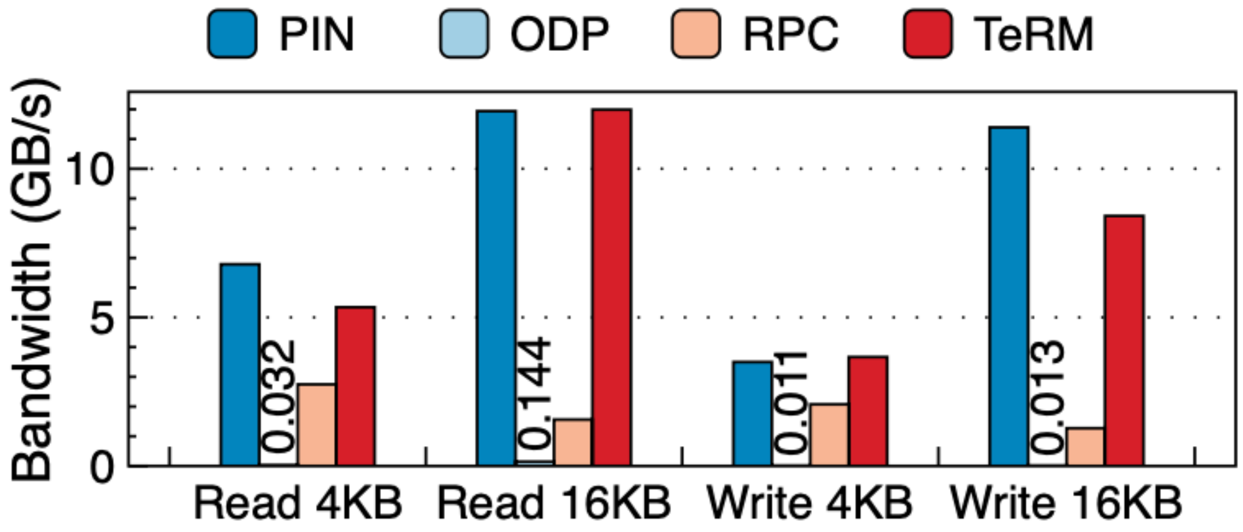
Evaluation: Dynamic Workloads

- **Change hotspots at the 60th second**
  - **Performs stably:** drops by only 6.82%
  - **Promoting fast:** returns to the peak in 1 second



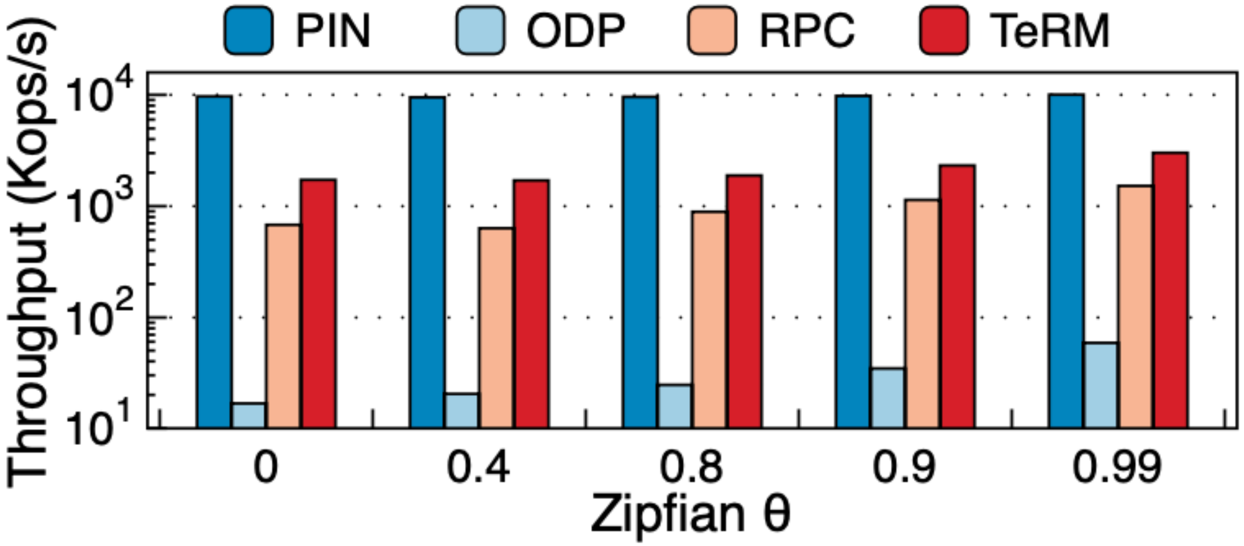
Evaluation: RDMA-based storage system

- **Octopus: A File System [OSDI'20]**
  - **Workloads:** read/write the file
  - **Results:** up to 642.23x ODP, 7.68x RPC



Evaluation: RDMA-based storage system

- **XStore: A Key-Value System [ATC'17]**
  - **Workloads:** YCSB-C, read 8B keys and 128B values
  - **Results:** Up to 102.97x ODP, 2.69x RPC



Conclusion

- TeRM proposes an efficient approach to extending RDMA-attached memory with SSD.
- TeRM onloads exception handling from hardware to software and eliminates RNIC & CPU page faults on the critical path.
- TeRM implements a userspace shared library to replace libibverbs and run unmodified RDMA applications transparently.
- TeRM outperforms the hardware-only ODP MR by up to 642.23x, and the software-only RPC approach by up to 7.68x.

Thanks! Q&A

ARTIFACT EVALUATED usenix ASSOCIATION AVAILABLE

ARTIFACT EVALUATED usenix ASSOCIATION FUNCTIONAL

ARTIFACT EVALUATED usenix ASSOCIATION REPRODUCED

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yangz18@mails.tsinghua.edu.cn

https://github.com/thustorage/TeRM