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NUMA-Aware Thread Migration for High Performance NVMM File Systems

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Outline

- Background & Motivation
- NThread design
  - Reduce remote access
  - Reduce resource contention
  - Increase CPU cache sharing
- Evaluation
- Summary

Background

- Non-Volatile Main Memories(NVMMs) provide **low latency**, **high bandwidth**, **byte-addressable** and **persistent storage**
  - PCM, MRAM, RRAM, 3D Xpoint[1]
    - Intel releases Optane DC Persistent Memory (Optane PMM)

[2]	R lat.	W lat.	R BW.	W BW.
DRAM	60ns	69ns	20 GB/s	~15 GB/s
Optane PMM	305ns	81ns	~6GB/s	~2GB/s
NVMe SSD	120us	30us	2GB/s	500MB/s
HDD	10ms	10ms	0.1GB/s	0.1GB/s

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    - Intel releases Optane DC Persistent Memory (Optane PMM)
- File system can be directly built on memory
  - Improve file system I/O performance

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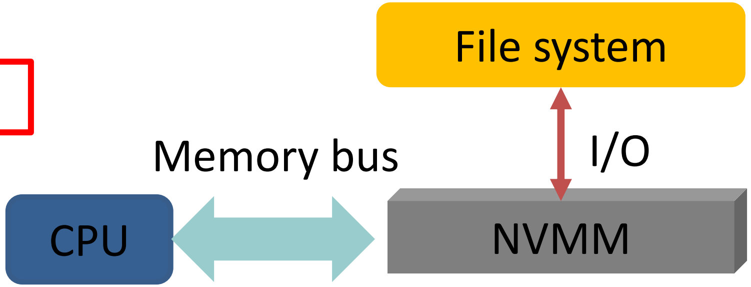

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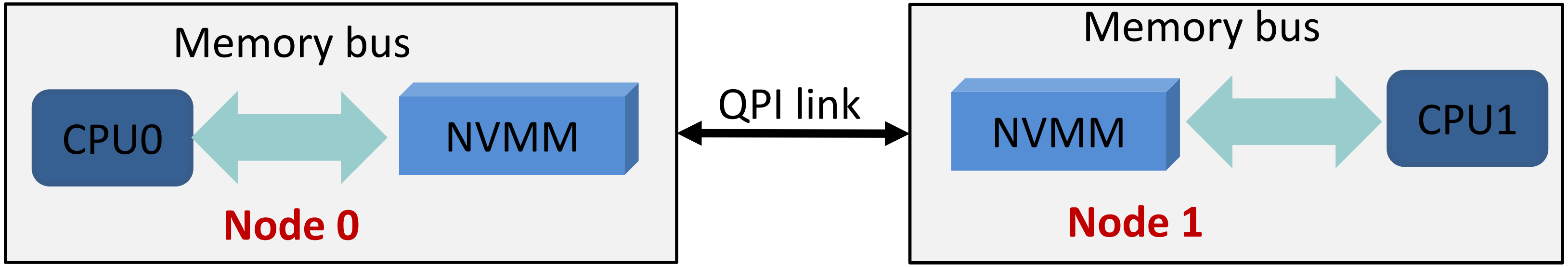
- Non-Uniform Memory Access architecture(NUMA) is widely used in data center [1,2,3,4,5,6,7]



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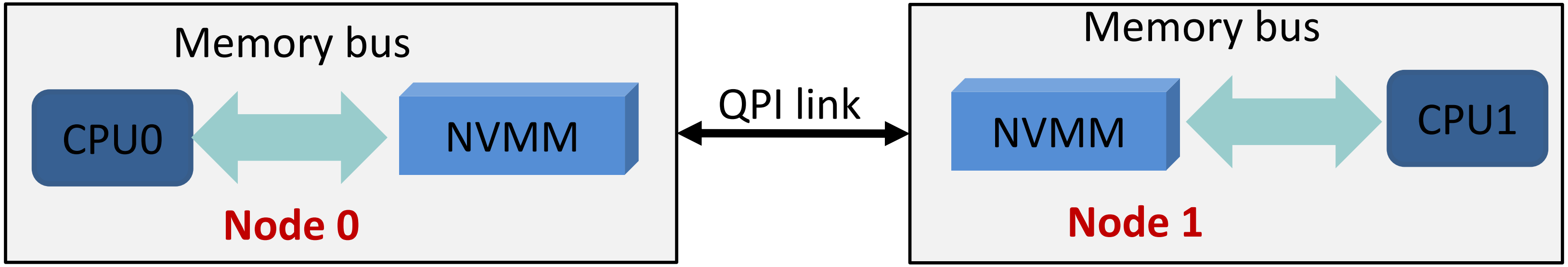

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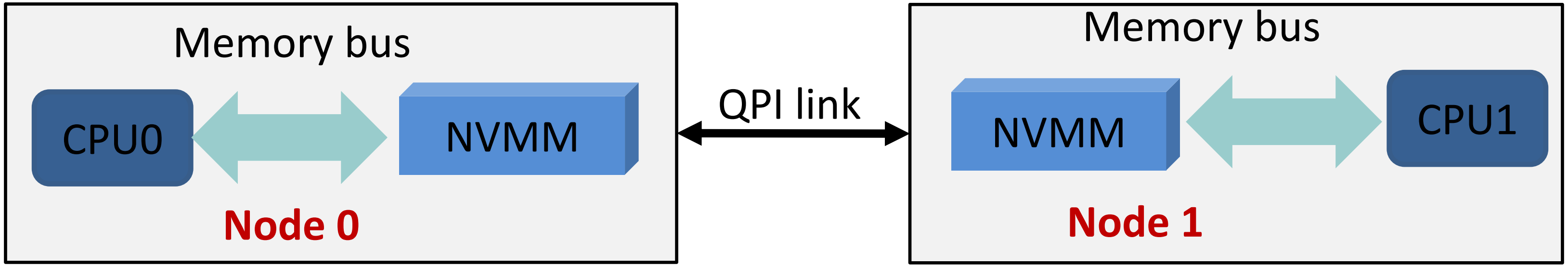

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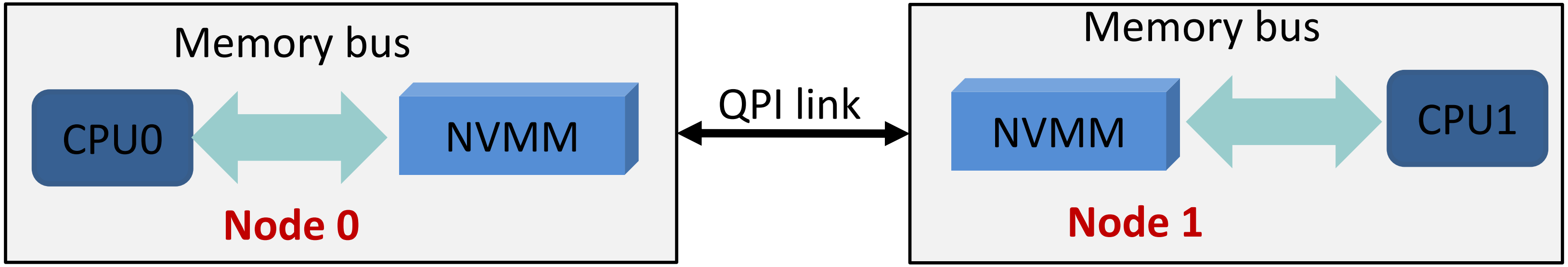
    - Each node can run in parallel without interference



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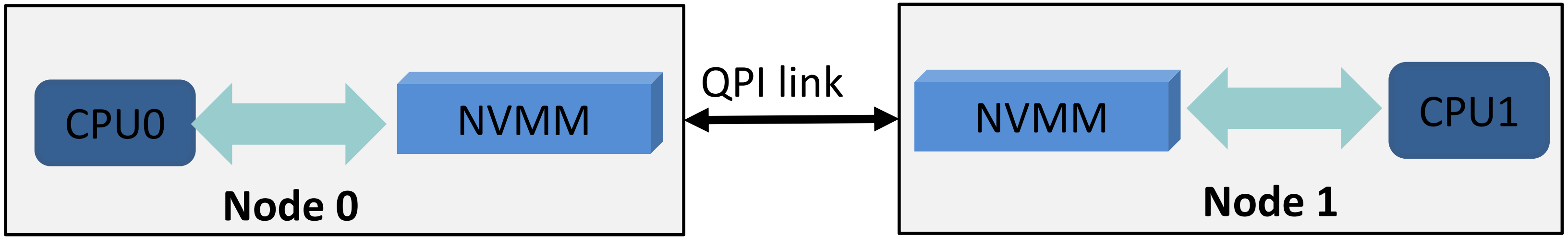

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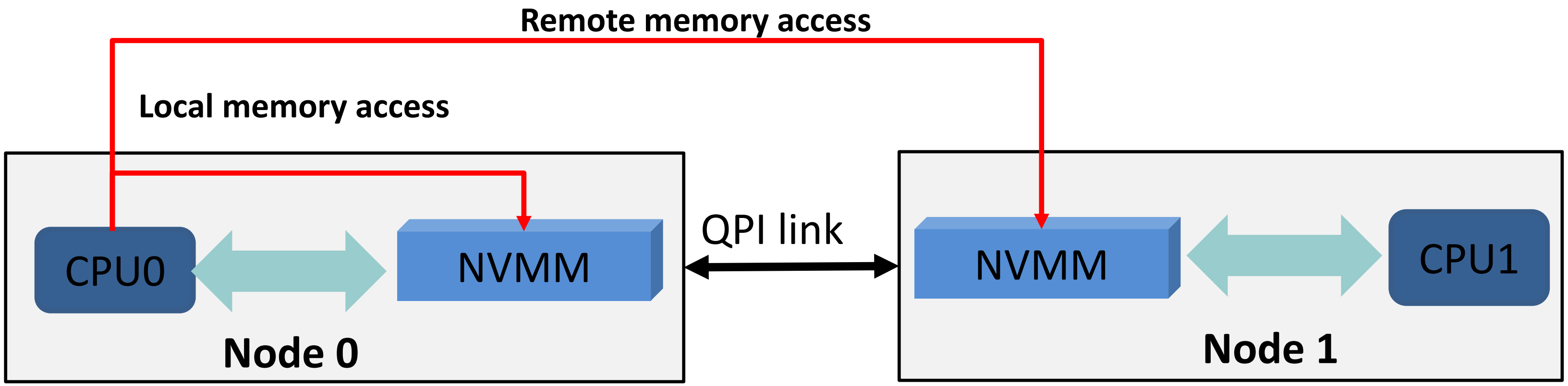
  - Remote nodes is accessed in more time than local ones



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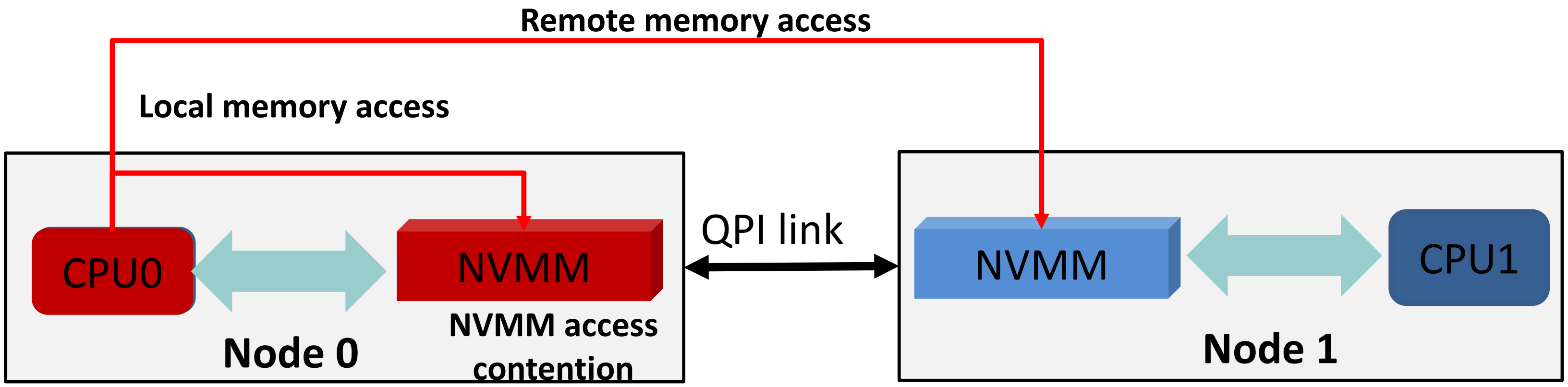
  - Remote nodes is accessed in more time than local ones
  - Unbalanced resource usage among nodes causes resource contention, reducing system performance
    - Memory (DRAM, NVMM), CPU



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  - Remote nodes is accessed in more time than local ones
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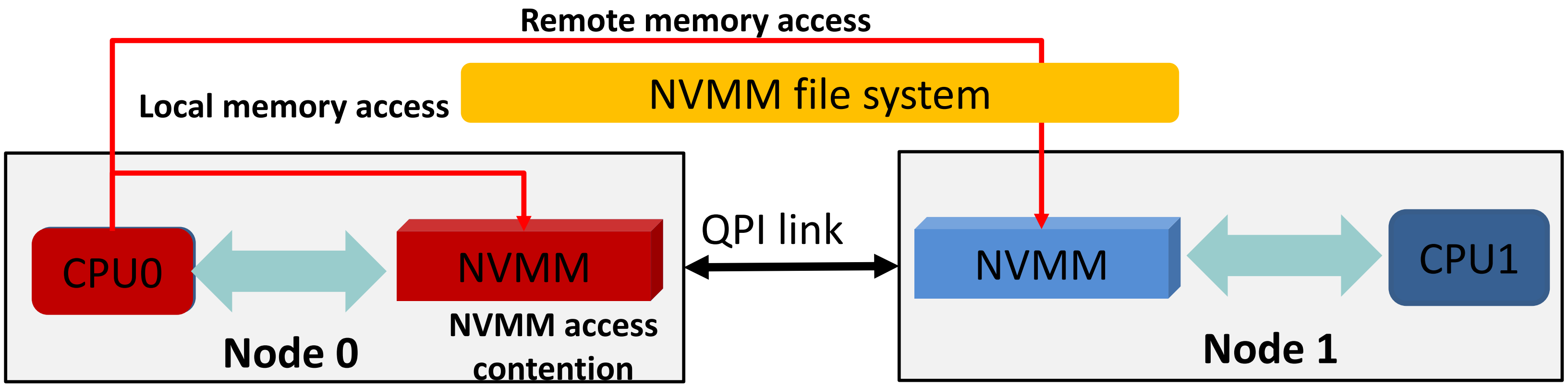
    - Memory (DRAM, NVMM), CPU
- The I/O performance of NVMM file system is affected by the these factors



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- Existing NVMM file systems are not aware of NUMA
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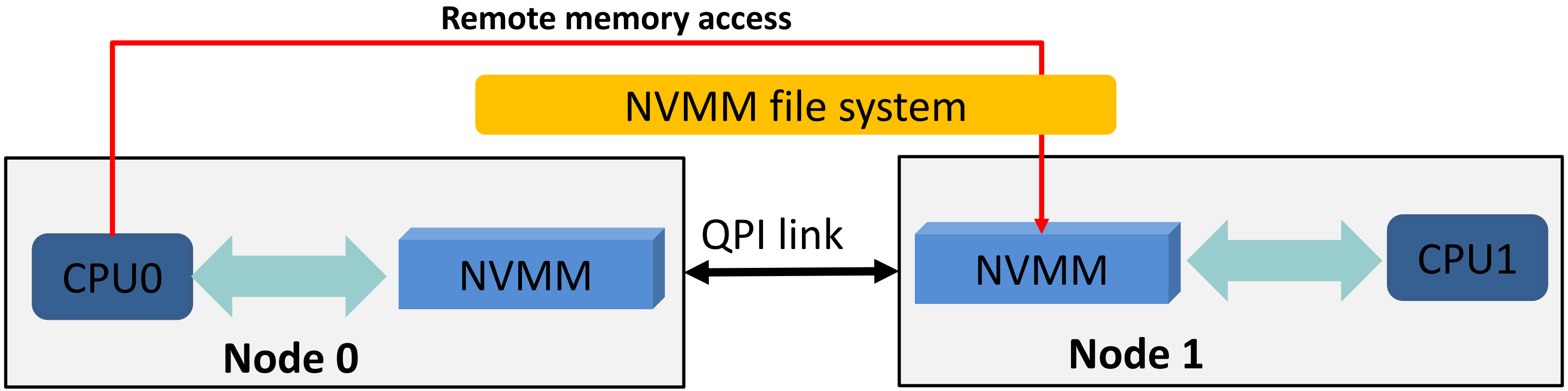

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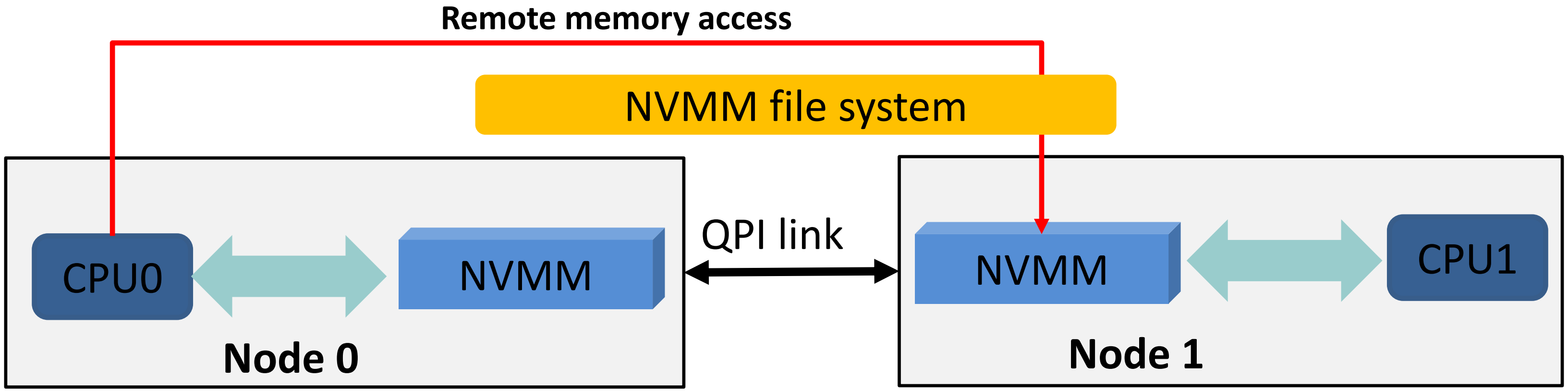

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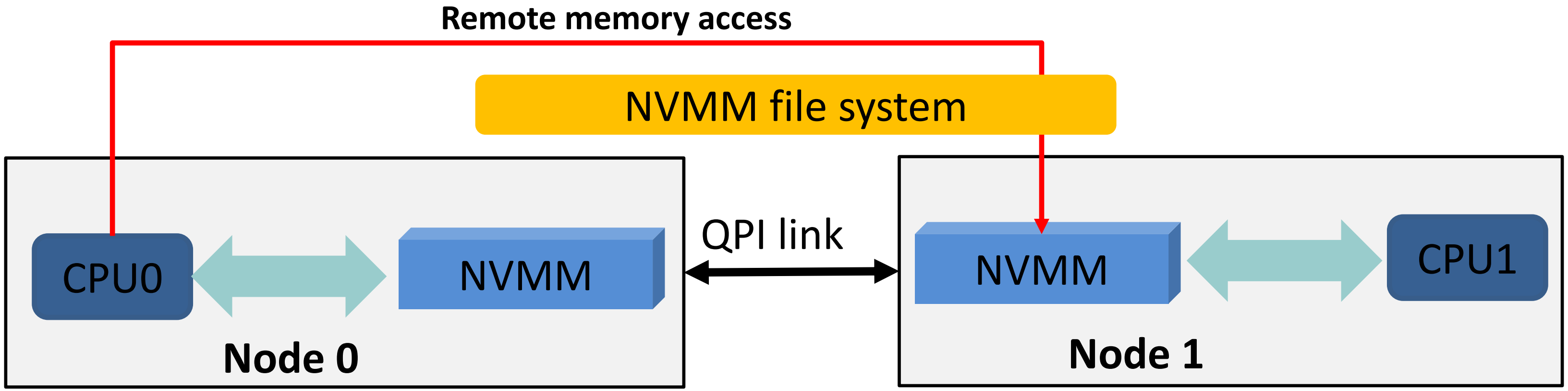

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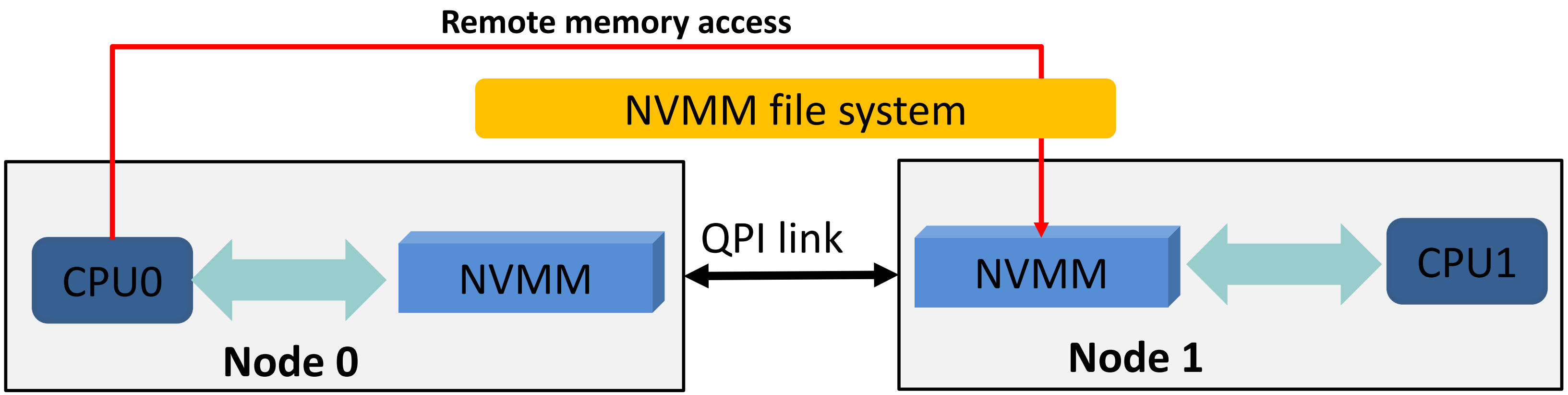
    - Remote NVMM accesses increase the read latency of NVMM file system by 65.6%



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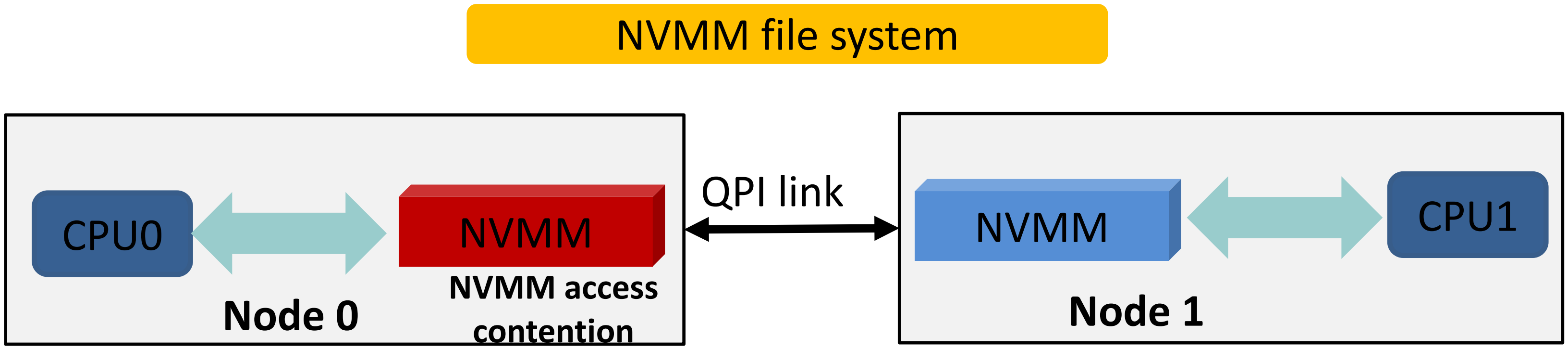

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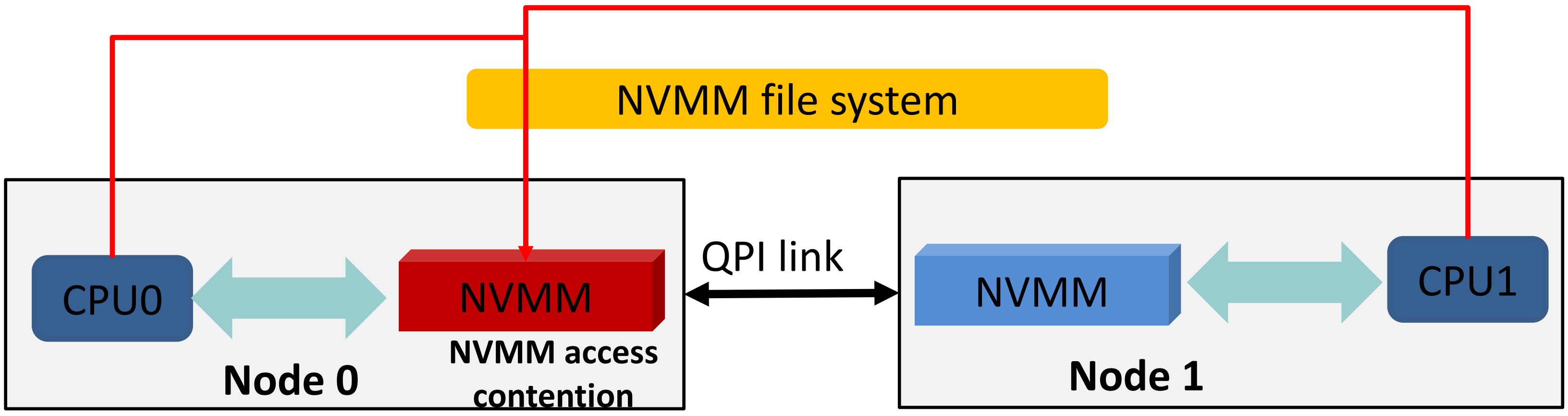

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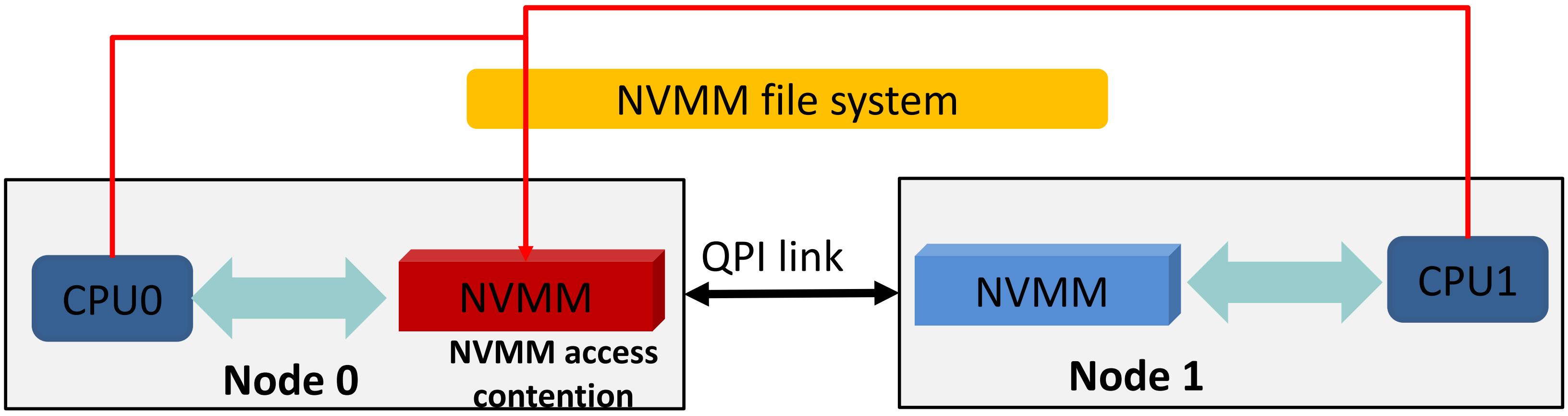
    - NVMM access contention can increases file access latency by 120.5%



Existing works

- For memory applications

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  - Allocating memory on the memory node where the thread runs
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Existing works

- For memory applications
  - Allocating memory on the memory node where the thread runs
    - Cannot solve the problem of NVMM contention
  - Migrating thread and thread data (such as stack, heap) [1,2,34]
    - Reduce remote access
    - Reduce resource contention by unbalanced use of resources
    - A lot of data migration overhead

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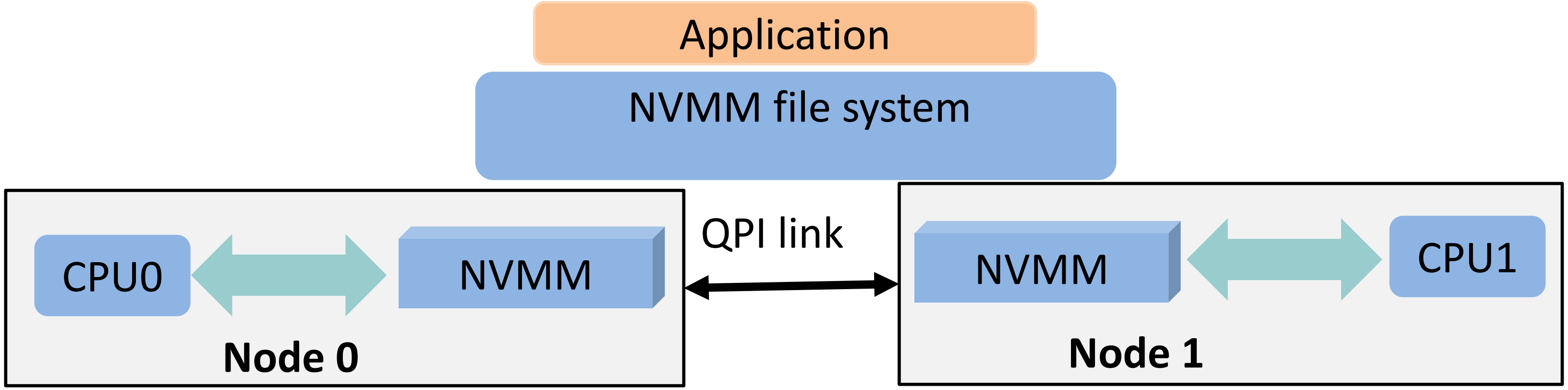
- NVMM has low write endurance
  - Reduce the lifetime of NVMM

Contribution

- A NUMA-Aware thread migration for NVMM FS



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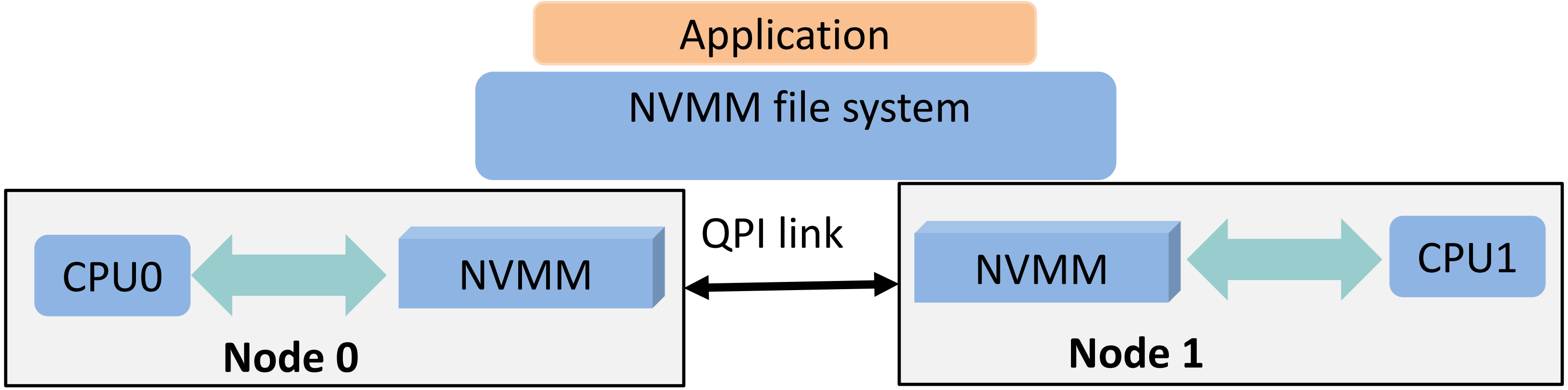

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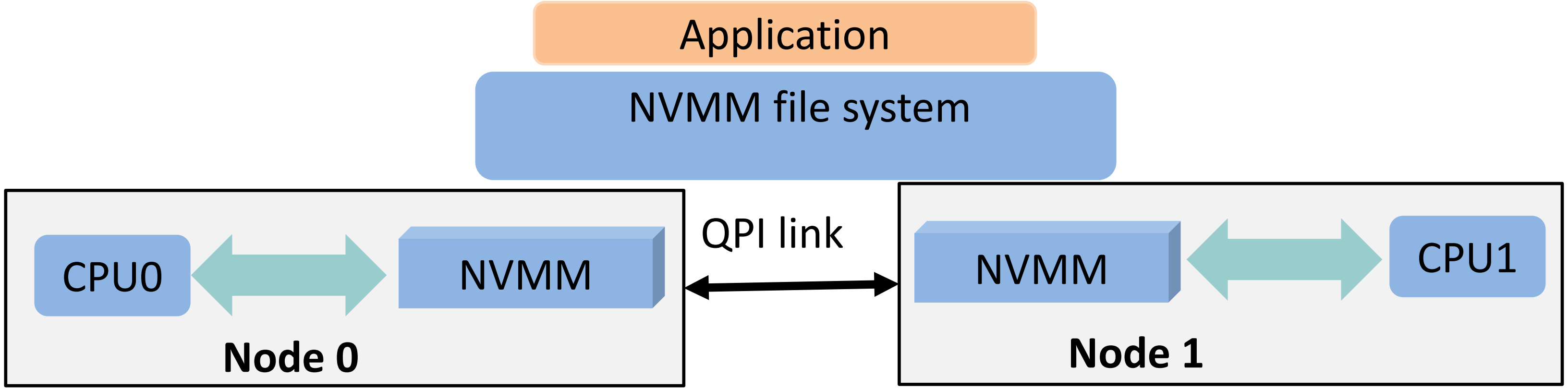

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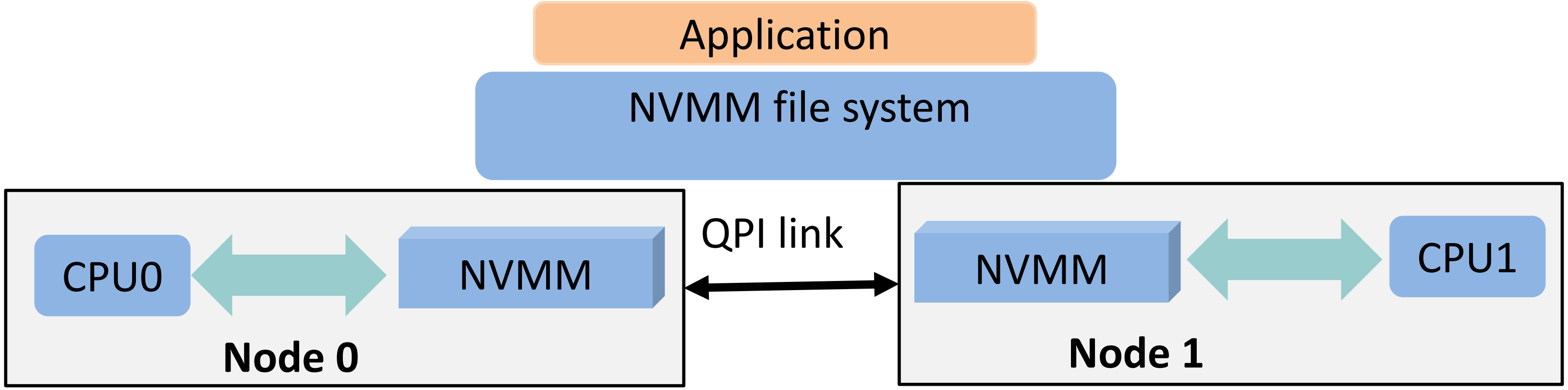

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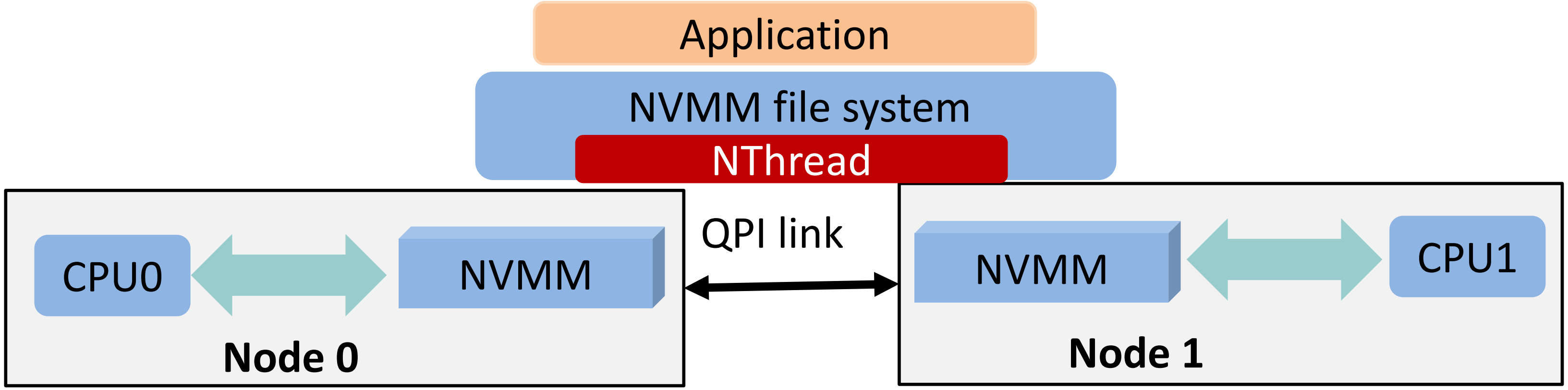

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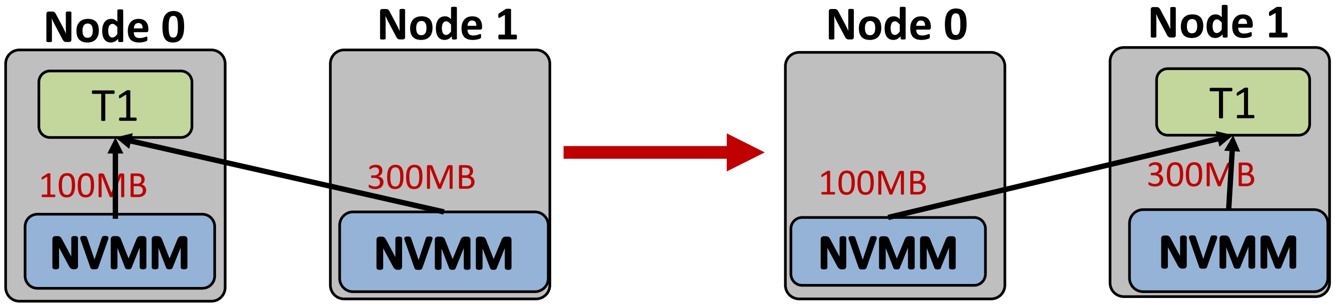
    - When the read size of a thread on one node is higher than all other nodes by a value per period (such as 200 MB per second)



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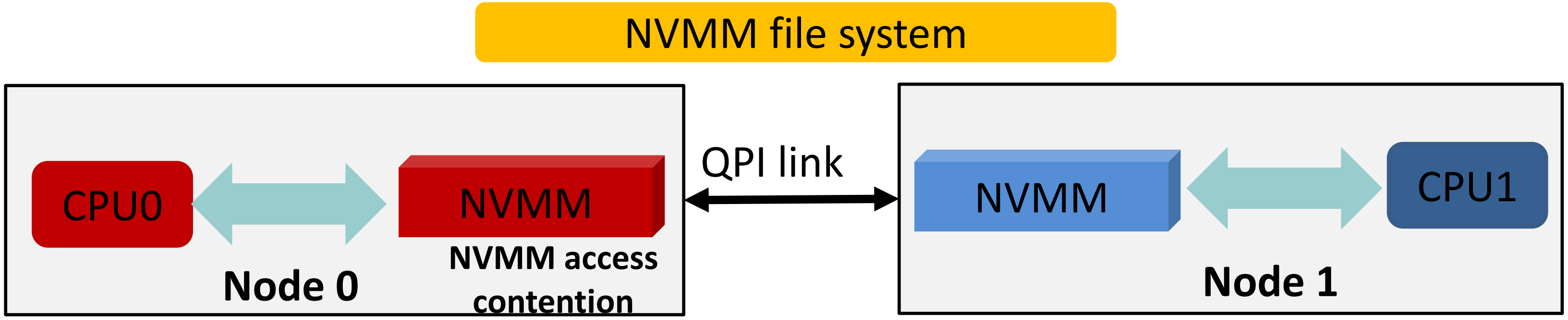
- Problems
  - How to find contention
  - How to reduce contention
  - How to avoid new contention



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      - Considering the theoretical bandwidth with running bandwidth of NVMM
      - Bandwidth = read bandwidth + write bandwidth

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  - How to define access amount
    - Bandwidth !!!!
      - Considering the theoretical bandwidth with running bandwidth of NVMM
      - Bandwidth = read bandwidth + write bandwidth
    - However
      - The write bandwidth of NVMM is about 1/3 of the read bandwidth

Reduce NVMM contention

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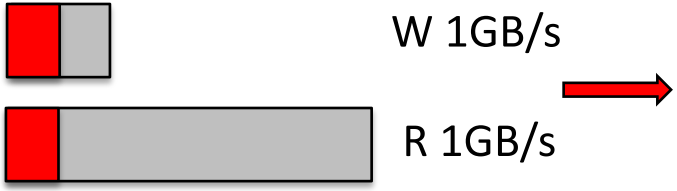
      - Read 1 GB/s + Write 1 GB/s = 2GB/s → low contention

Low Contention



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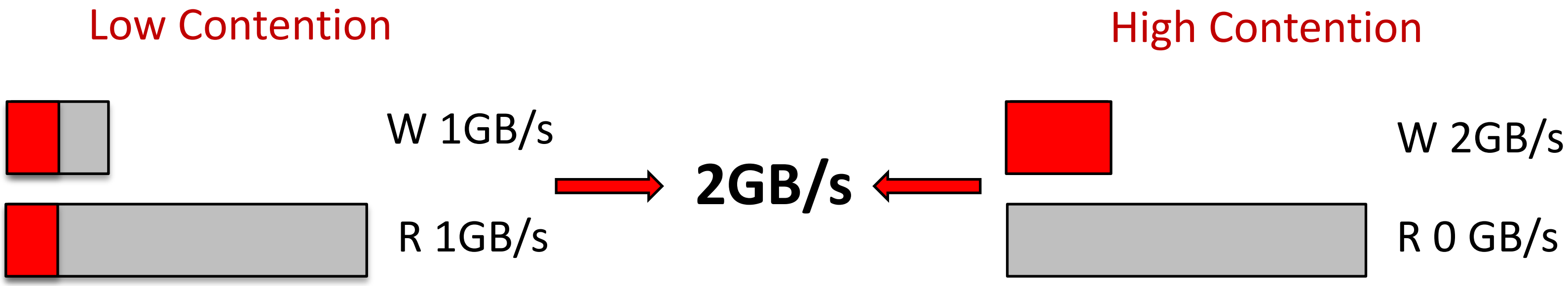

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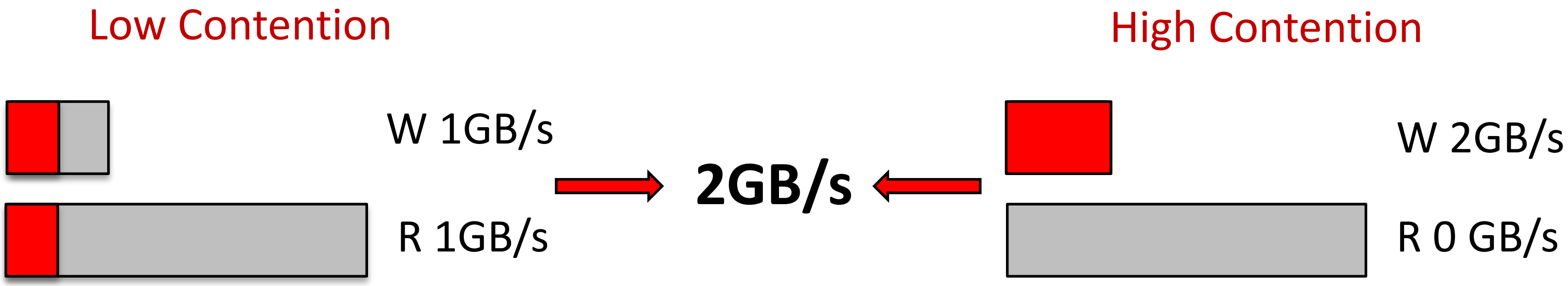
      - Read 0 GB/s + write 2 GB/s = 2GB/s → high contention
    - Solution
      - Change the read and write weight of bandwidth
        - » $BW_N = NWr_N * 1/3 + BWw_N$ (Refer to paper)



Low Contention

High Contention

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Reduce NVMM contention

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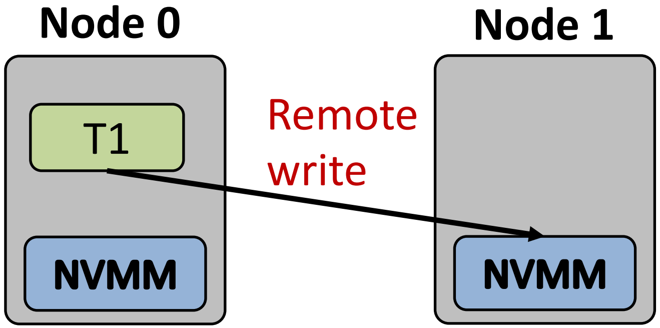
      - Specify the node where data is written
      - Long remote write latency: reduce performance by 65.5%



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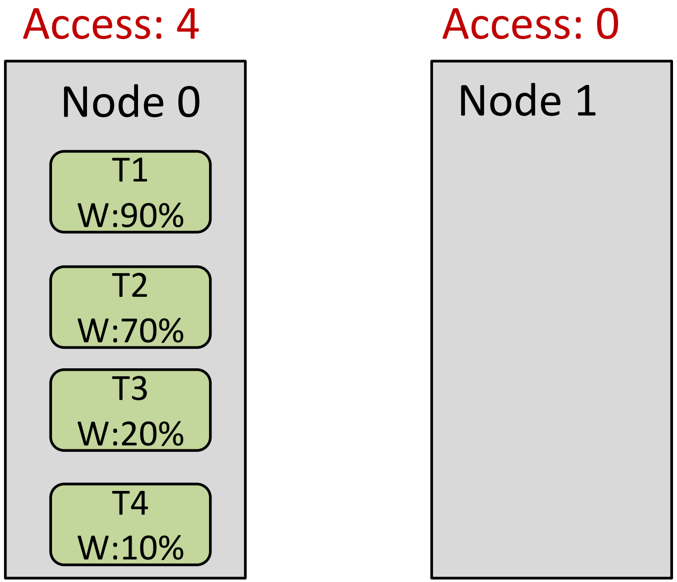

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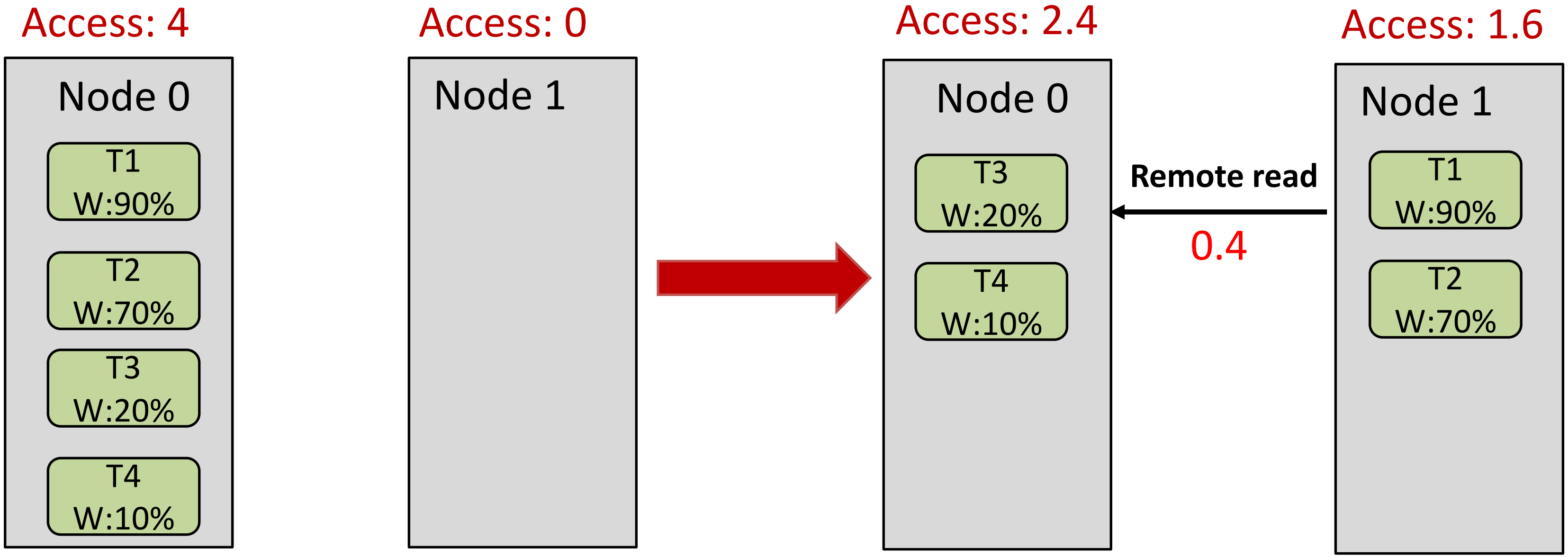

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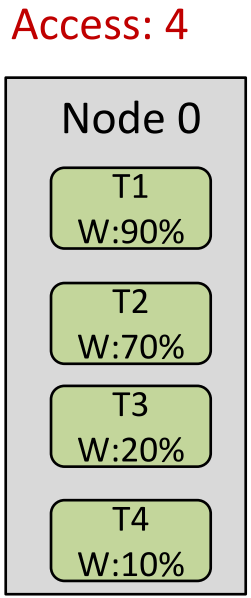

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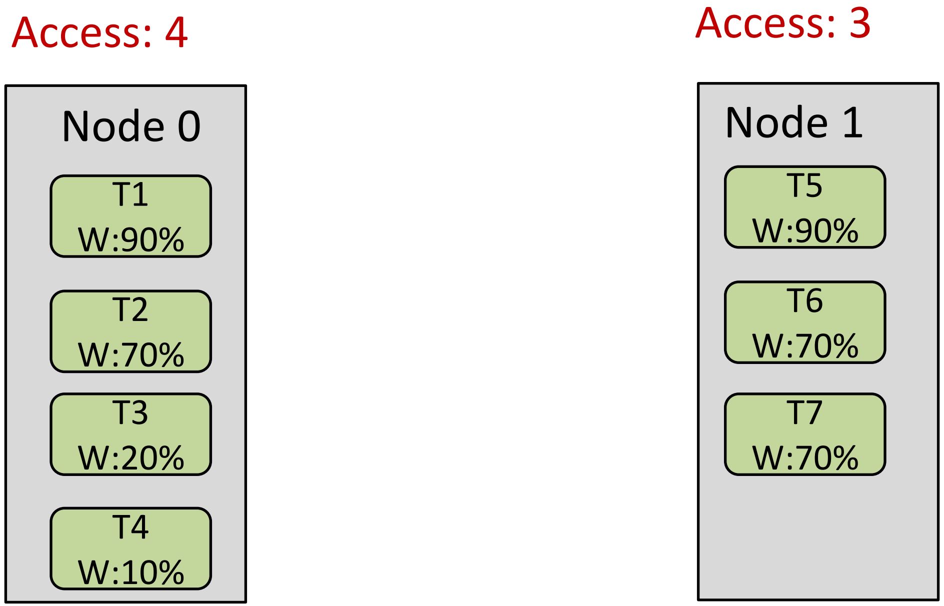

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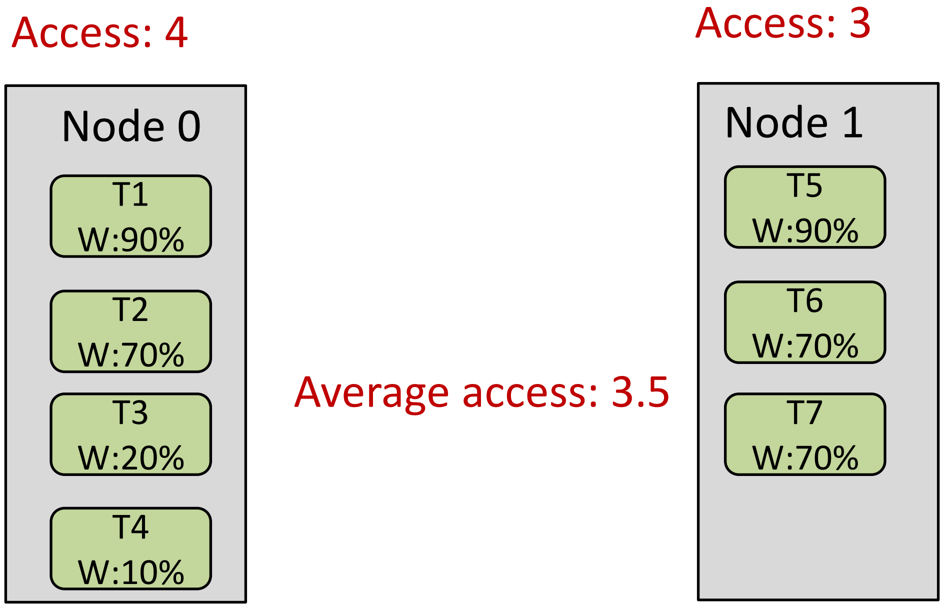

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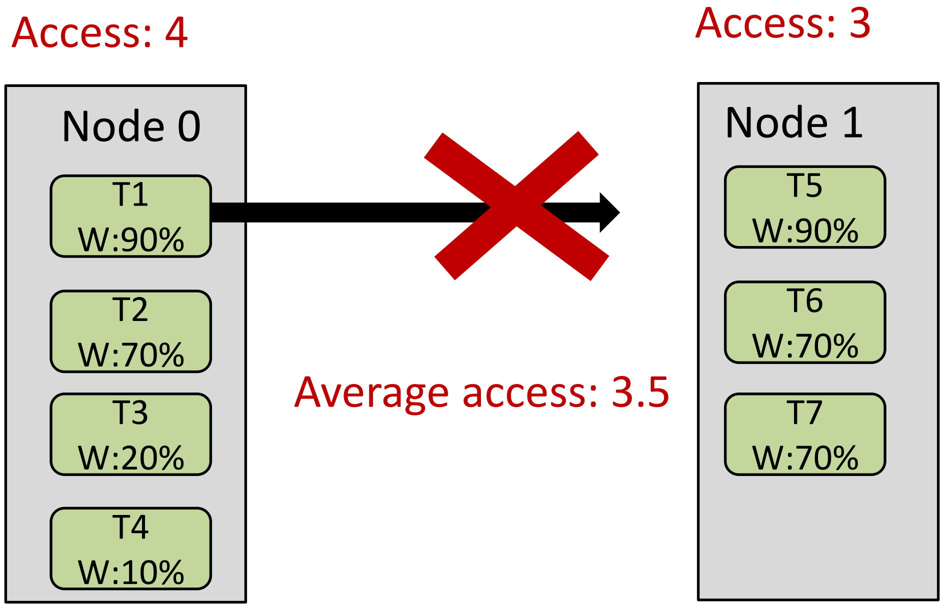

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- How to reduce contention
  - Migrating threads from NUMA node with high CPU utilization to other low CPU utilization node
- How to avoid new contention
  - If the CPU utilization of migrate thread and target NUMA node does not exceed 90%, migrating thread

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- How to increase CPU cache sharing
  - Reducing remote memory access

Composing Optimizations together

- Remote access, resource contention and CPU cache sharing

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- Remote access, resource contention and CPU cache sharing
  - Reduce remote access can increase CPU cache sharing
    - Threads accessing the same data run in the same node, sharing CPU cache

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    - Threads accessing the same data run in the same node, sharing CPU cache
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Composing Optimizations together

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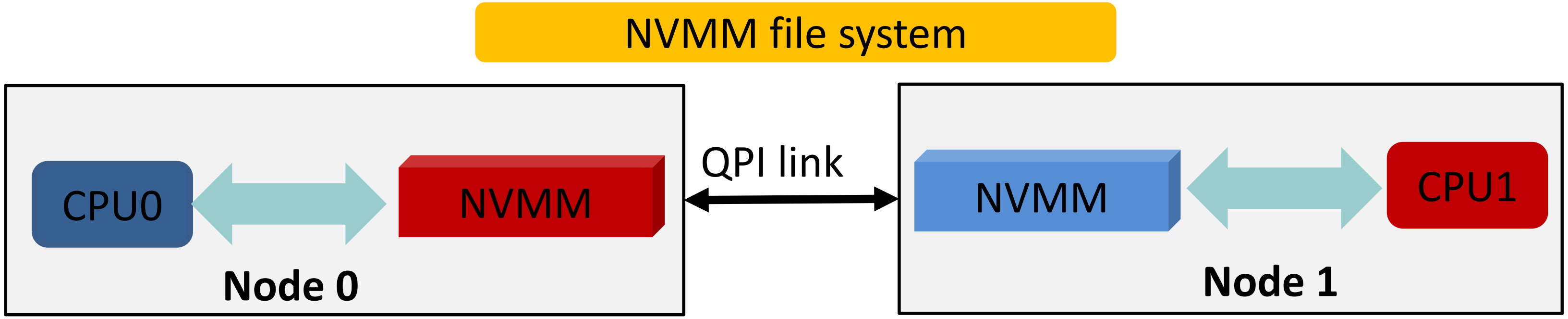
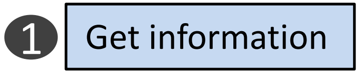
    - Threads accessing the same data run in the same node, sharing CPU cache
  - Reduce resource contention may increase remote memory access and destroy CPU cache sharing
  - Reduce NVMM contention may increase CPU contention



Composing Optimizations together

- What-if analysis

Composing Optimizations together



❶ Get information

- What-if analysis
  - Get information each second
    - Data access size, NVMM bandwidth, CPU utilization and data sharing

Composing Optimizations together

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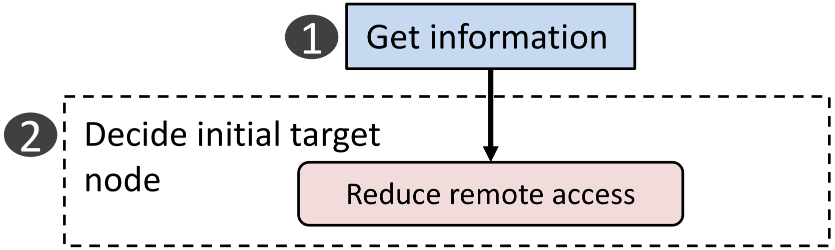
  - Get information each second
    - Data access size, NVMM bandwidth, CPU utilization and data sharing
  - Decide initial target node
    - Reduce remote memory access



Composing Optimizations together

- What-if analysis
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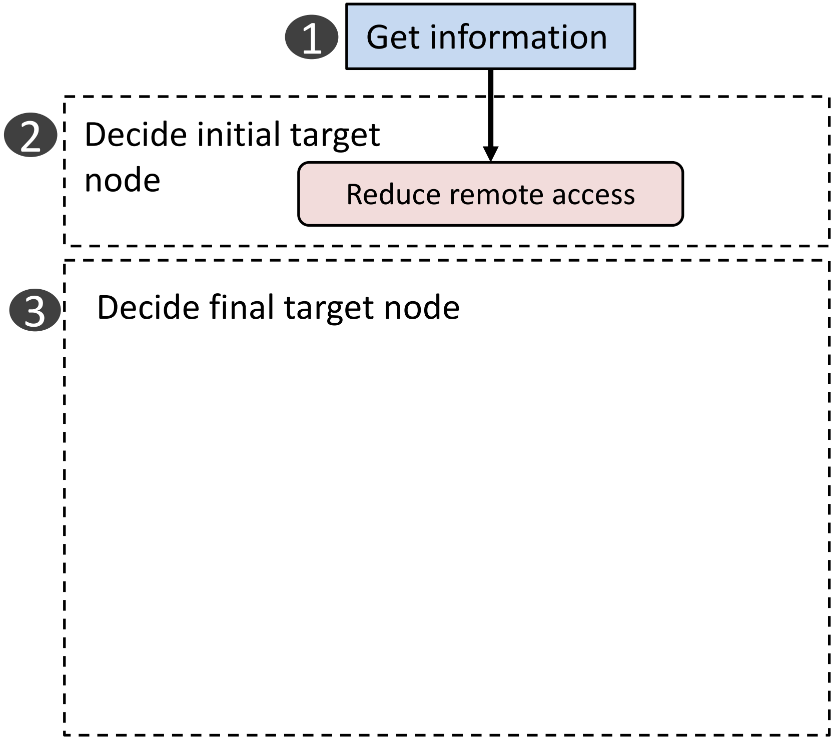
    - Reduce remote memory access
  - Decide final target node
    - Reduce NVMM and CPU contention



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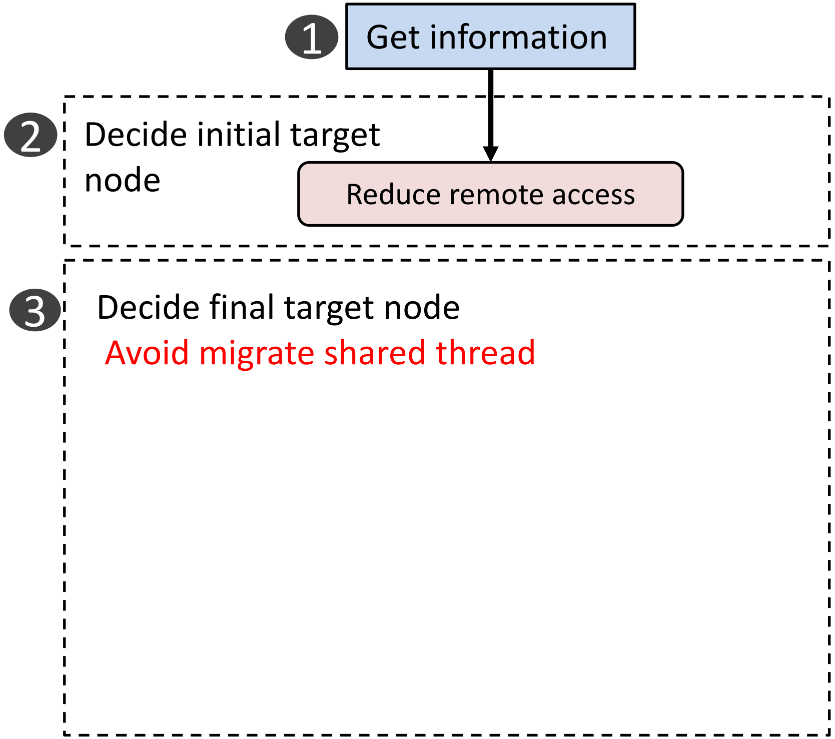
      - Avoid migrate shared thread



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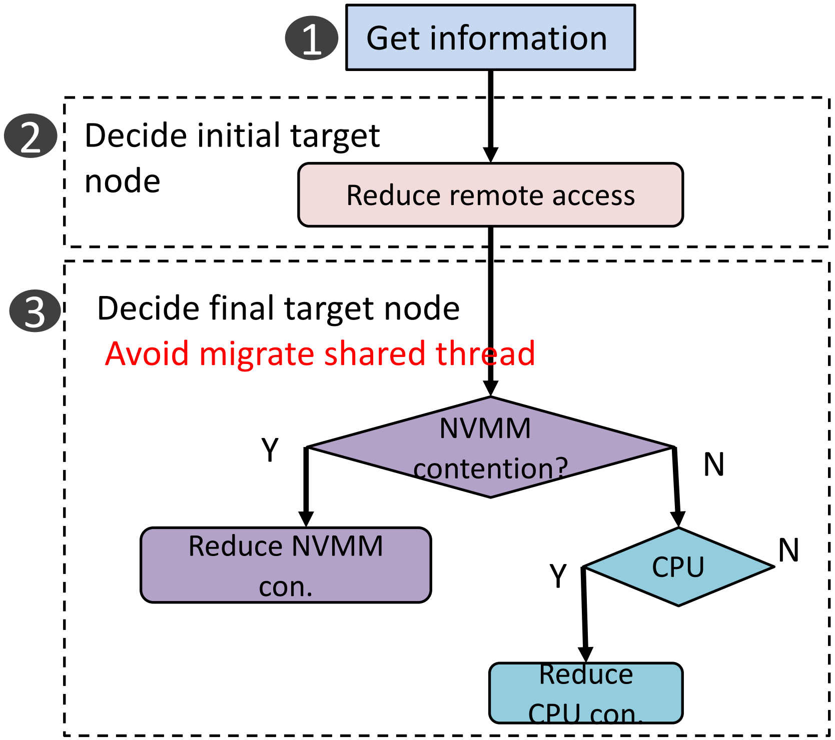

Composing Optimizations together

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  - Decide initial target node
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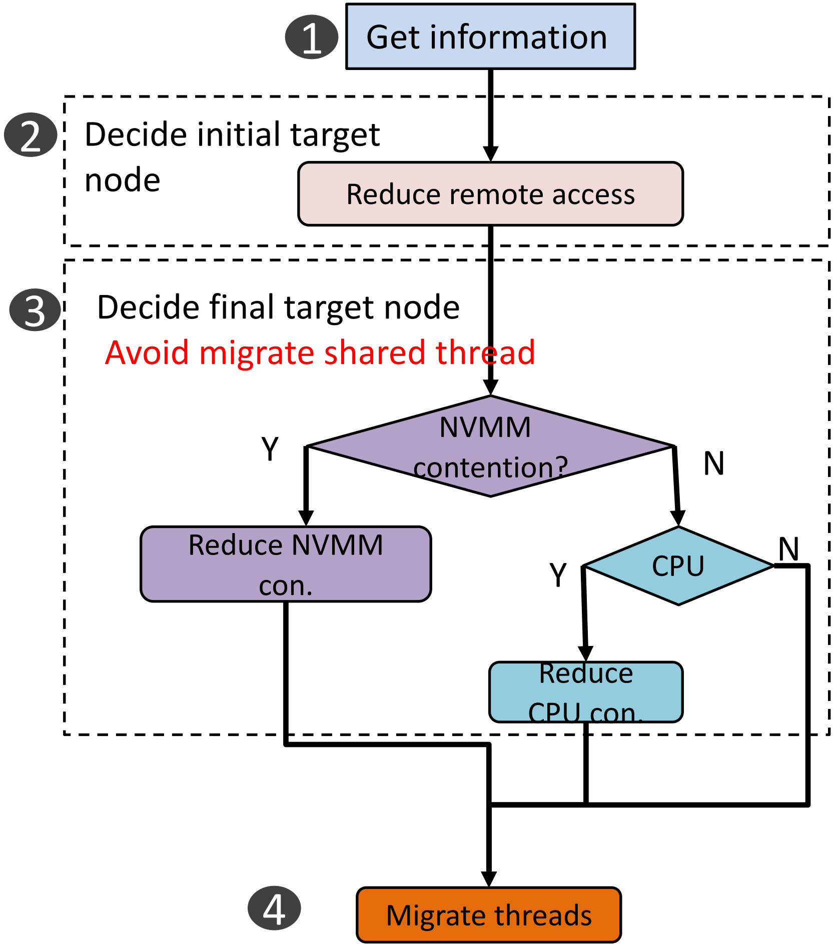
    - Reduce NVMM and CPU contention
      - Avoid migrate shared thread
      - NVMM > CPU (Refer to paper)
  - Migrate threads



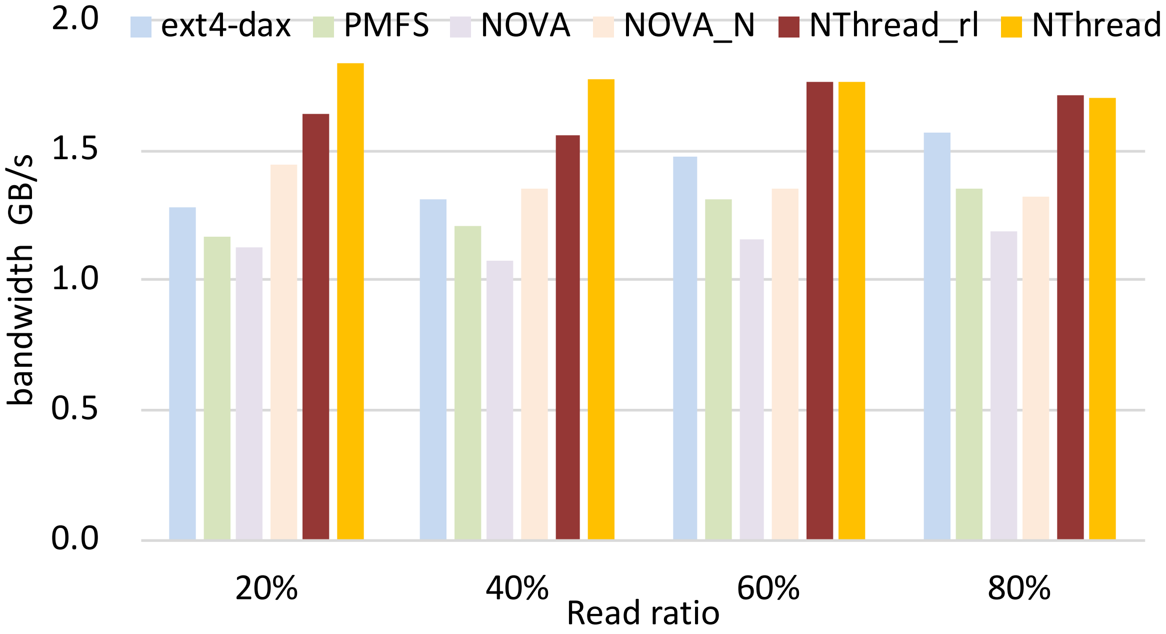
Outline

- Background & Motivation
- NThread design
  - Reduce remote access
  - Reduce resource contention
  - Increase CPU cache sharing
- Evaluation
- Summary

Evaluation

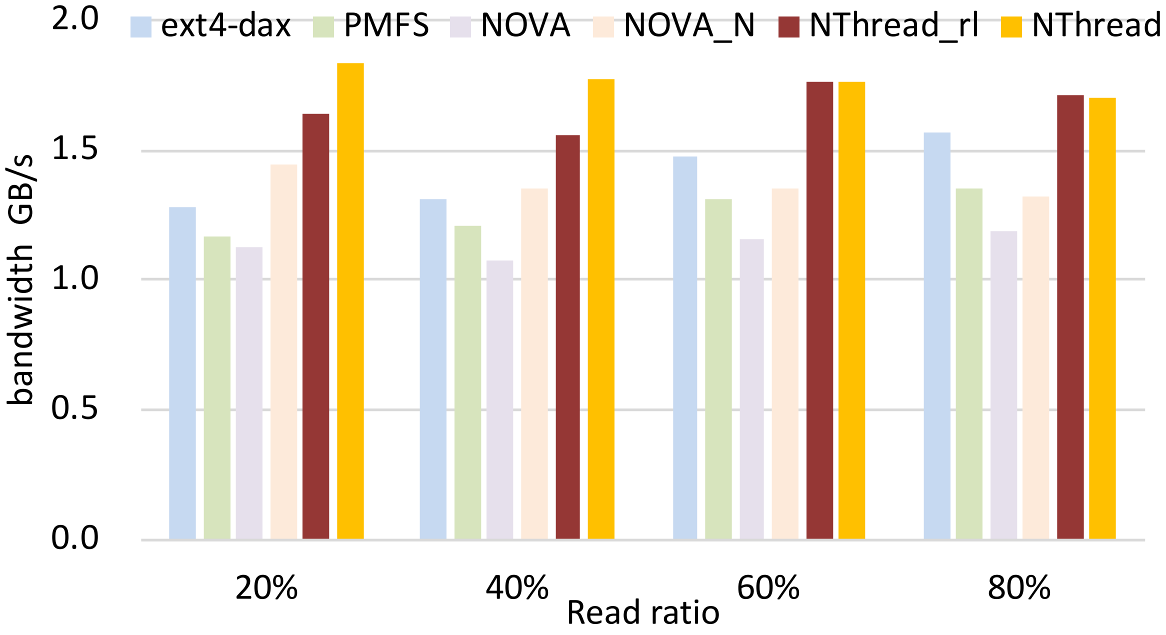
- Platform
  - Two NUMA nodes
    - Intel Xeon 5214 CPU，10 CPU core
    - 64G DRAM, 128G Optane PMM
  - Four NUMA nodes
    - Intel Xeon 5214 CPU，10 CPU core
    - 4GB DRAM, 12GB Emulated PMM
- Compared system
  - Existing FS: Ext4-dax, PMFS, NOVA, NOVA_n
  - Modified FS: NOVA_n (A NOVA-based multi-node support FS)

Micro-benchmark: fio



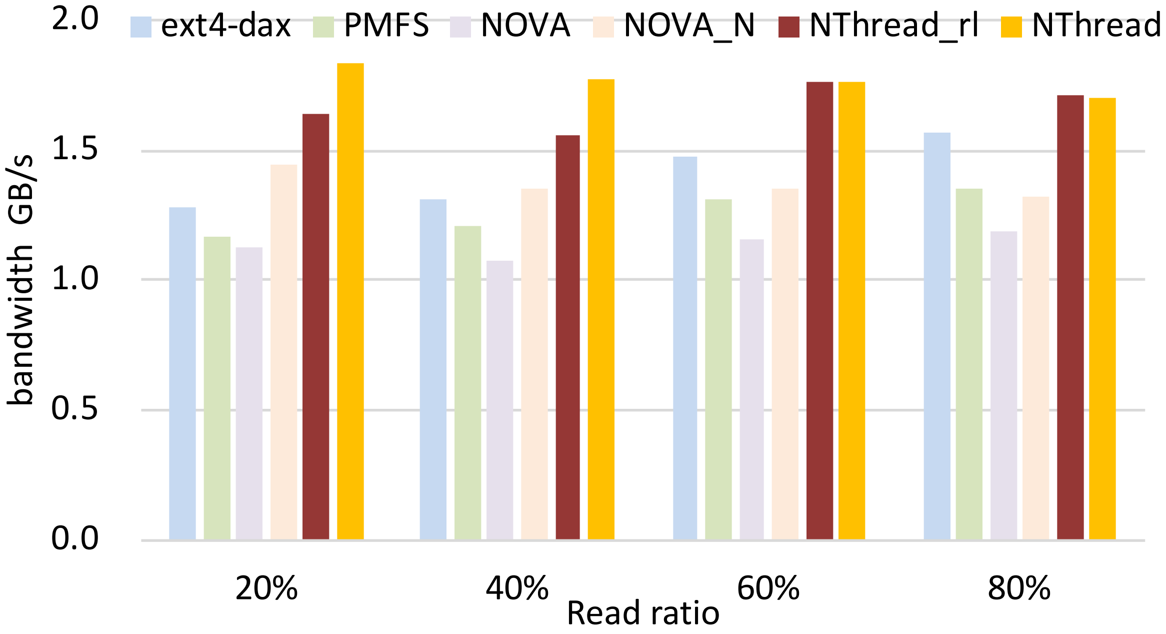
Micro-benchmark: fio

- NThread_rl: reduce remote access
  - The bandwidth is increased by 26.9% when the read ratio is 40%



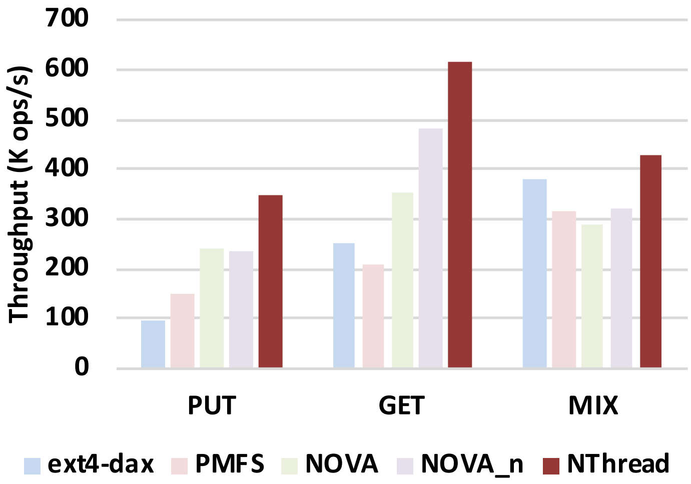
Micro-benchmark: fio

- NThread_rl: reduce remote access
  - The bandwidth is increased by 26.9% when the read ratio is 40%
- NThread: reduce remote access, avoid contention and increase CPU sharing
  - Bandwidth increased by an average of 43.8%

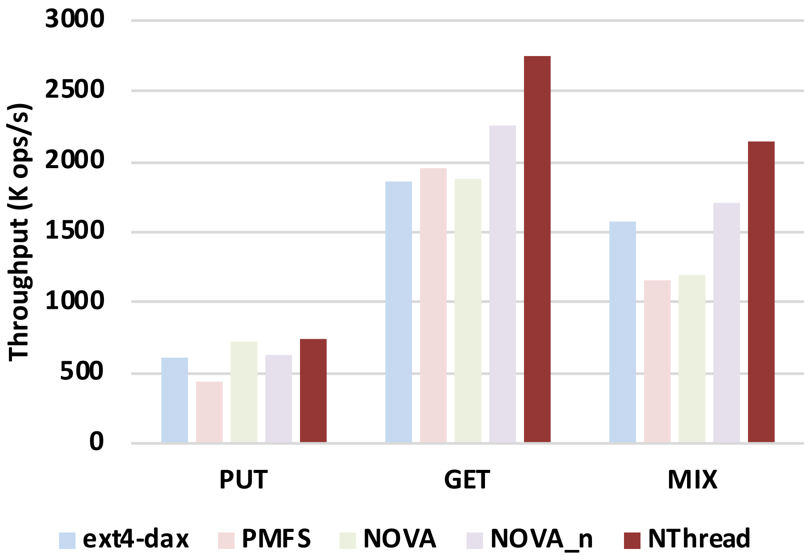


Application: RocksDB

- NThread increases the throughput by 88.6% on average when RocksDB runs in the NVMM file system



Two NUMA nodes



Four NUMA nodes

Outline

- Background & Motivation
- NThread design
  - Reduce remote access
  - Reduce resource contention
  - Increase CPU cache sharing
- Evaluation
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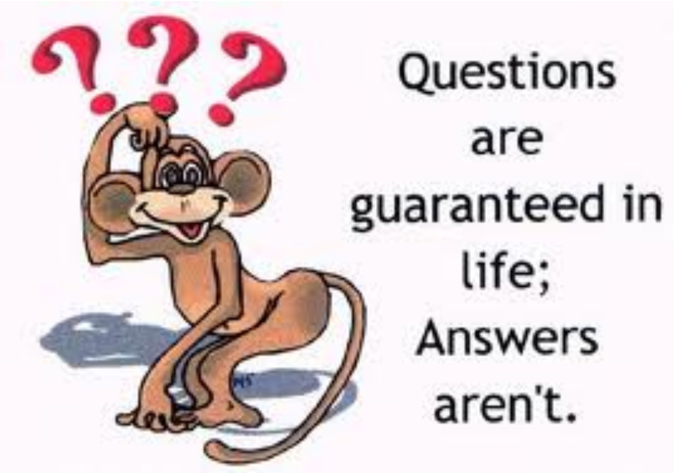
  - Apply what-if analysis to decide the execution orders of these optimizations
  - Increase application throughput by 88.6% on average

Thanks！



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