Designing MPI Library with On-Demand Paging (ODP) of InfiniBand: Challenges and Benefits

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Outline

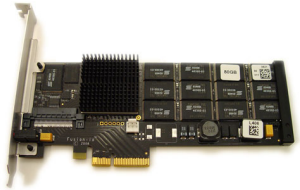
- Introduction
- Problem Statement
- Analyze ODP Performance at Verbs-level
- Design an ODP-Aware MPI Runtime
- Performance Evaluation
- Conclusion and Future Work

Drivers of Modern HPC Cluster Architectures

Multi-core Processors

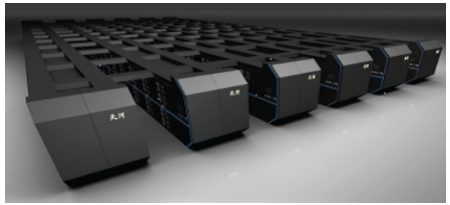
High Performance Interconnects - InfiniBand
<1usec latency, 100Gbps Bandwidth>

Accelerators / Coprocessors high compute density, high performance/watt
>1 TFlop DP on a chip



SSD, NVMe-SSD, NVRAM

- Remote Direct Memory Access (RDMA)-enabled networking (InfiniBand and RoCE)
- < 1usec latency, 100Gbps bandwidth



Tianhe – 2

Titan

Stampede

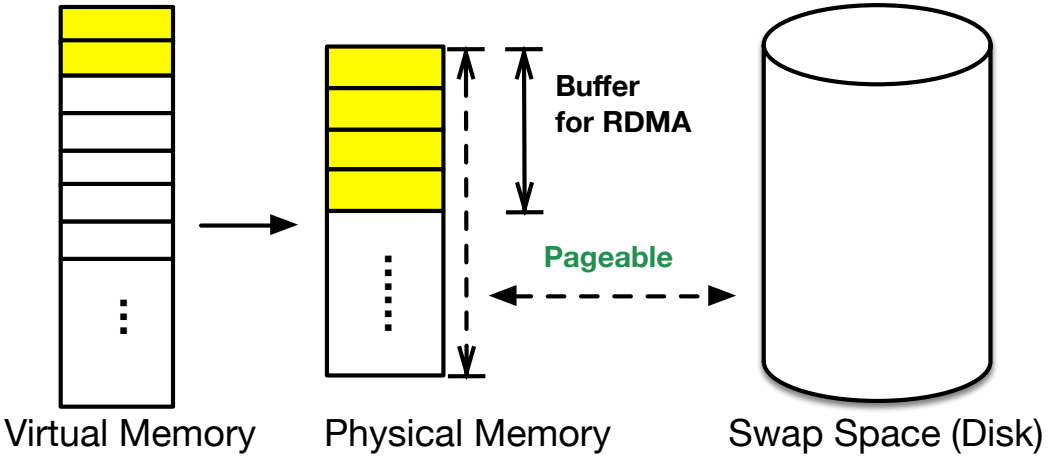
Tianhe – 1A

Existing RDMA Communication on InfiniBand

- Pin-down pages of communication buffer for RDMA operations
  - Pin-down/Unpin pages is costly
- MPI stacks on InfiniBand
  - Pinned bounce buffers: small messages
  - Pin-down cache: large messages
- Bottlenecks with existing scheme
  - Limit physical memory resources for computation
  - Contentions between multiple jobs on the same node
  - Pinned buffers have to fit in physical memory

On-Demand Paging (ODP)

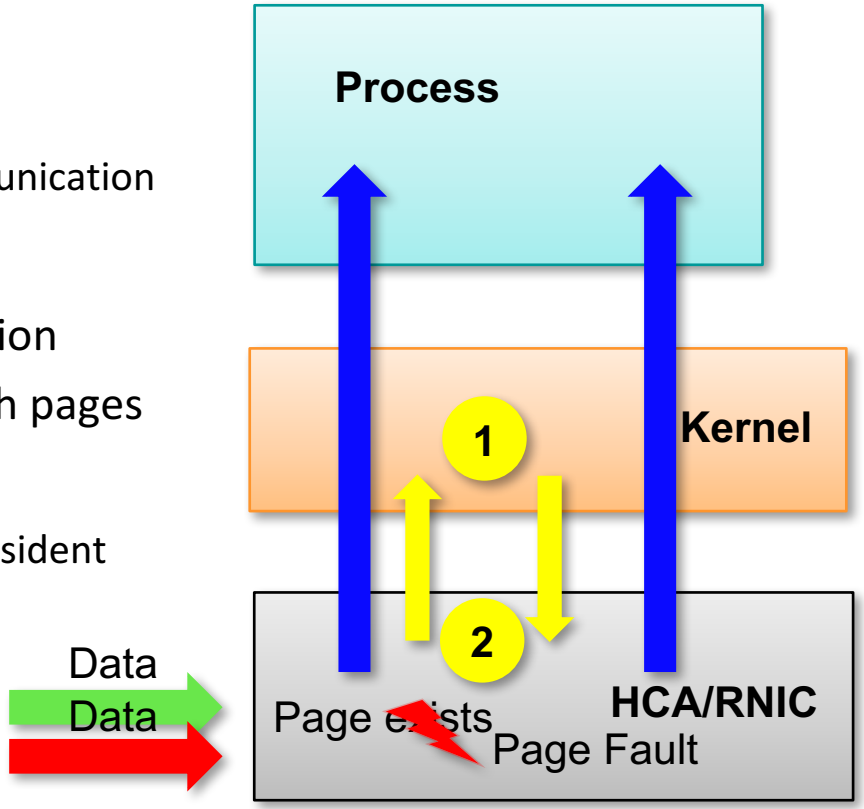
- A new feature of IB introduced by Mellanox for RDMA communications
- Communication buffers are no longer pinned
  - Paged in when the host channel adapter (HCA) needs them
  - Swapped out when reclaimed by the OS



Overview of ODP

- How page fault is handled:
  - 1: Get pages, map to DMA
  - 2: Update mapping, resume communication

- Pre-fetch: a new verbs-level operation introduced by Mellanox to pre-fetch pages
  - Warm up communication buffers
  - No guarantee that pages remain resident



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Problem Statement

- What are the performance characteristics of ODP performance at IB verbs-level?
- Can we design an high performance ODP-Aware MPI runtime for point-to-point and one-sided routines?
- What kind of benefits can be achieved at applications using ODP-Aware MPI runtime?

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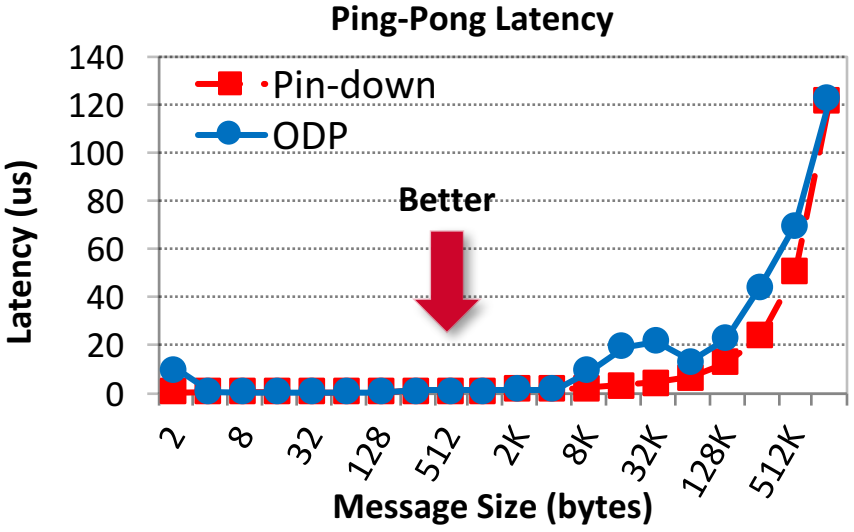
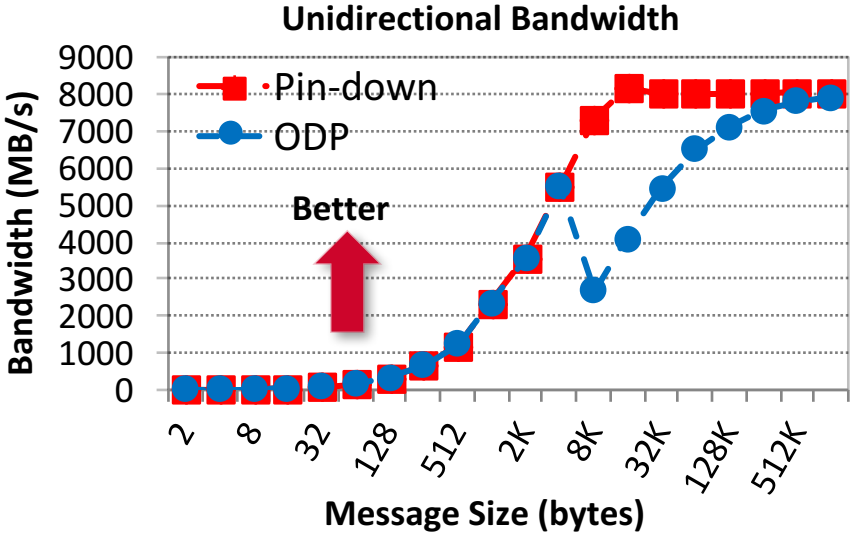
Experimental Setup

- ODP has not yet been deployed at any serious scale
- Nowlab Cluster
  - 4 Sandy Bridge, 2 Ivy Bridge, 2 Haswell Compute Nodes
  - MT4113 Connect-IB HCAs (56 Gbps data rate)
  - Mellanox OpenFabrics version 3.1-1.0.3
  - RHEL 7.1.1503 with kernel version 4.2.3
- A set of proposed verbs-level benchmarks to analyze ODP performance

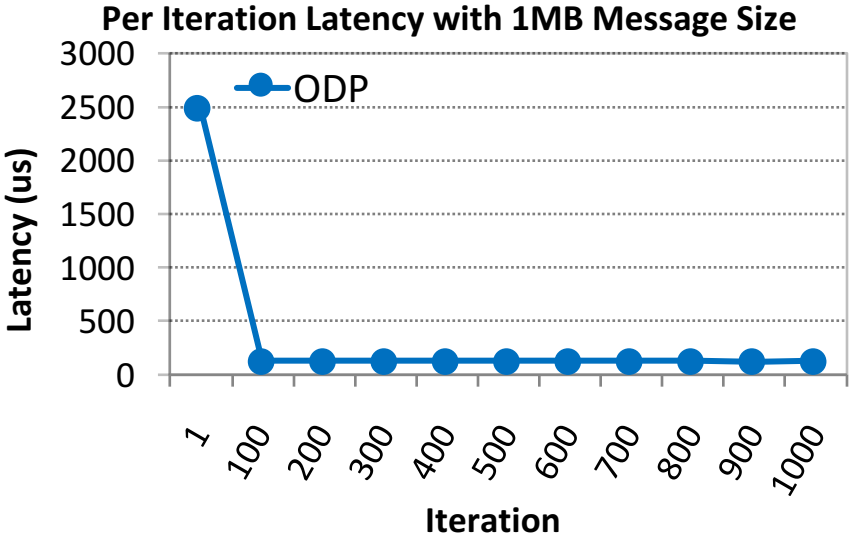
Verbs-level Latency & Bandwidth

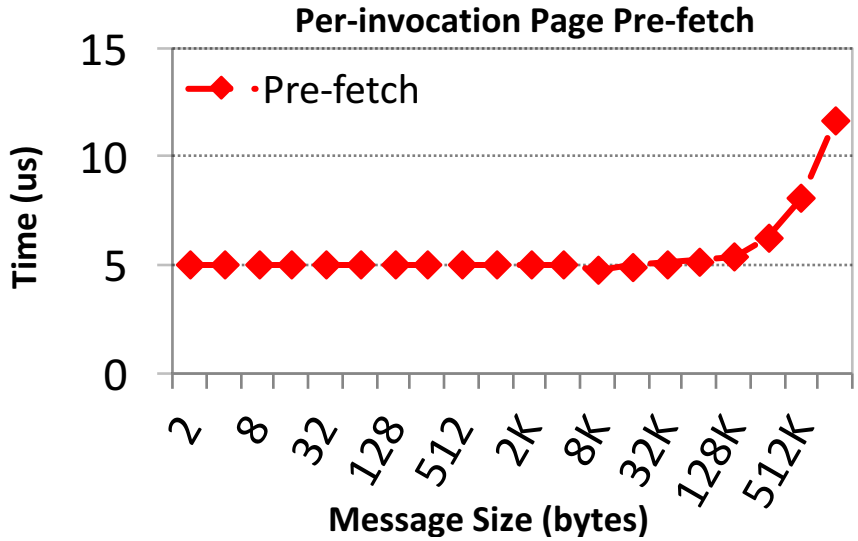




- A 4MB send/receive buffer on each process, one process per node
- ODP achieves the same performance as Pin-down if there is no page fault
- A memory region is touched does not imply that the HCA has a mapping for it

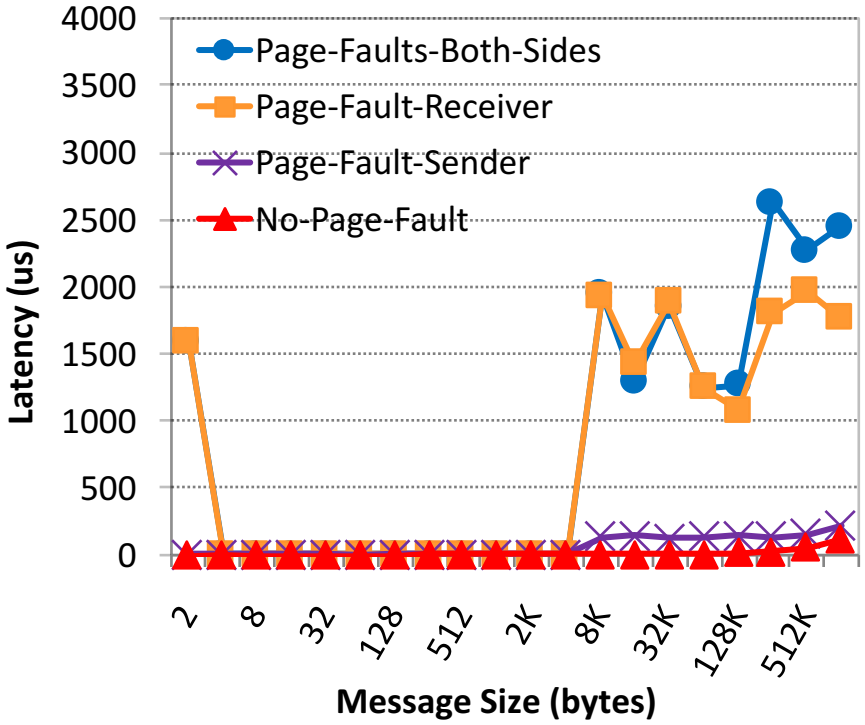
Page Fault / Page Pre-fetch Overhead





- Page fault only happens in the first iteration, but the overhead is high
- The pre-fetch operation needs around 5us to warm up 2 bytes buffer

Page Fault Overhead at Sender/Receiver



- Pre-fetch operation works very effectively to avoid page faults
- Overhead of resolving page fault at sender or receiver is different
- Page fault at receiver side needs to suspend Queue Pair (QP) to avoid congestion

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Challenges of High Performance ODP-Aware MPI Runtime

- A native design uses ODP for RDMA operations
  - Adds page fault overhead in critical paths
- An enhanced design with pre-fetch optimization
  - Incurs page pre-fetch overhead in critical paths
- The following challenges need to be resolved:
  - How to reduce the number of page faults?
  - When should pre-fetch operations be issued?
  - How to ensure that pre-fetched buffers are still valid (resident, mapping)?
  - How to apply these designs for different protocols?

MPI Point-to-Point with ODP (1)

- Most MPI stacks have two protocols for data transfers
  - Eager protocol: eagerly sends data to the other process
  - Rendezvous protocol: handshake before data exchange

- Eager Protocol:
  - Bounce buffers are around few MBs per process
  - Small messages are latency sensitive
  - Pre-fetch bounce buffer before send incurs overhead

MPI Point-to-Point with ODP (2)

- Rendezvous protocol with blocking primitives
  - Pre-fetched buffer after RTS/CTS messages

- Rendezvous Protocol with non-blocking primitives
  - Issue pre-fetch for the same buffer again
  - Pre-fetch operations could be overlapped with the handshake phase

MPI Remote Memory Access (RMA) with ODP

- RMA window with ODP
  - Overhead of pre-fetch could not be overlapped
  - Pre-fetched window buffer could be invalidated

- RMA communication with ODP
  - Pre-fetch window buffers in synchronization operation
  - Get: pre-fetch origin buffers after RDMA operation has been issued

Overview of the MVAPICH2 Project

- High Performance open-source MPI Library for InfiniBand, Omni-Path, Ethernet/iWARP, and RDMA over Converged Ethernet (RoCE)
  - MVAPICH (MPI-1), MVAPICH2 (MPI-2.2 and MPI-3.0), Started in 2001, First version available in 2002
  - MVAPICH2-X (MPI + PGAS), Available since 2011
  - Support for GPGPUs (MVAPICH2-GDR) and MIC (MVAPICH2-MIC), Available since 2014
  - Support for Virtualization (MVAPICH2-Virt), Available since 2015
  - Support for Energy-Awareness (MVAPICH2-EA), Available since 2015
  - Support for InfiniBand Network Analysis and Monitoring (OSU INAM) since 2015
  - **Used by more than 2,675 organizations in 83 countries**
  - **More than 401,000 (> 0.4 million) downloads from the OSU site directly**
  - Empowering many TOP500 clusters (Nov '16 ranking)
    - **1th ranked 10,649,600-core cluster (Sunway TaihuLight)** at National Supercomputing Center in Wuxi
    - 13th ranked 241,108-core cluster (Pleiades) at NASA
    - 17th ranked 462,462-core cluster (Stampede) at TACC
    - 40st ranked 74,520-core cluster (Tsubame 2.5) at Tokyo Institute of Technology and many others
  - Available with software stacks of many vendors and Linux Distros (RedHat and SuSE)
  - http://mvapich.cse.ohio-state.edu
- Empowering Top500 systems for over a decade
  - System-X from Virginia Tech (3rd in Nov 2003, 2,200 processors, 12.25 TFlops) ->
  - Stampede at TACC (12th in Jun'16, 462,462 cores, 5.168 Plops)

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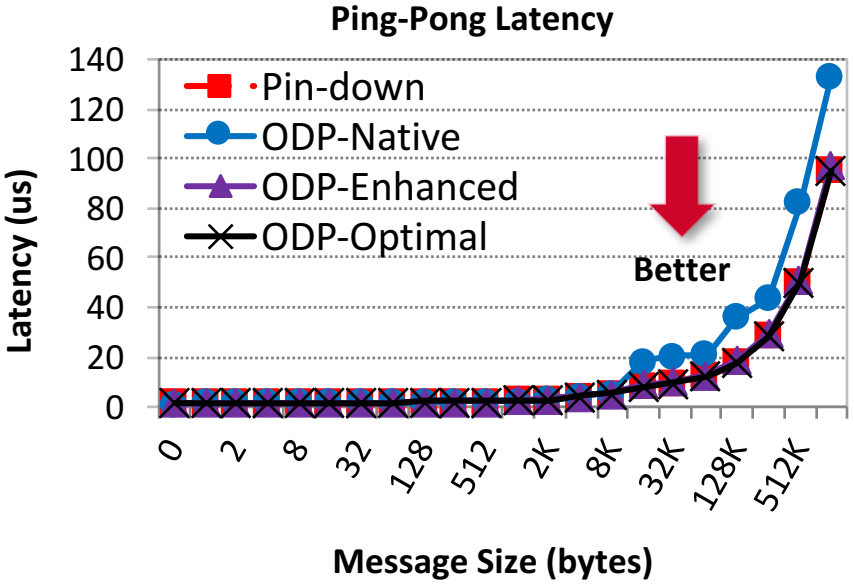
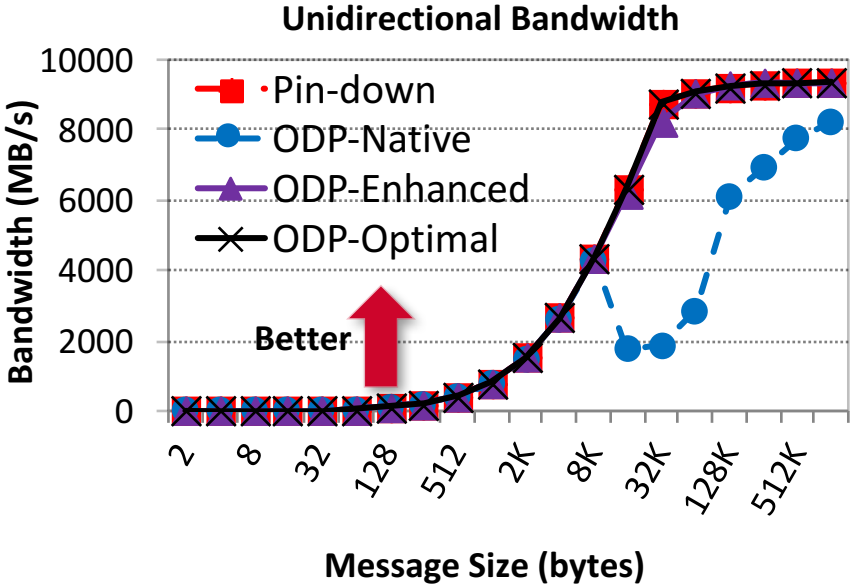
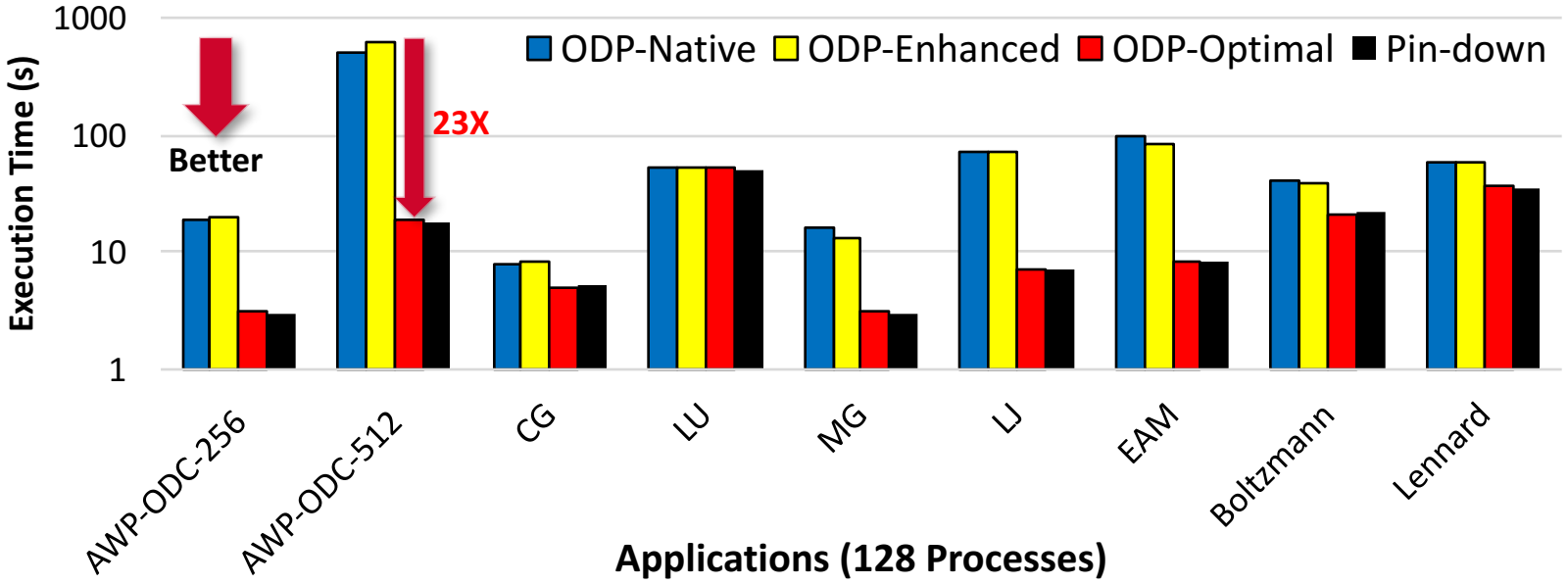
MPI Level Point-to-Point Latency & Bandwidth





- Both ODP-Enhanced and ODP-Optimal schemes achieve the same performance as the pin-down scheme
- The performance degradation with ODP-Native scheme is caused by page fault

Application Level Experiments



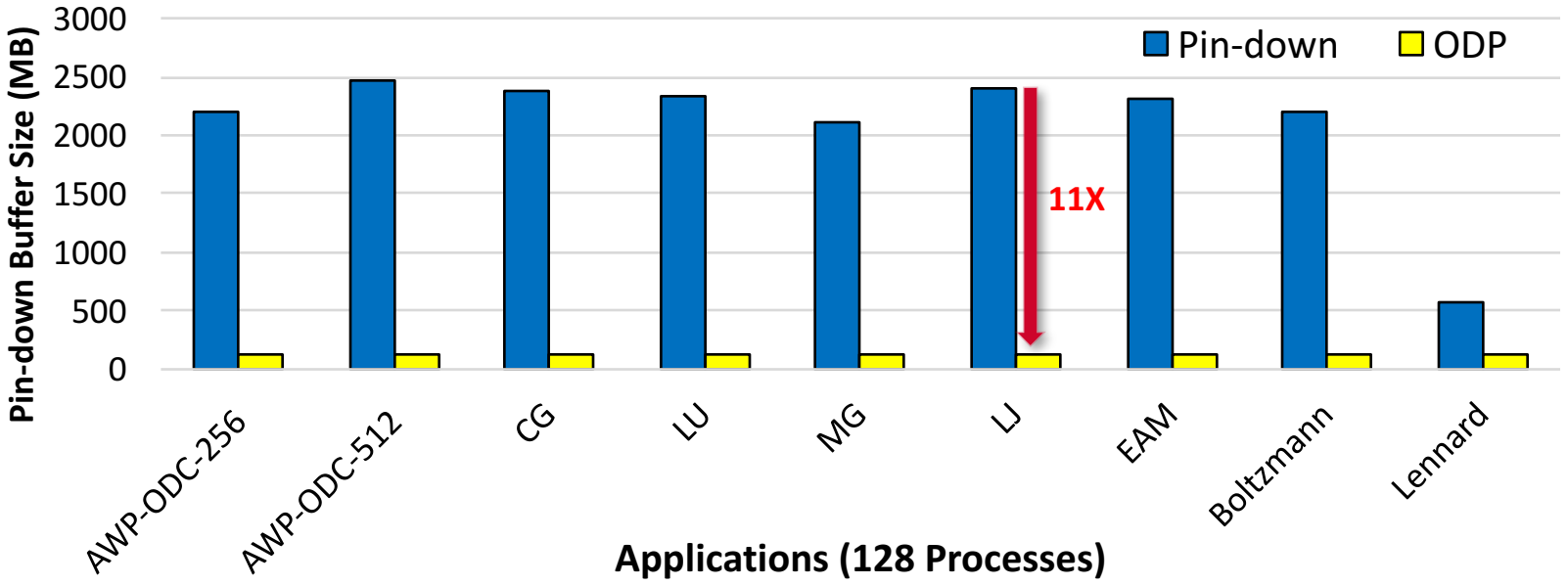
- ODP-Optimal scheme achieves the same performance as the pin-down scheme
- For AWP-ODC with input size 512X512X512, ODP-Optimal scheme could reduce the total execution time by 23X compared with other ODP schemes

Application Level Performance Analysis

Apps.	# Page Fault Events			#Pre-fetched Pages	
	ODP-Native	ODP-Enhanced	ODP-Optimal	ODP-Enhanced	ODP-Optimal
NAS-CG	245	143	0	1224	6177
NAS-LU	280	180	0	1912	18630
NAS-MG	986	730	0	5330	10944
Lammps-LJ	3023	2880	4	22378	52266
Lammps-EAM	5701	4430	4	20849	63790
AWP-ODC (256^3)	2986	2014	0	4358	11229
AWP-ODC (512^3)	20638	17252	53	28730	67332
Boltzmann	1052	704	0	3528	17139
Lennard	1745	1623	0	4032	25382

- Profile the number of page fault events and pre-fetched pages to analyze the performance difference
- For AWP-ODC with input size 512X512X512, ODP-Optimal scheme could significantly reduce the number of page fault events

Application Level Pin-down Buffer Sizes



- Pin-down buffer size is significantly reduced with ODP schemes
- For LJ application, the size of pin-down buffers could be reduced by 11X

Conclusion & Future Work

- Presented the ODP feature and analyzed its performance characteristics with IB verbs-level micro-benchmarks
- Designed a high performance ODP-Aware MPI runtime to support MPI point-to-point and RMA routines
- Proposed ODP-Aware MPI runtime shows good performance at micro-benchmarks and applications
- Plan to evaluate proposed designs at scale

Thank You!

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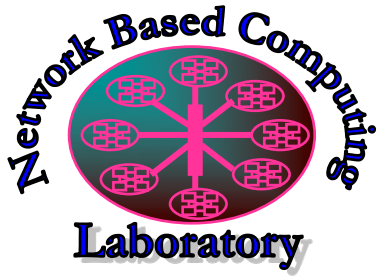

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