Hybrid MPI - A Case Study on the Xeon Phi Platform

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Hybrid MPI - Motivation

- MPI – dominant programming model in HPC
- Hybrid MPI – MPI implementation specialized for intra-node point to point communication
  - Fast point to point communication over shared memory hardware
- Evolving processor architectures
  - Single Core → Dual Core → Quad Core → Multi-Core → Many-Core/Clusters
  - High compute density and performance per watt
  - Robust shared memory hardware
- Motivation – maximize use of many core hardware
  - Maximum use of shared memory hardware of the Xeon Phi
  - Gain Maximum communication performance from available bandwidth of the Xeon Phi hardware

Agenda

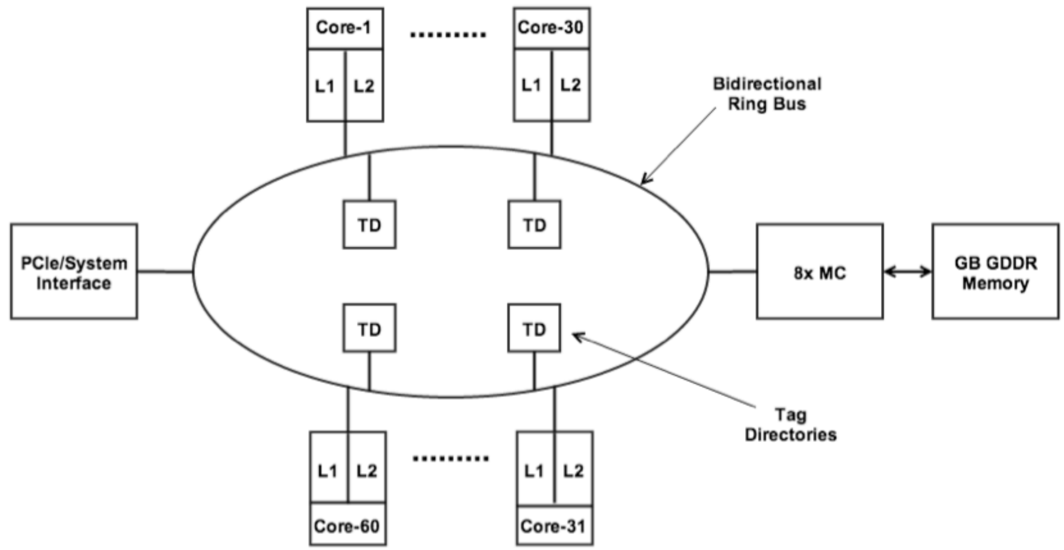
- Xeon Phi Platform
- Traditional MPI Design
- Hybrid MPI
  - A Shared Heap
  - Communication
- Experimental Evaluation
  - Micro-benchmarks
  - Applications
- Hybrid MPI Highlights
- Towards Hybrid MPI Future

Xeon Phi Platform

- Intel Many Integrated Core Architecture (MIC) → Xeon Phi (earlier known as Knights Corner - 50 cores)
  - Utilized in #1 supercomputing cluster – Tianhe-2 (http://top500.org/)
  - STAMPEDE @ TACC
- Xeon Phi processor → 61 cores with 4 Hardware Threads
  - No out of order execution
  - x86 compatibility
  - Shorter instruction set pipeline
- Simpler cores → higher power efficiency

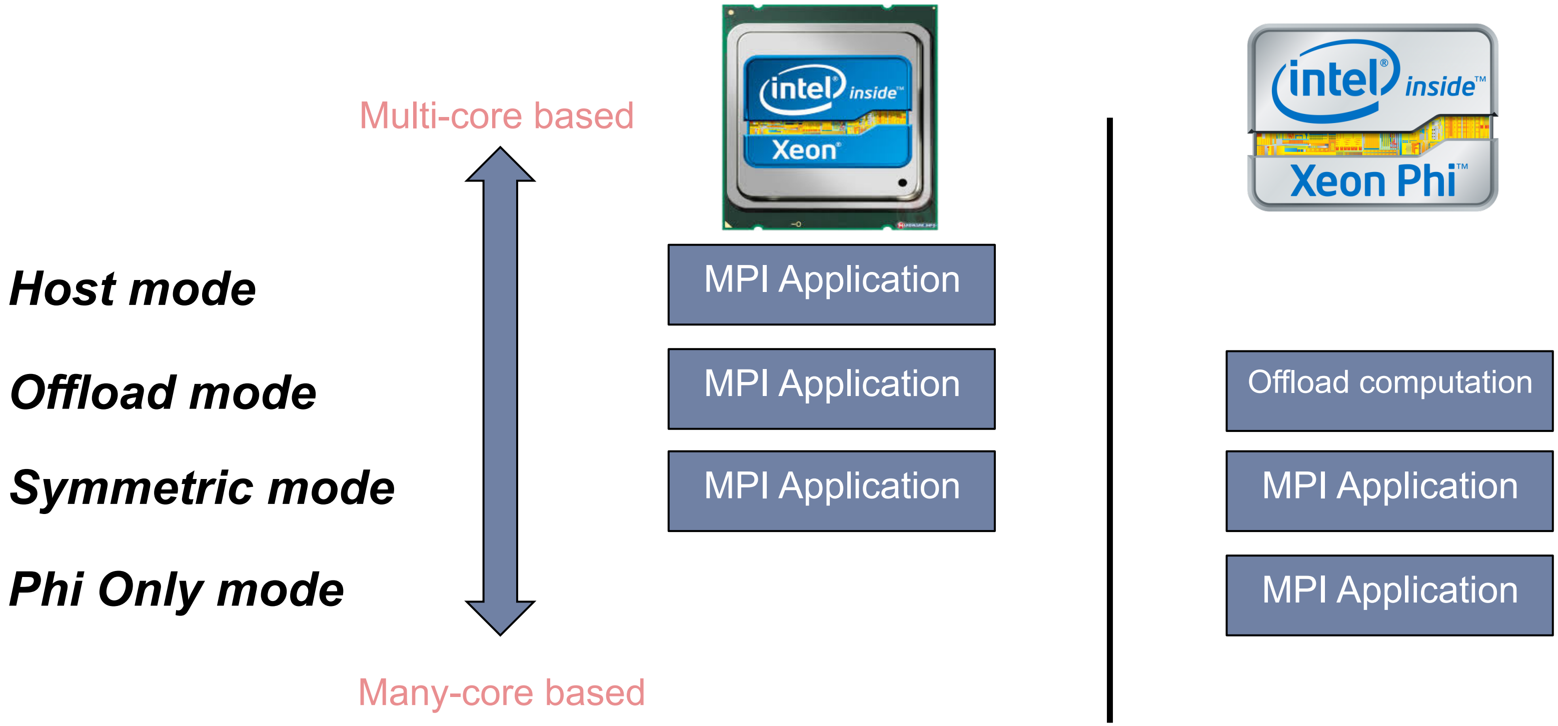
Xeon Phi Platform

- Inter core communication
  - Bi-directional ring topology interconnect
- ~320GB/s Aggregated Theoretical bandwidth



- 4 modes of operation (MPSS)
  - Host
  - Offload – offloads computation
  - Symmetric – ranks in both Host and Phi
  - Phi Only

Xeon Phi Software Model/Stack (MPSS)



- Offload/Symmetric/Phi-only supported via Intel Many-core Platform Software Stack(MPSS)
  - Shared memory/ SHM
  - SCIF
  - IB verbs/ IB-SCIF

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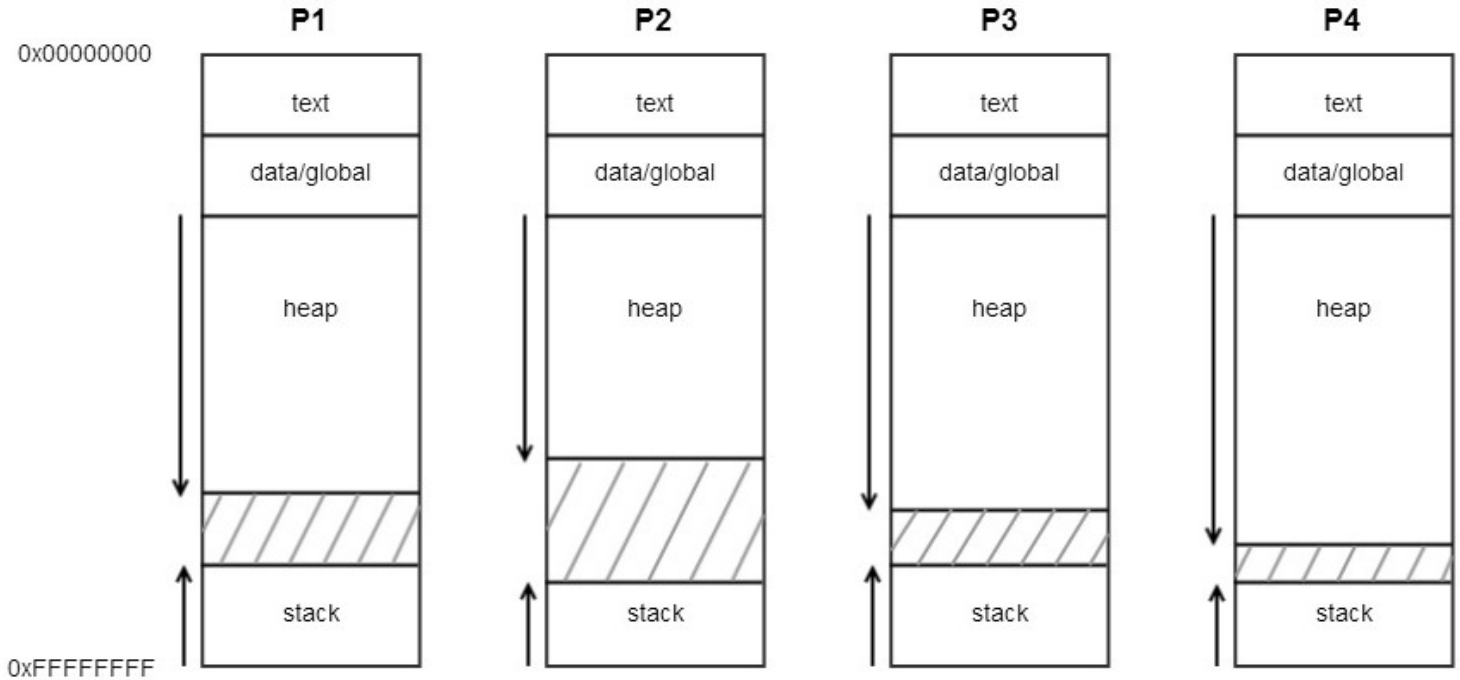
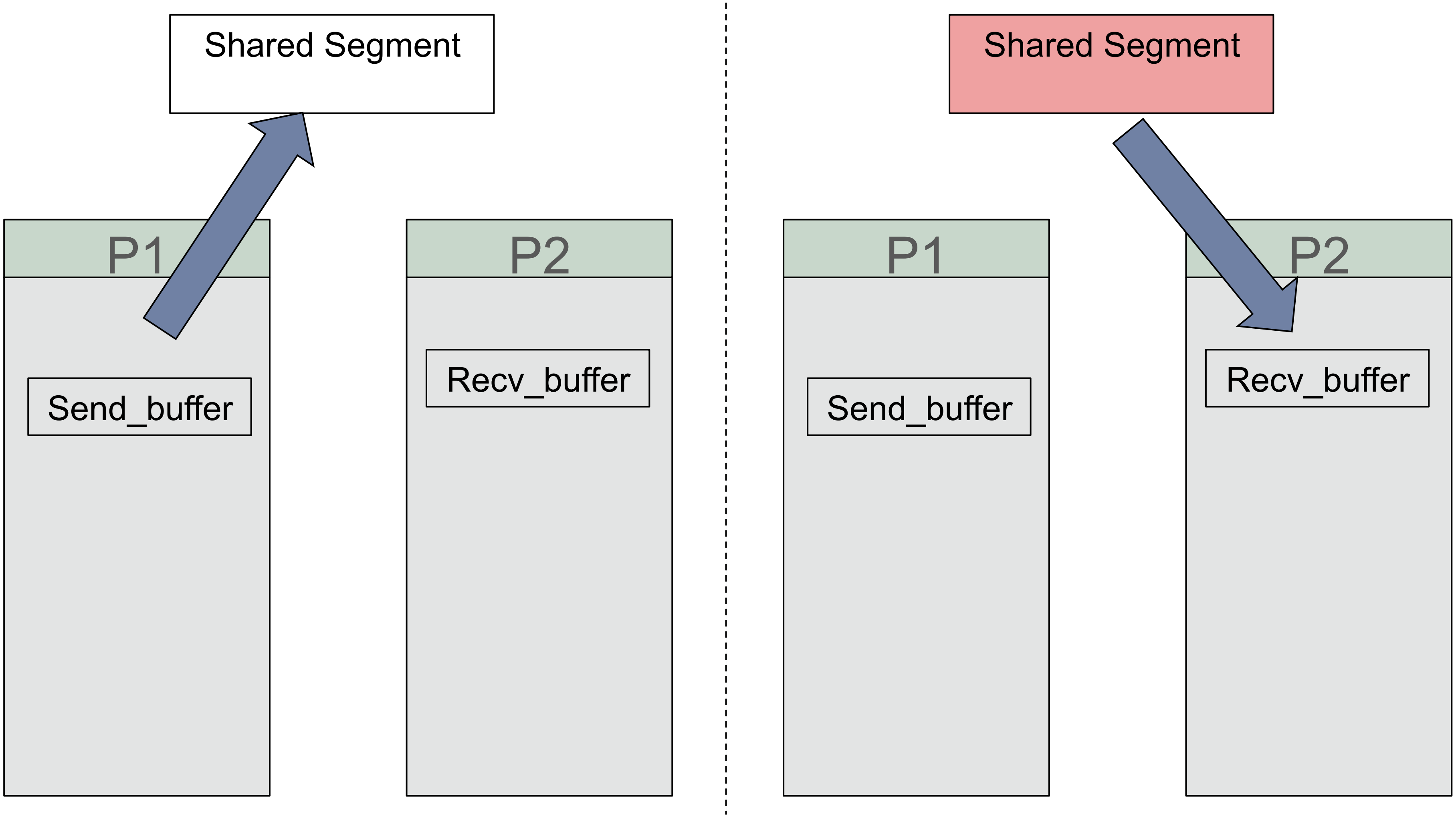
Traditional MPI with Disjoint Address Spaces



- Process based ranks - Regular process abstraction - Shared nothing
- Communication
  - Disjoint address spaces – multiple copies
  - IPC/Kernel buffers/ shared buffers – resources grow rapidly with number of ranks

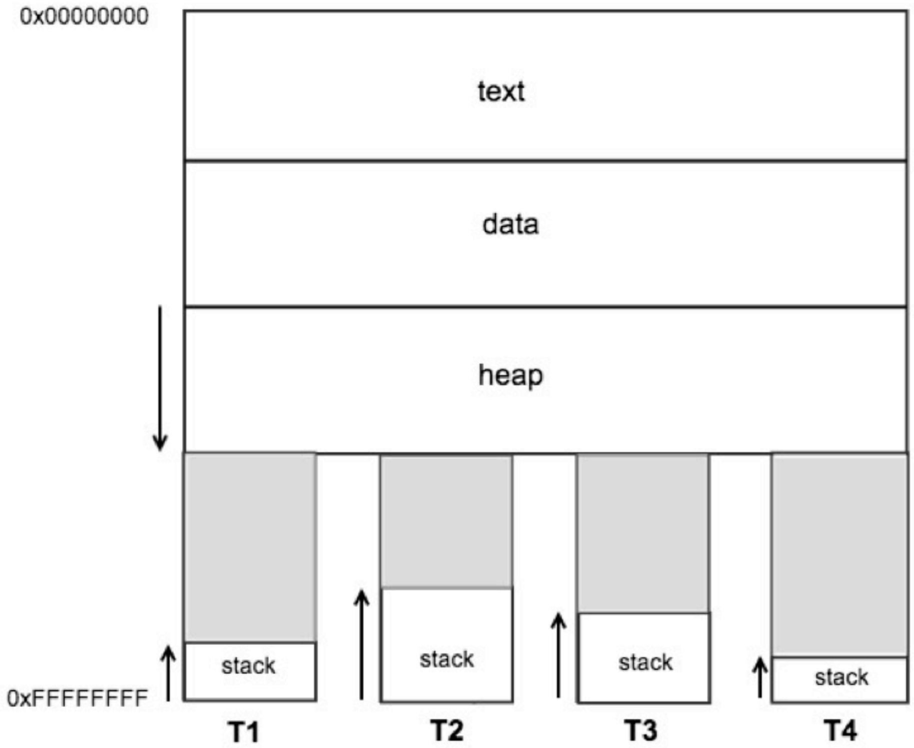
Traditional MPI with Disjoint Address Spaces (contd..)



- Two Copies – resources grow as ranks increase

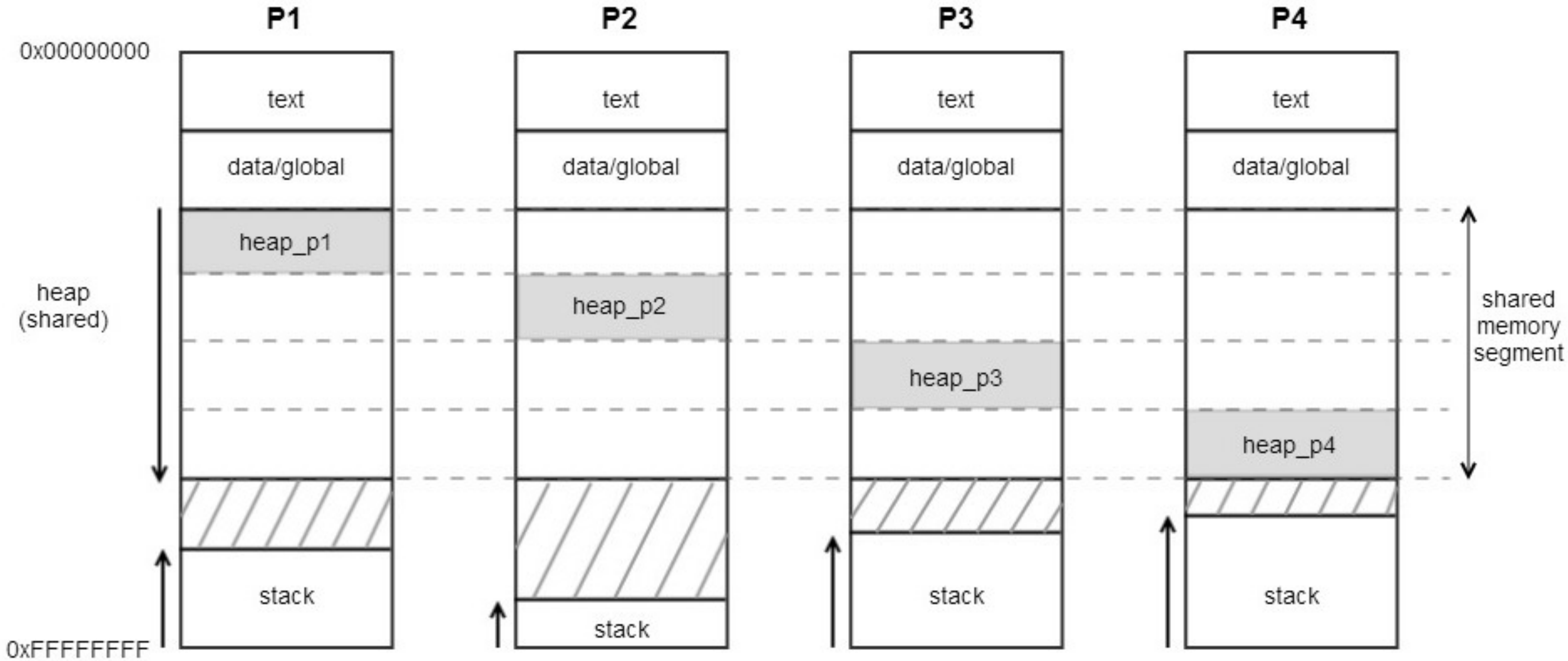
Alternative MPI – Avoid Copies

- Necessary to share memory
  - Thread based
  - Share everything
    - Heap/data/text segments are shared among threads
- Thread pinning to Xeon Phi cores via KMP_AFFINITY
  - scatter/compact/fine



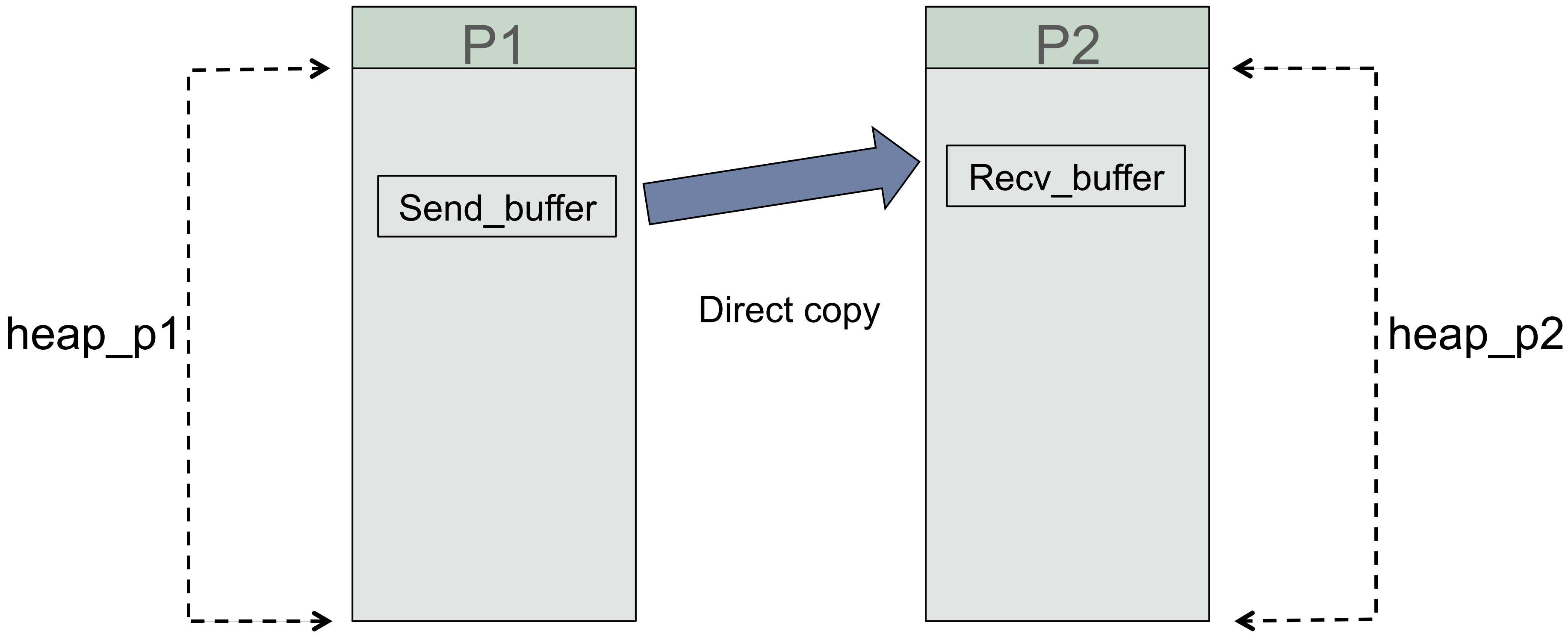
- However few problems arise when resources are shared
  - Ensure mutual exclusion
  - Transform globals/heap vars to thread local
  - *Network resource contention*

Hybrid MPI – A Shared Heap



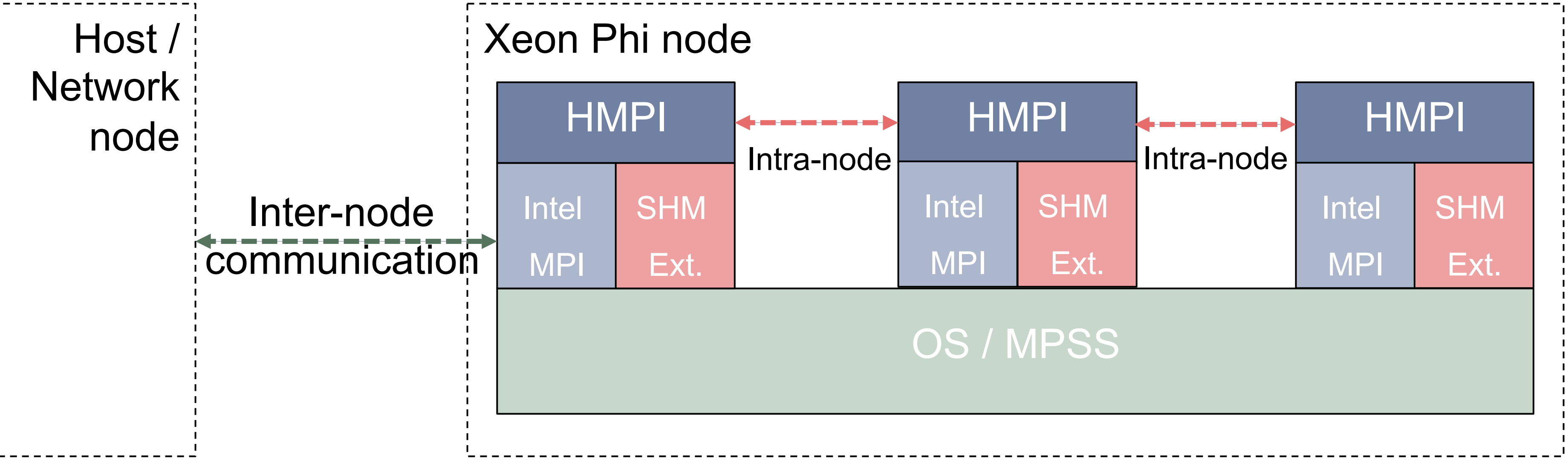
- Hybrid MPI approach
- Each rank P1, P2, P3, P4 heap is *mmap()* ed to a shared segment
  - Has access to entire shared segment
- Each process allocates memory on their own chunk → heap_p1, heap_p2, heap_p3, heap_p4

Hybrid MPI – A Shared Heap (contd..)



- Single Copy using the unified shared address space of Hybrid MPI
- Implementation with mmap()
  - **MAP_SHARED , MAP_FIXED** features

Hybrid MPI View on Xeon Phi



- Hybrid MPI has its own Shared Memory extension for Intra-node communication
- Inter-node communication via Intel MPI
  - Infiniband network
  - TCP/IP
  - PCIe(PCI express) / SCIF (Symmetric Communication Interface)

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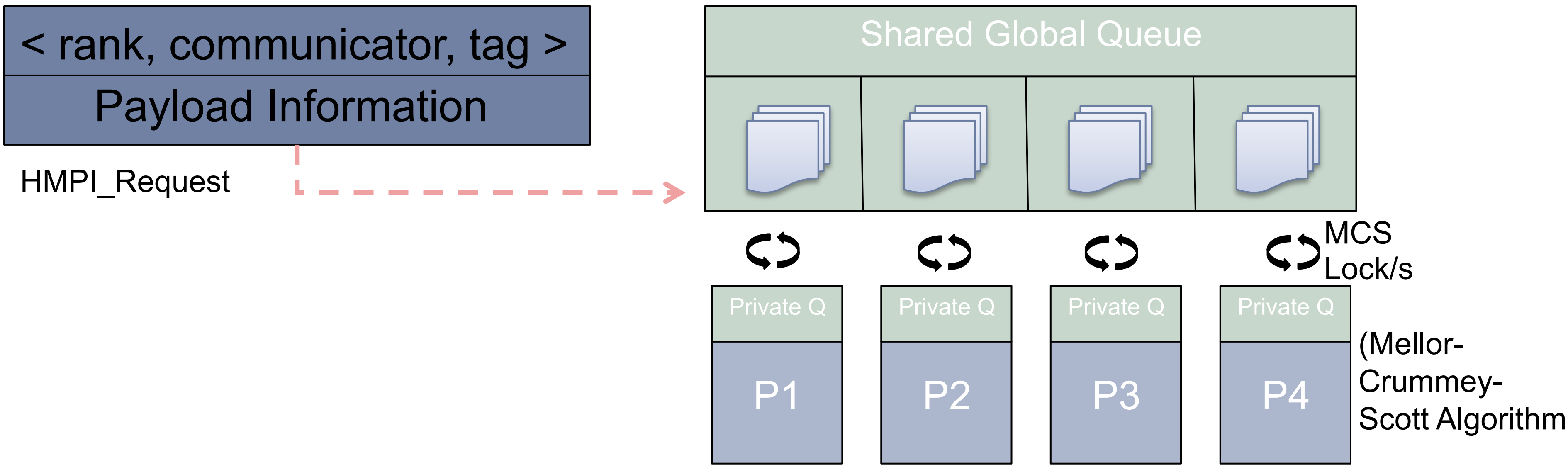
Hybrid MPI – Message matching



- ‘send’ requests are matched with local ‘receive’ requests in *HMPI_Progress*
  - Match for tuples <rank, comm, tag>
- Two Queues used
  - Shared – protected by global MCS lock
  - Private – where match is performed, drained from global queue
  - Minimize contention

Hybrid MPI – Communication protocols

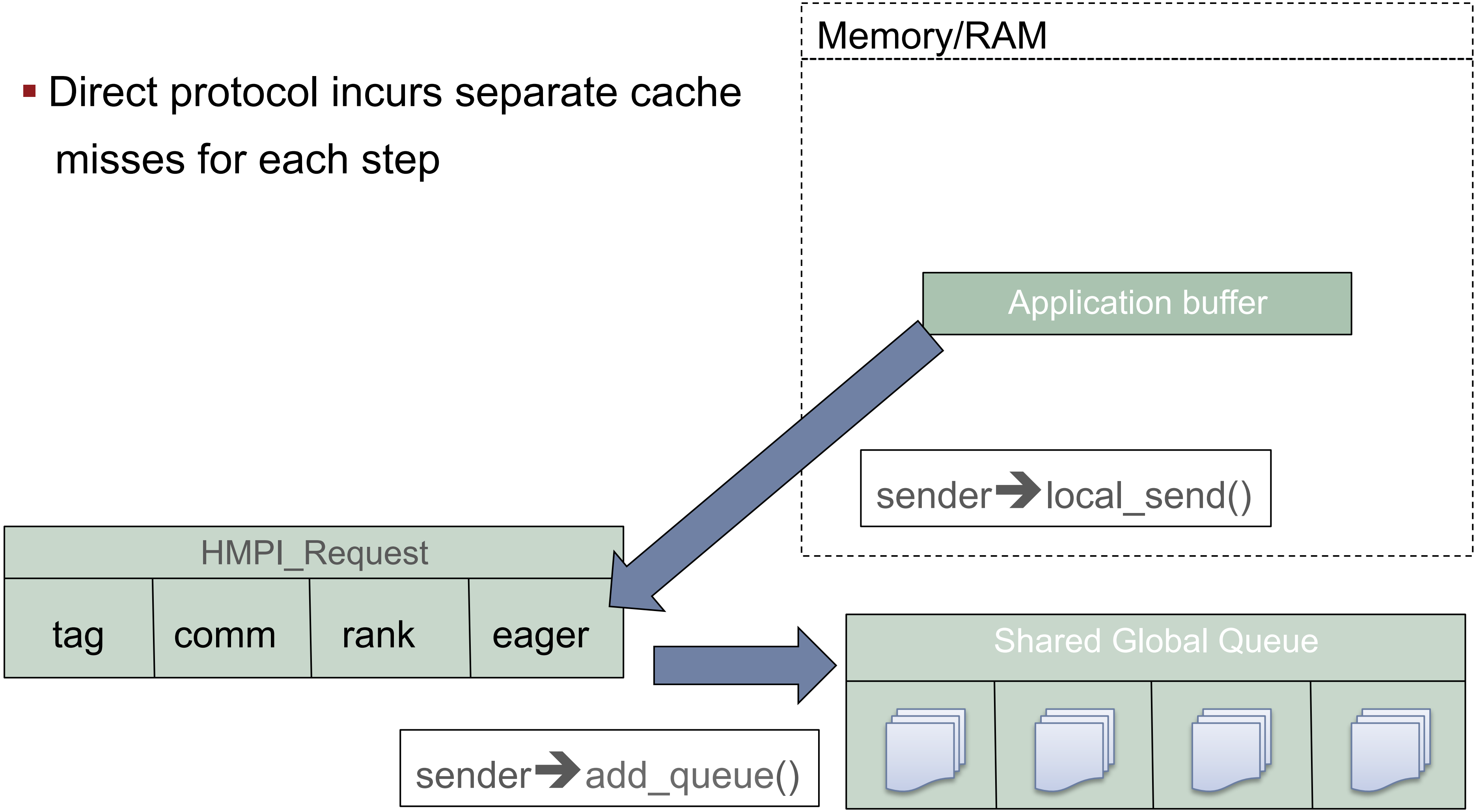
- 3 protocols
  - Direct Transfer
  - Immediate Transfer
  - Synergistic Transfer

- Direct Transfer
  - Single *memcpy*() to transfer from sender's buffer to receive
  - Applied when message is medium sized (512b ≤ m ≤ 8KB)

- Immediate Transfer
  - Applied when message size is small (≤ 512 bytes)
  - Payload is transferred immediately with HMPI request (header)
  - Message is cache aligned to fit the cache lines and 32KB L1 cache
    - Avoids 2 copies → use temporal locality, payload will already be in receivers' L1/L2 cache

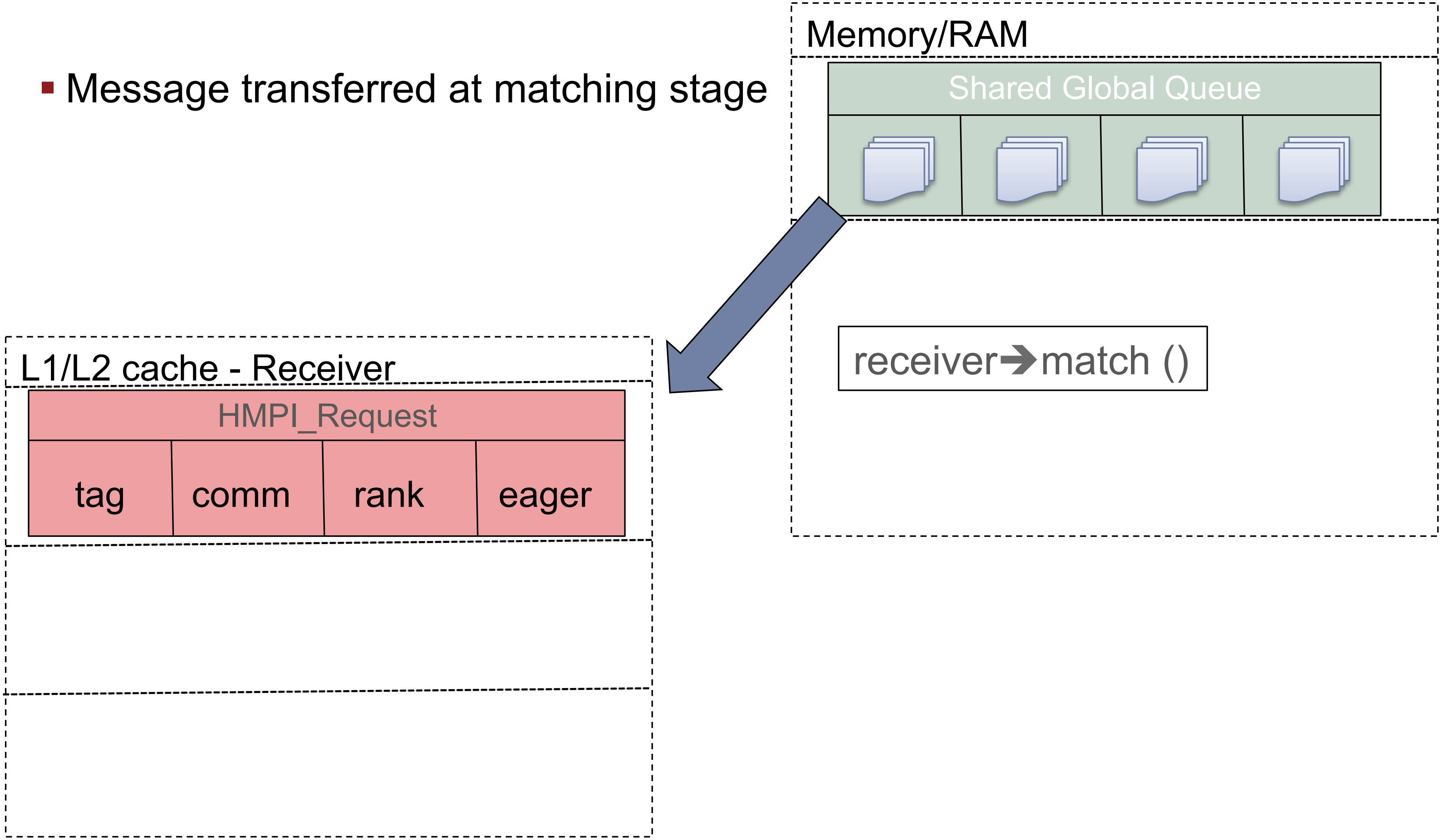
Hybrid MPI – Immediate protocol

- Direct protocol incurs separate cache misses for each step



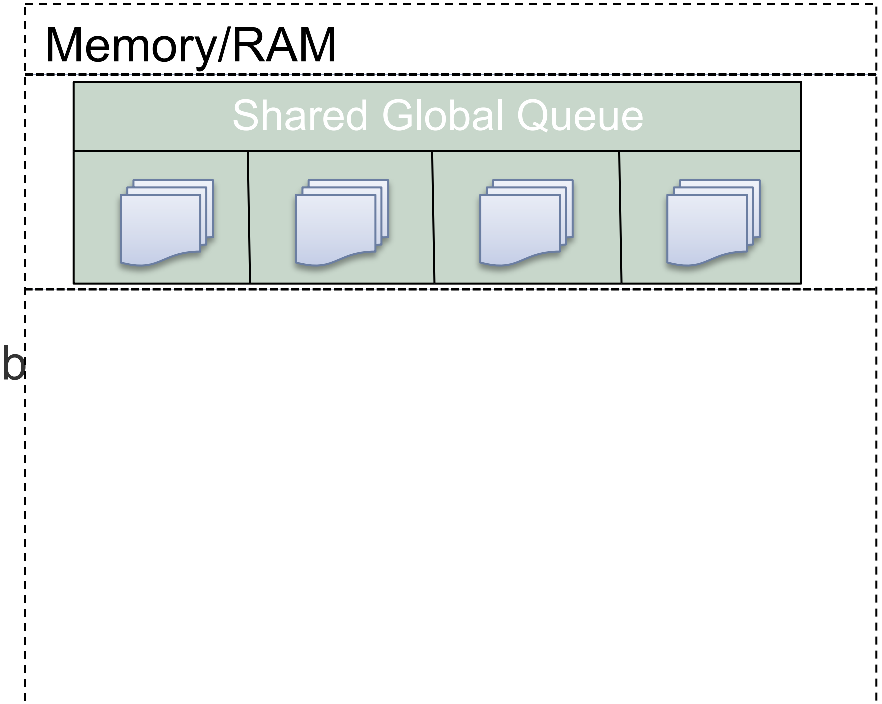
Hybrid MPI – Immediate protocol

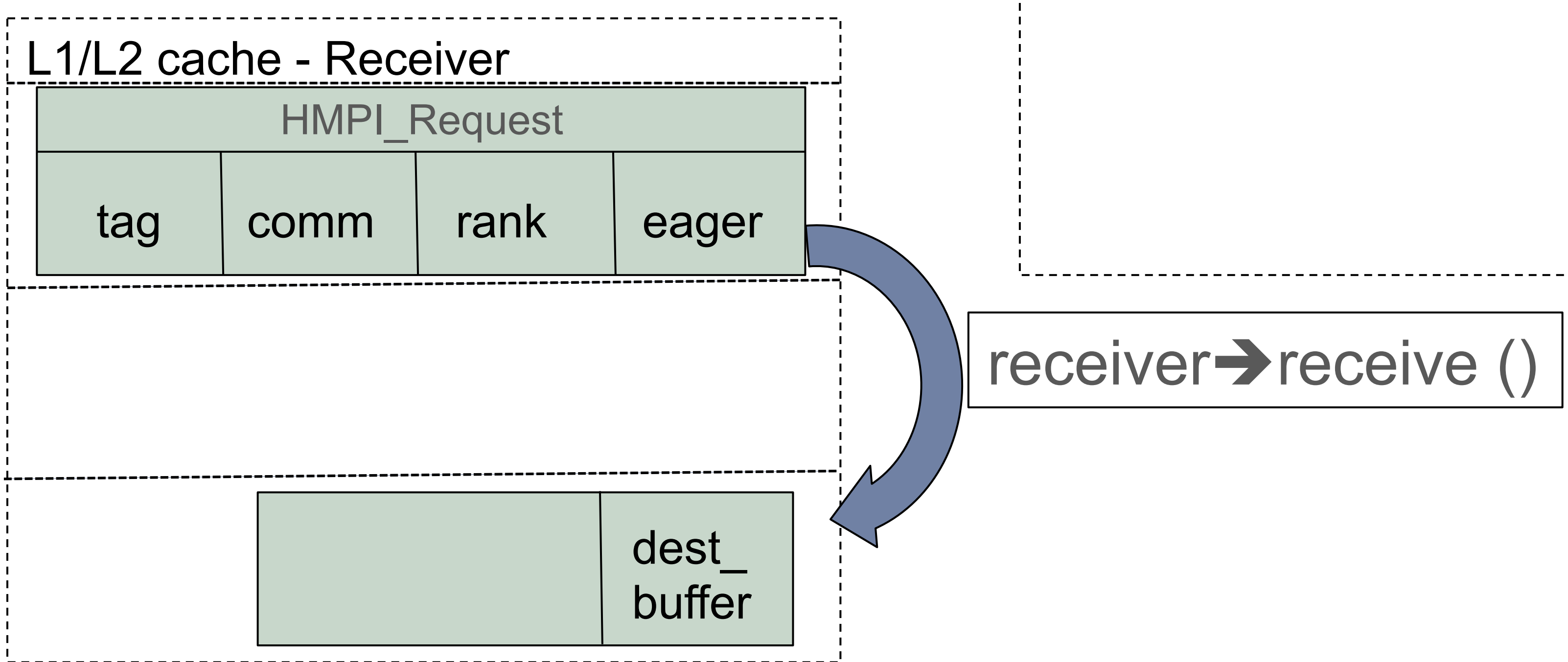
- Message transferred at matching stage



Hybrid MPI – Immediate protocol

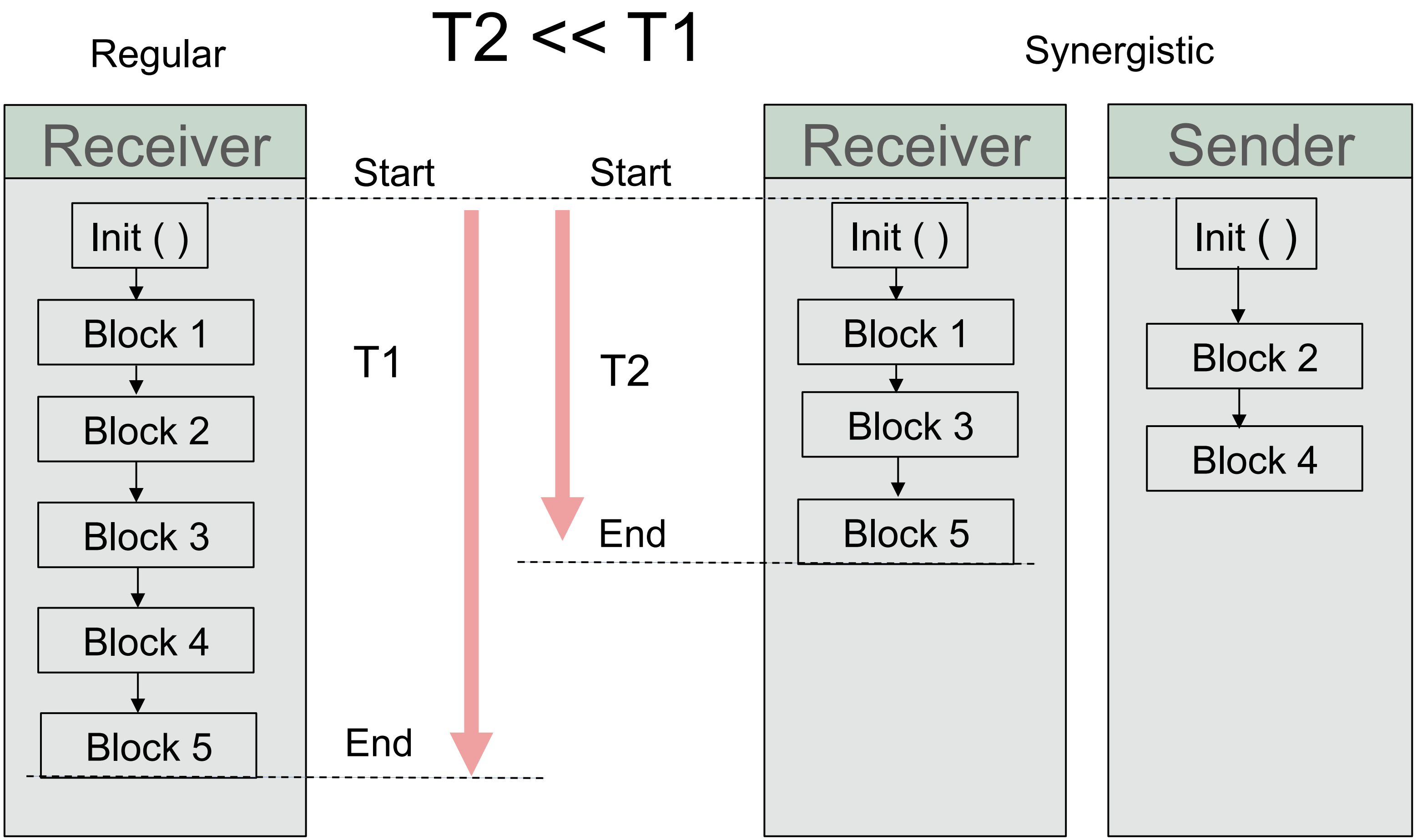
- At the data transfer
  - No cache miss to fetch data
  - If destination buffer is already on cache then extremely fast copying
  - 43% - 70% improvement over 32b – 512b





Hybrid MPI – Communication protocols

- Synergistic Transfer
  - Large messages (>=8KB) both sender and receiver engage actively in copying the message to destination



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Experimental Setup

- TACC STAMPEDE node
  - Host processor
    - Xeon E5, 8 core, 2.7GHz, 32GB DDR3 RAM , Cent OS 6.3
  - Co processor
    - Xeon Phi, 61 cores, 1.1 GHz, 8GB DDR5 RAM
    - Linux based Busy Box OS (kernel version 2.6) / MPSS
    - Intel icc/mpicc Compiler – cross compile for Xeon Phi
- ***Presta*** benchmark*, "purple suite"*
- 2 types of experiments
  - Intra-node
    - Single STAMPEDE node (from 2 ranks to 240 ranks in one node)
    - All experiments run in *'Phi-Only'* mode – only in coprocessor
    - Benchmarks used – **Presta Stress Benchmark - *com / latency***
  - *Inter-node*
    - *Between nodes but* in *'Phi-Only'* mode
    - Communication via infiniband FDR interconnect

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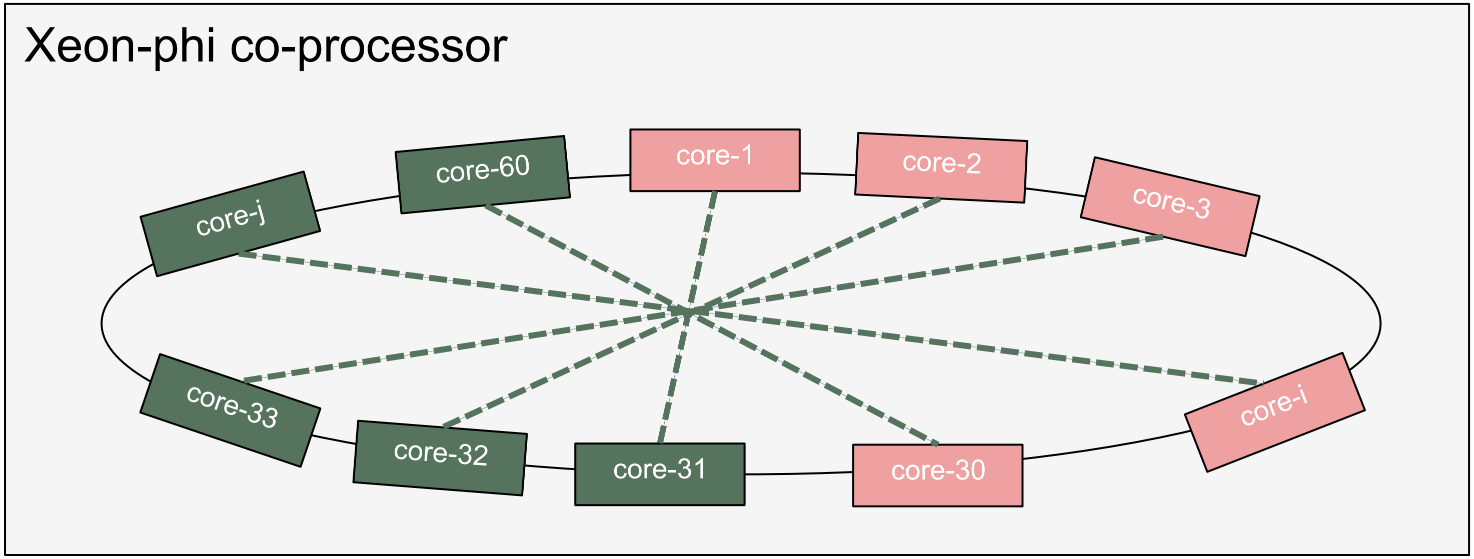
Intra-node Setup

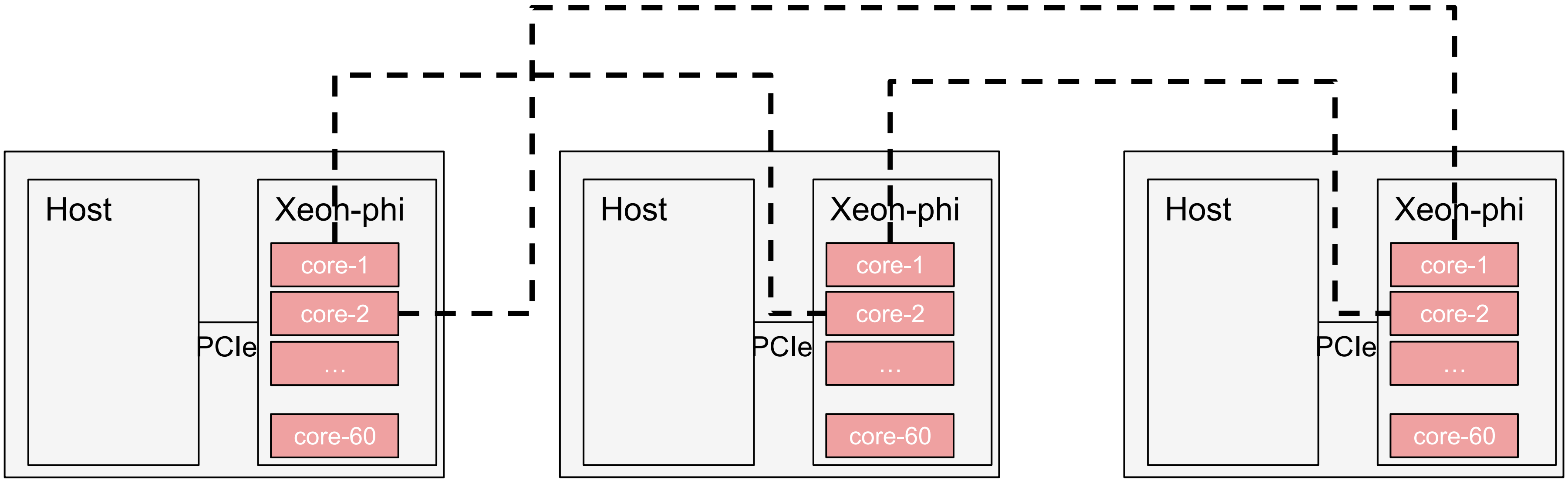
- Intra-node setup



- Each core is bound to a rank
  - All nodes tested have one Xeon Phi coprocessor
  - Rank pairs are formed in on opposite sides of ring interconnect

Inter-node Setup

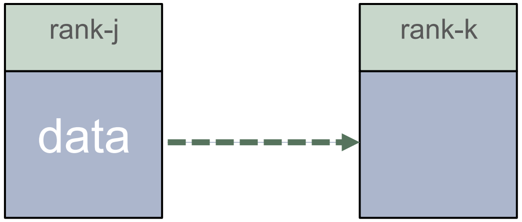
- Inter-node setup



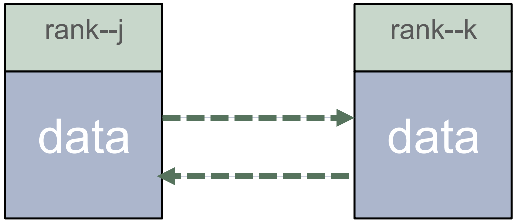
- Subset of cores/ranks from each node are selected
  - Communication in symmetric mode – Phi to Phi
  - RDMA with Infiniband

Presta *com* benchmark

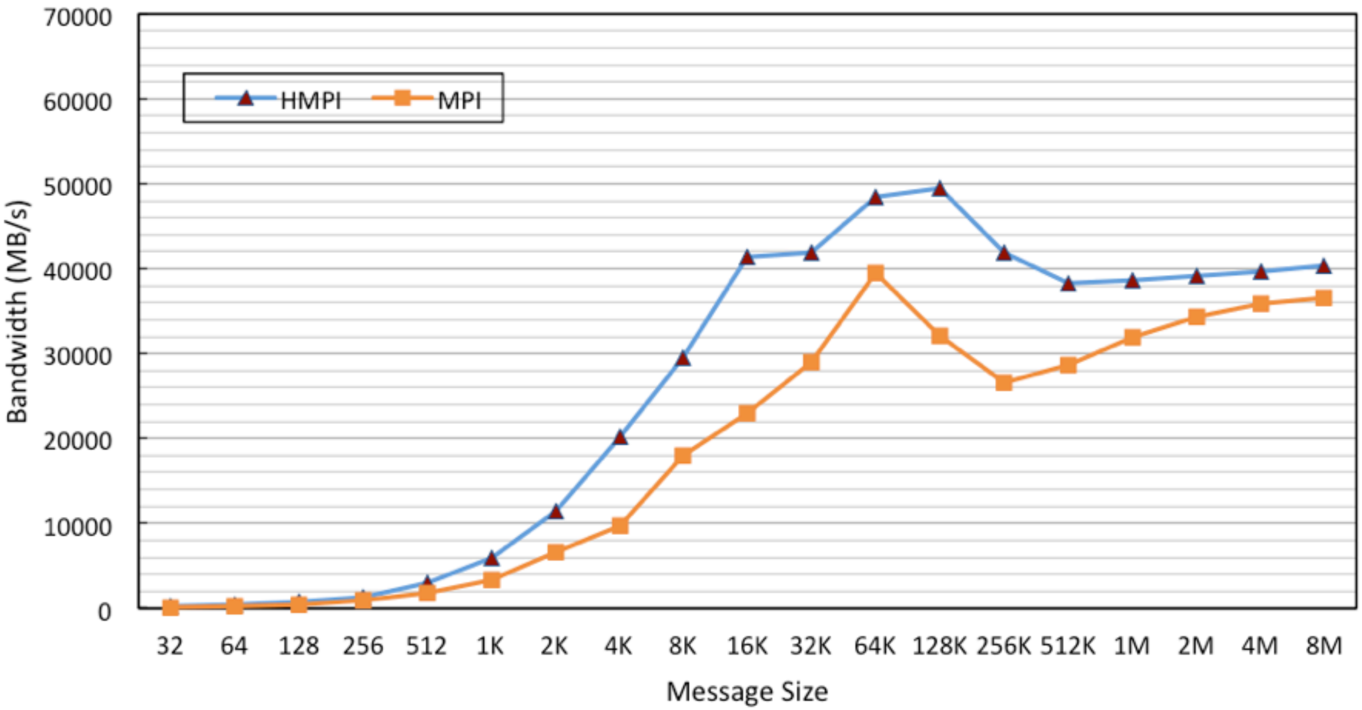
- 2 types of Presta ***com benchmark*** measurements
  - Uni-directional
    - One-way communication
    - MPI_Send / MPI_Recv



  - Bi-Directional
    - Two-way communication
    - MPI_Sendrecv
    - Full duplex – both sender and receiver transfer data at the same time
    - Generate rank pairs, similar to Uni-directional benchmark



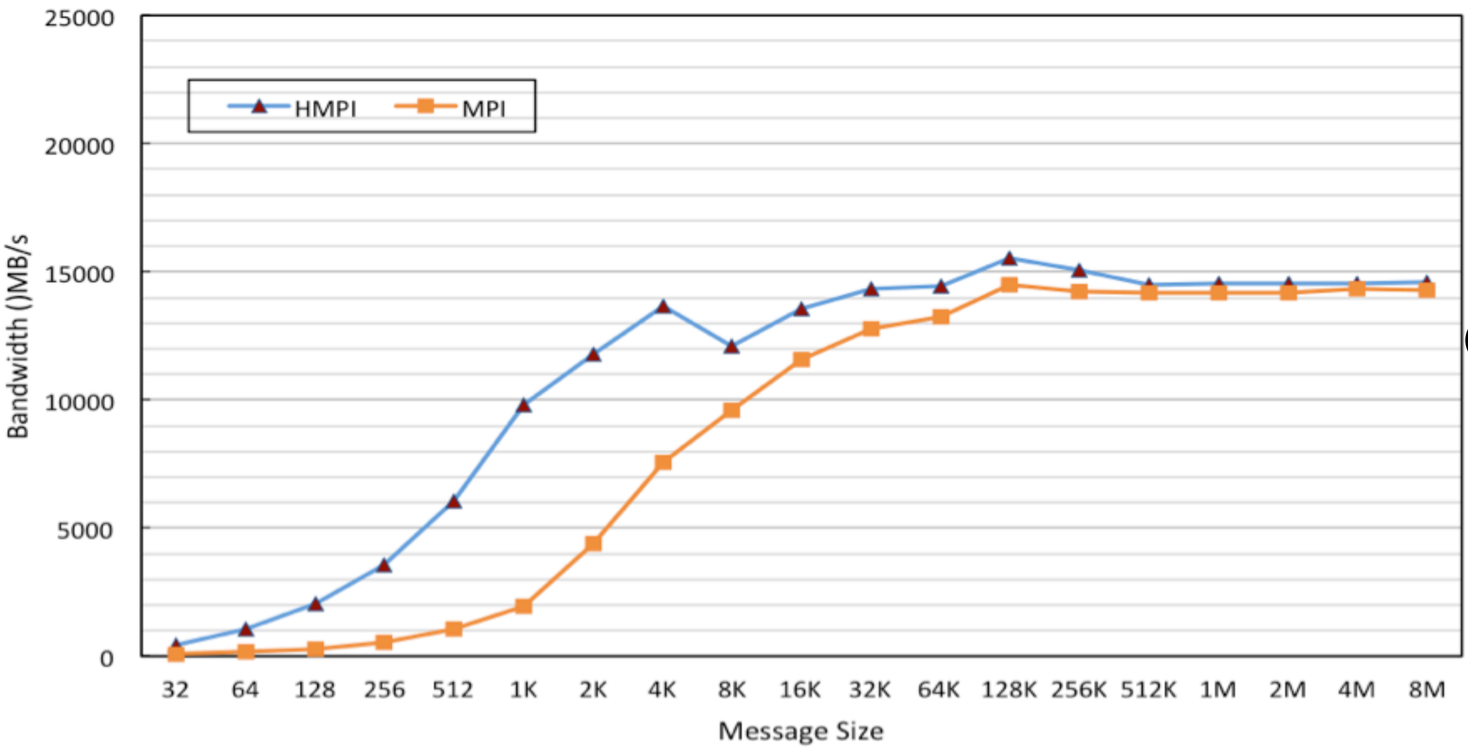
Intra vs Inter node Point to Point Communication



Intra-node BW
(60 ranks – 1 node)

- Intra node Hybrid MPI peak bandwidth ~50GB/s >> MPI peak bandwidth ~40GB/
- For Intra node communication with 60
  - For small messages , Hybrid MPI outperforms Intel MPI - speedup due to immediate protocol
  - Medium/Large messages → direct copy, synergistic protocol

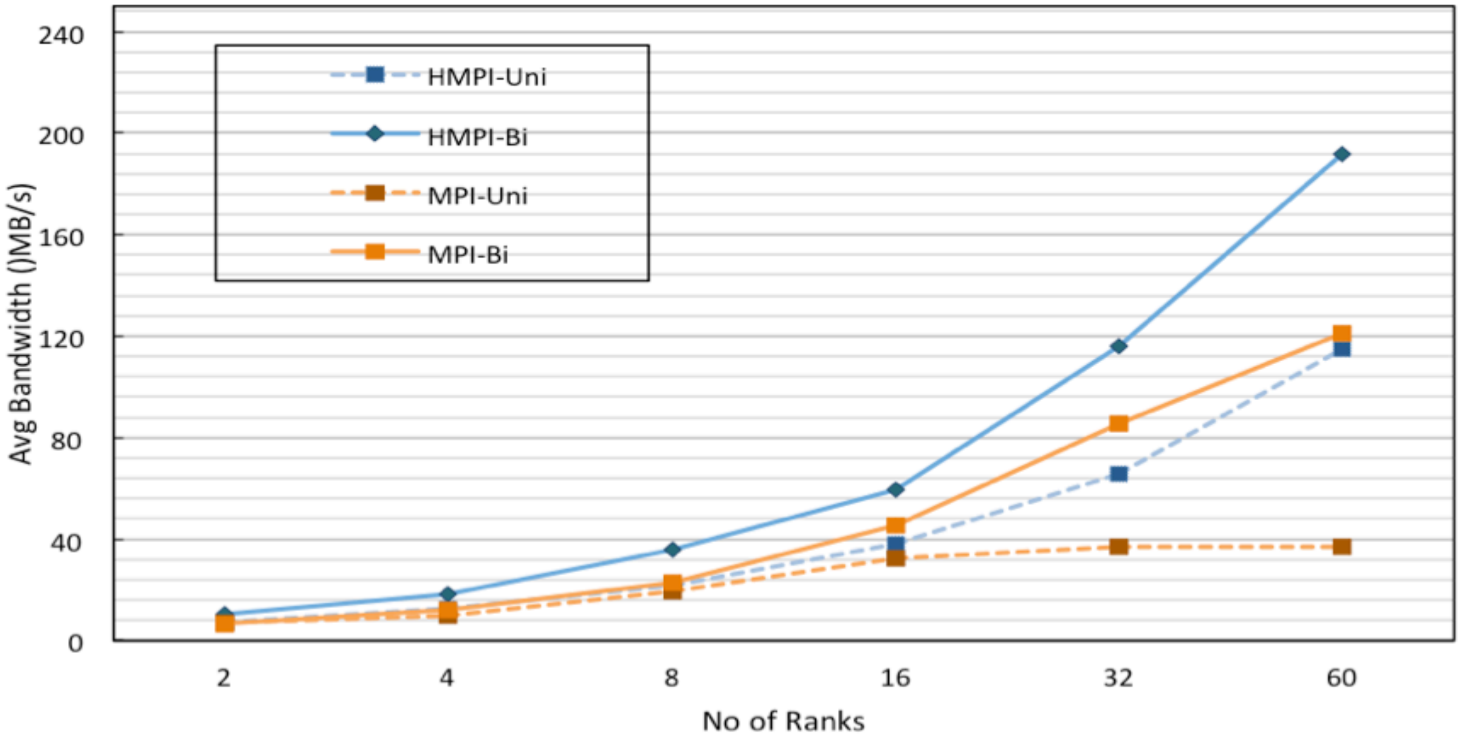
Inter node Point to Point Communication



Inter-node BW
(960 ranks – 16 nodes)

- Inter-node Bi-directional bandwidth
  - Smaller bandwidth difference
  - Due to noise in measurements, subtleties in message patterns, etc

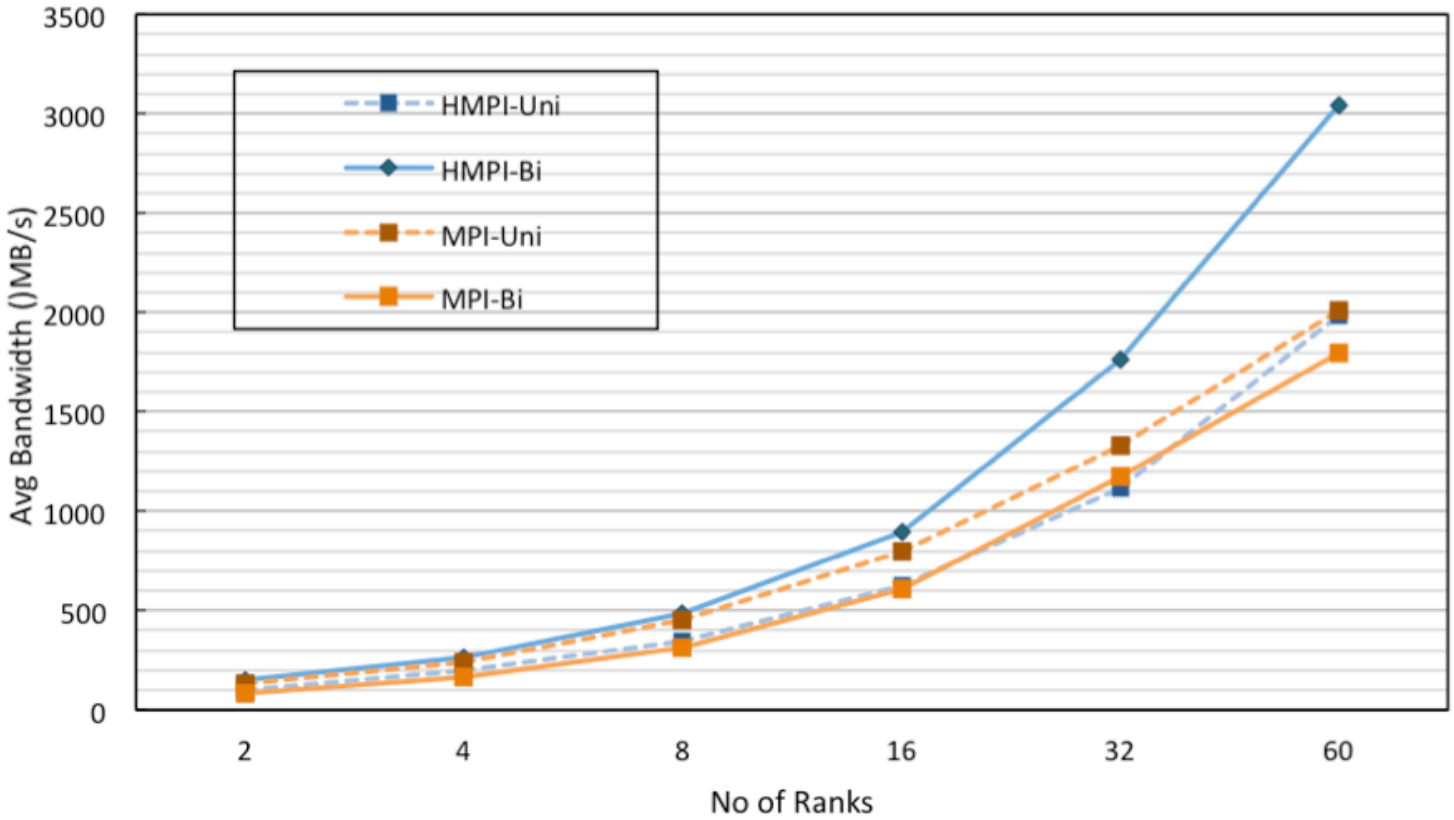
Intra-node Message Size Specific - small



Message size
32 bytes

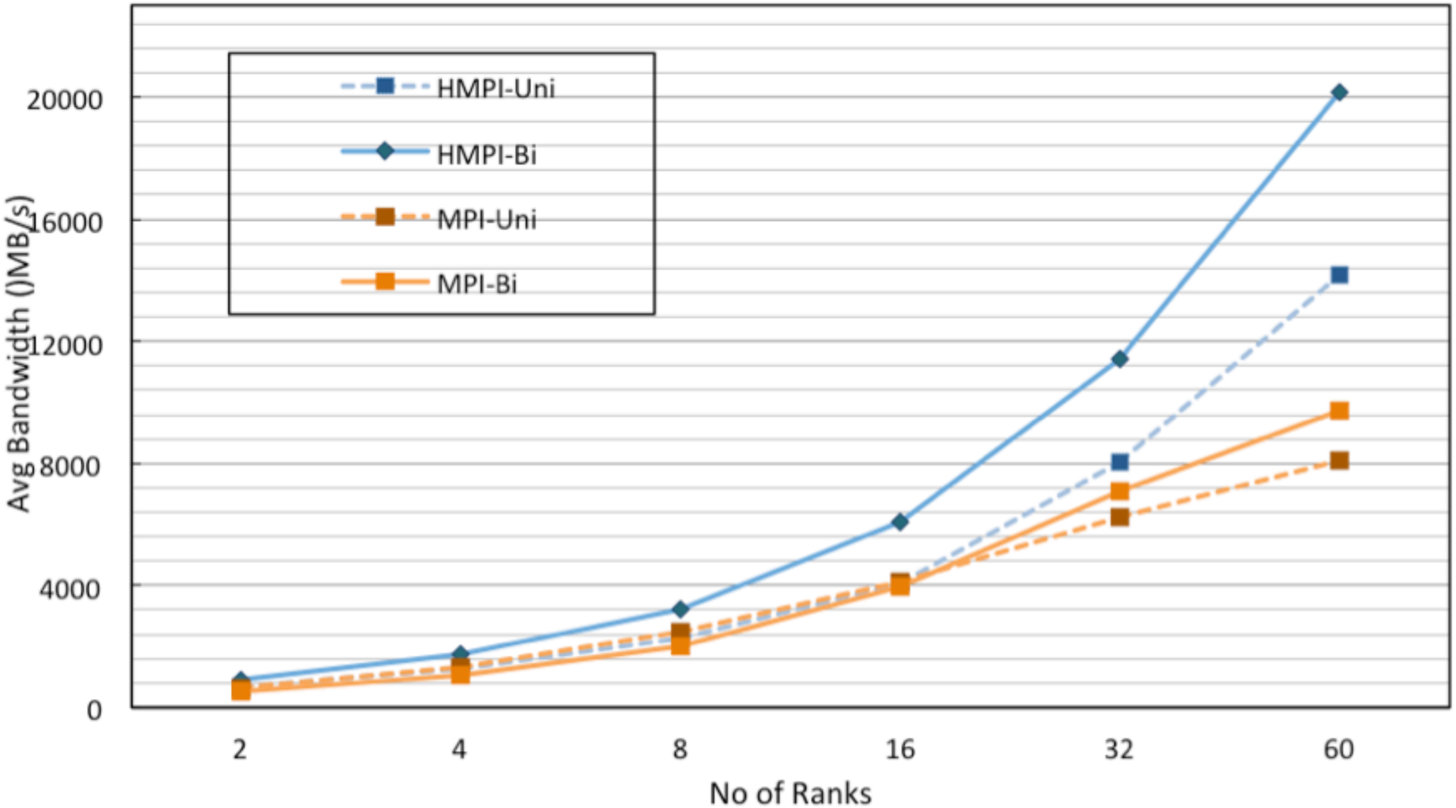
- Shows the effect of Hybrid MPI Immediate protocol
  - fast copying due to temporal locality
- Message size (32 bytes) fit a cache line on Xeon Phi core
- Hybrid MPI bi-directional benchmark outperforms others types for all ranks

Intra-node Message Size Specific - small



Message size
512 bytes

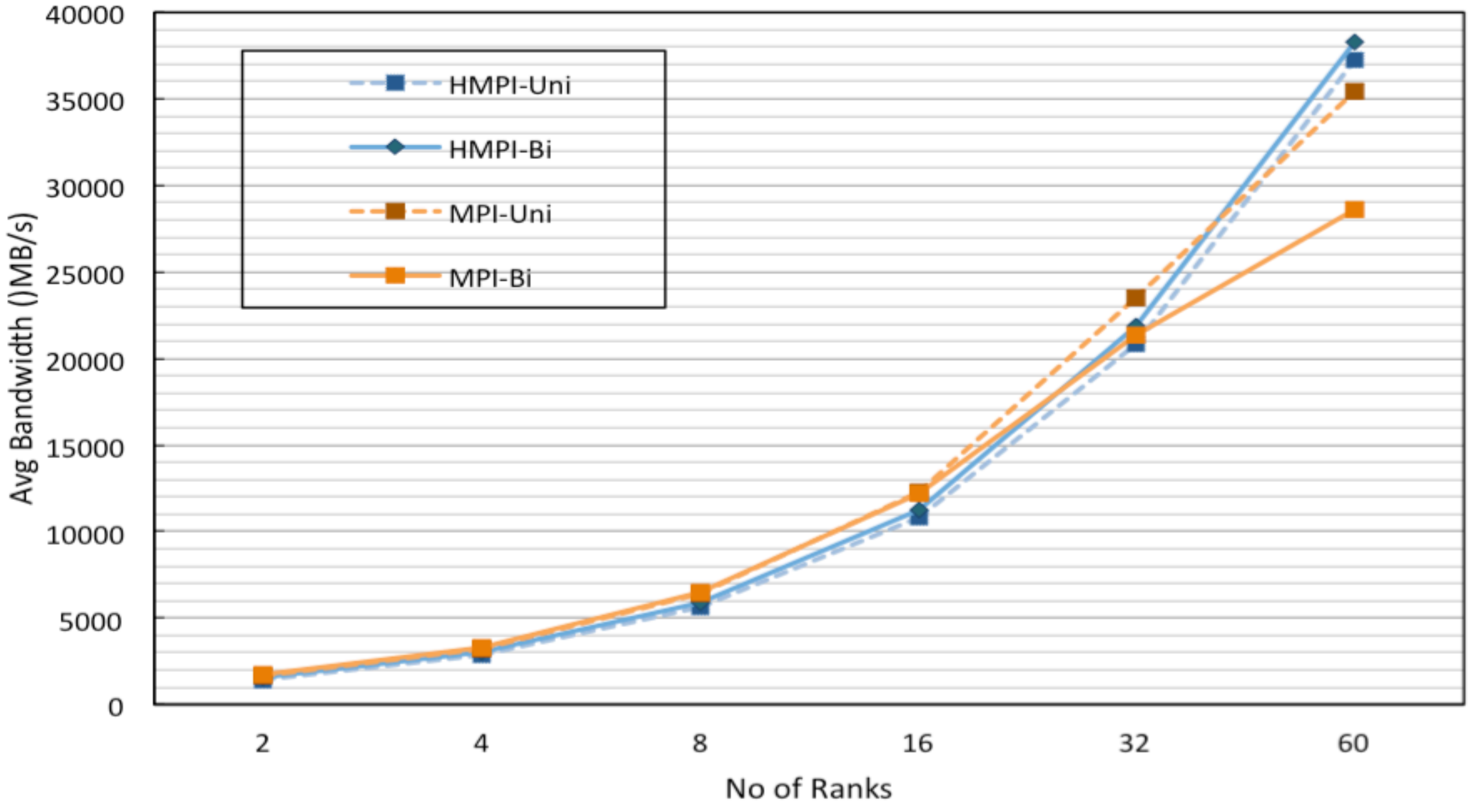
Intra-node Message Size Specific - medium



Message size
4 KB

- Hybrid MPI direct protocol
- Both Hybrid MPI's Uni-directional and Bi-directional transfers performs well over Intel MPI
  - Bi-directional BW >> Uni-directional

Intra-node Message Size Specific - large



Message size 512 KB

- Positive impact of Hybrid MPI ‘s synergistic protocol visible when number of ranks are 60
- For 512KB messages → 39GB/s peak BW, but 8MB is even better
- For 8MB messages → 50GB/s peak BW

Intra-node Message Size Specific Performance

- Bandwidth increases rapidly with the number of ranks
  - More cores are engaged in active data transfer
  - More memory Load/Store requests dispatched to controllers
  - Prefetching and cache coherence effects during transfer
  - More activity implies higher aggregated bandwidth

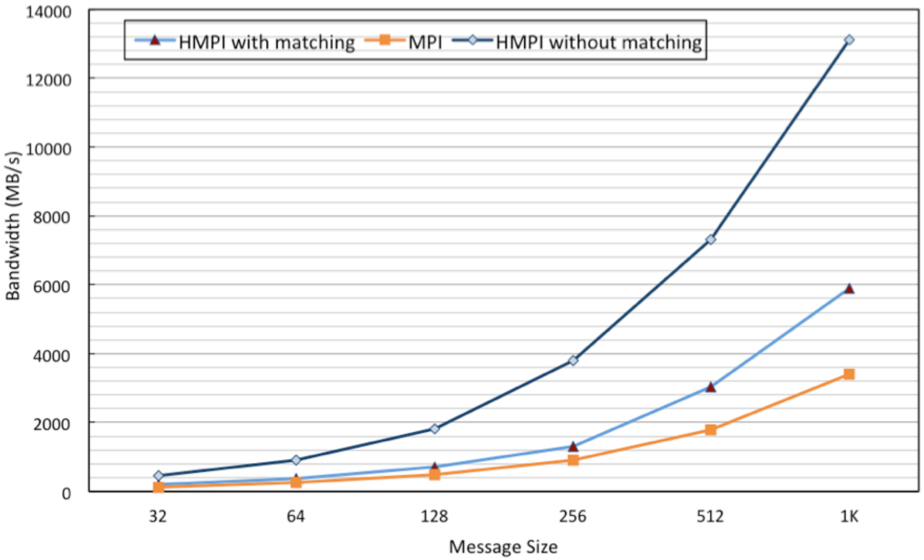
- In general for Medium/Large Messages, Bi-directional BW > Uni-directional BW
  - Hybrid MPI Peak Bi-directional BW ~50GB/s vs Intel MPI ~ 32GB/s - message size 128K 60 ranks
  - At synergistic transfer – multiple pairs of ranks can use multiple channels (on the ring interconnect) for simulataneous memcpy() in both directions

A Benchmark Without Message Matching

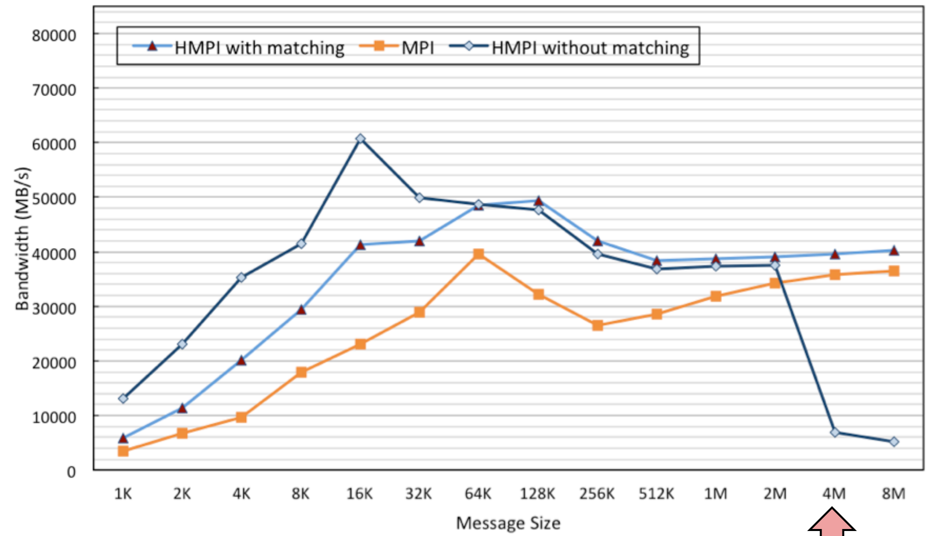
- Experimentally controlled to measure cost of message matching in MPI
  - Upper limit on Bandwidth and latency

- Algorithm
  - Initialize a shared memory pool to store source and destination memory pointers for messages
    - Use the extended heap of Hybrid MPI for shared access
  - Presta com benchmark with MPI message matching replaced by atomic synchronization
    - All Hybrid MPI protocols (direct, immediate, synergistic) in-lined in the benchmark
    - Use atomic spin locks (ie:- *sync_bool_compare_and_swap* ()) to synchronize between sender and receiver – synchronize sender/receiver → next iteration

A Benchmark Without Message Matching (contd..)



a) Small messages (<= 1KB)



b) Large messages (>= 1KB)

- Too much strain on memory sub system when → message size >> cache
  - saturates memory channels/interconnect quickly
- Peak BW of ~61 GB/s w/o message matching vs ~50 GB/s regular mode
  - 35% overhead for message matching at peak

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Application Benchmarks

- FFT2D Application
  - Representative benchmark developed by T. Hoefler and S. Gottlieb
    - Implements a simple parallel FFT (Fast Fourier) on a 2D array
    - Uses FFTW library (developed by M.I.T.) for 1-d decomposition

- Application performance based on FFT2D variants
  - FFT2D collective
    - Original MPI collective based implementation
    - Communication with MPI_Alltoall, MPI_Scatter, MPI_Gather ,etc
  - FFT2D Point to point
    - Since Hybrid MPI implements only Point to Point primitives → transform collectives to MPI_Send/Recv/Isend/Irecv/Wait pattern/s

- Performance measurements
  - Application time – time to complete the program
  - Comm time – time spent on the data exchange between ranks

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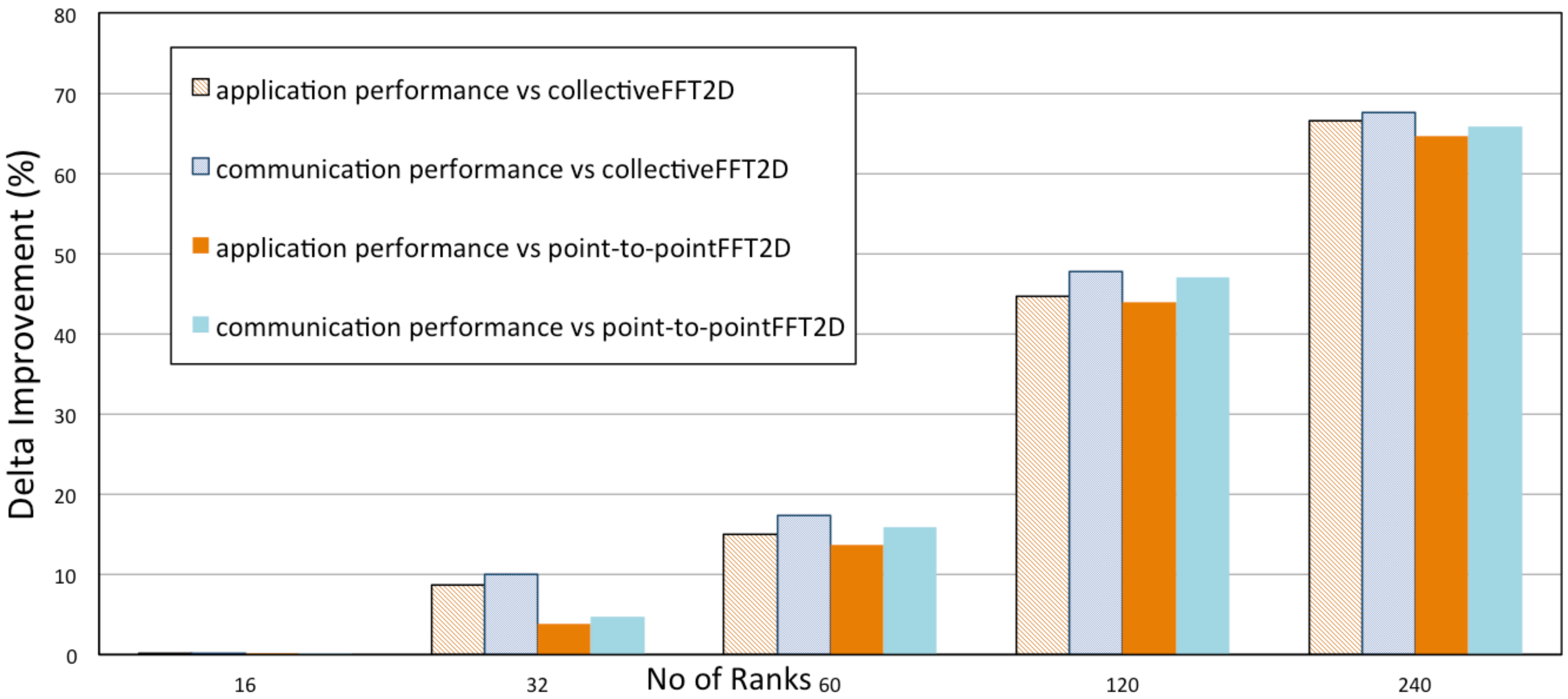
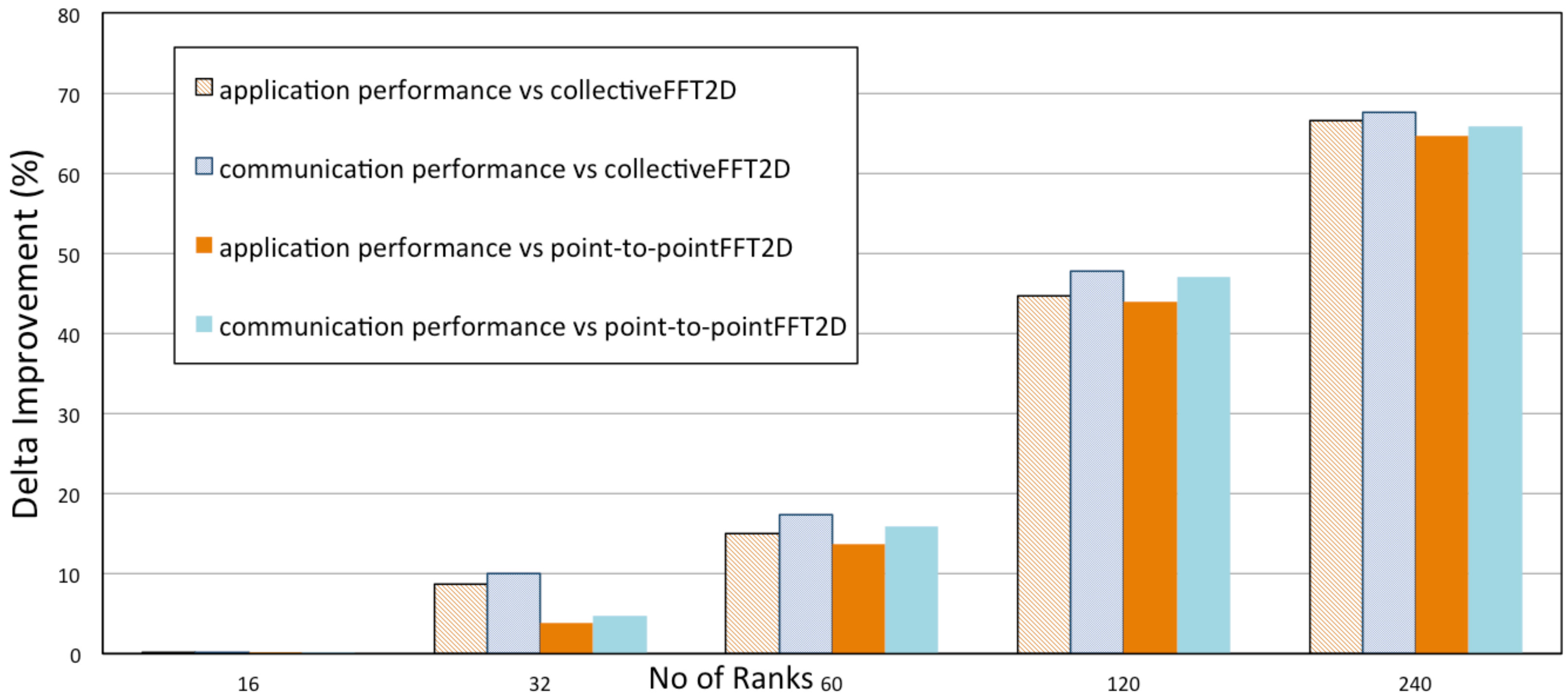
FFT2D Benchmark Intra-node



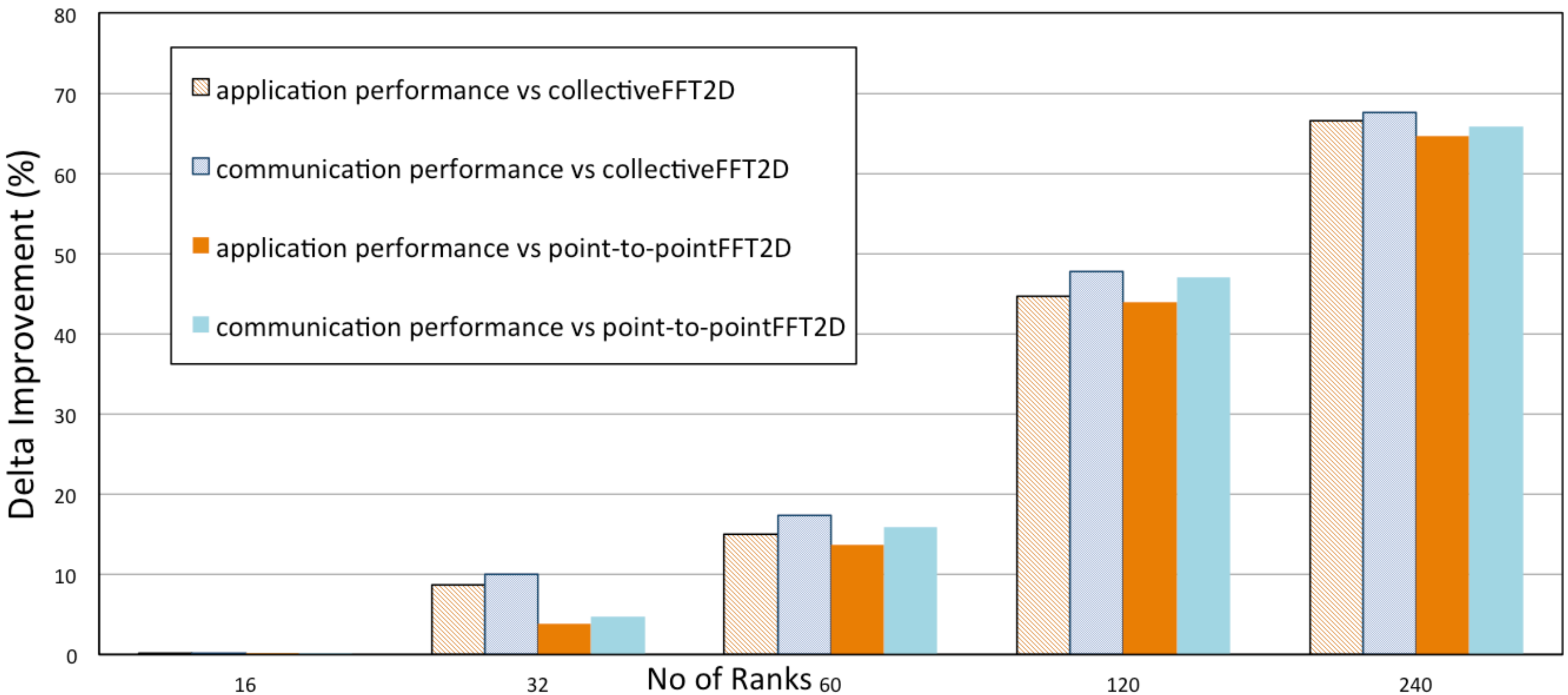
- Delta Improvement $= \dfrac{\text{Intel MPI time} - \text{Hybrid MPI time}}{\text{Intel MPI time}}\ \%$

FFT2D Benchmark Intra-node (contd..)



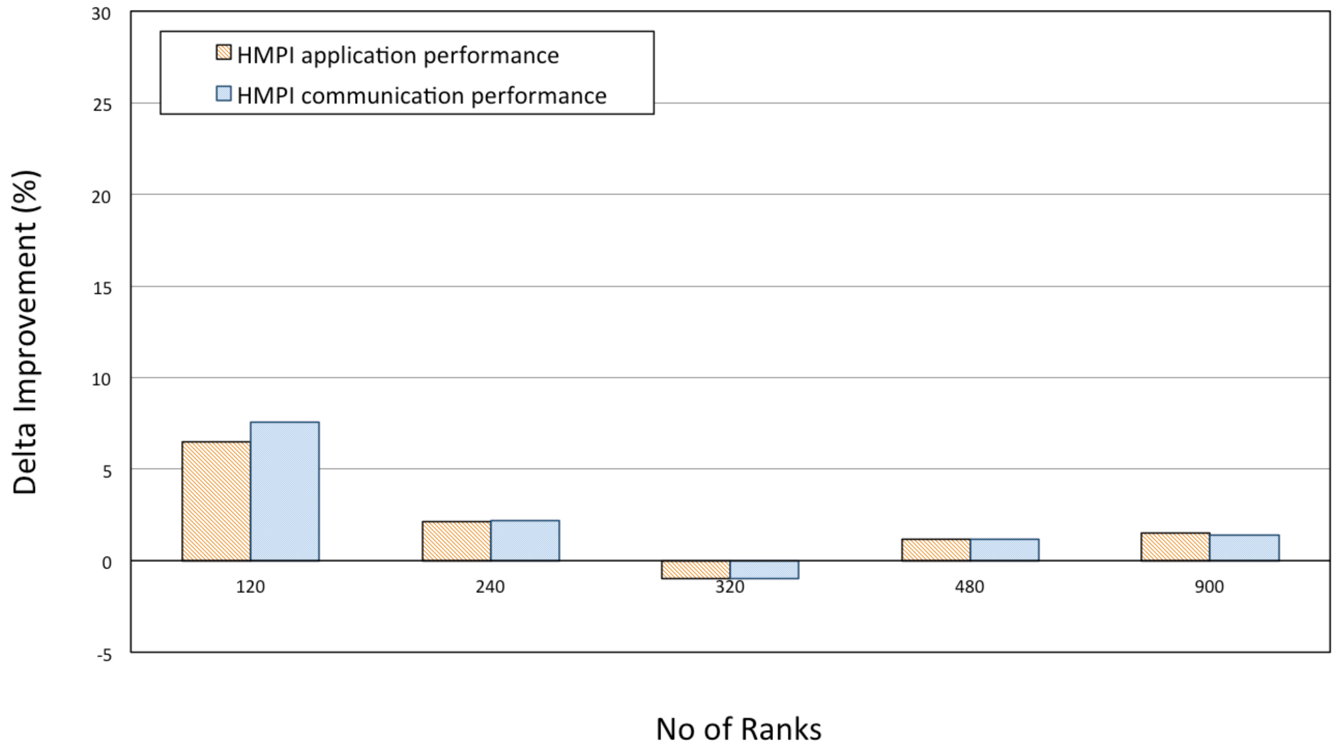
- Up to 240 ranks on phi (using 4 Hardware Threads per core)
- [app/comm]***-relative to point-to-pointFFT2D*** – Intel MPI baseline taken as modified point to point benchmark
- [app/comm]***-relative to collectiveFFT2D*** – Intel MPI baseline taken as original collective based benchmark

FFT2D Benchmark Intra-node (contd..)



- Considerable improvement in operational times
  - 5% to 66% - communication time, 4% to 65% - application time
  - Higher on phi ranks → higher improvement
  - ranks ≤ 16 → zero improvement
- Data don't show significant difference relative to point-to-point OR collective baselines – doesn't affect validity with P2P version

FFT2D Benchmark Inter-node



- Up to 900 ranks spanning 30 nodes
- Internode improvement/bottleneck is marginal – network overhead
  - Hybrid MPI delegates inter-node communication to underlying MPI layer
  - 6% improvement for 120 ranks → noise or other factors

Hybrid MPI Highlights

- Hybrid MPI highlights
  - Extremely high throughput via shared memory and single/zero copy techniques
    - 50 GB/s peak BW measurements
    - Overall significant improvements for all message sizes (use of Hybrid MPI protocols –immediate/direct/synergistic)

Message size	Improvement
Small (< 512b)	12% - 68%
Medium (512b – 8KB)	45% - 72%
Large (> 8KB)	65%

  - Results show improvement In FFT2D application and communication time
    - Upto 65% communication time improvement
  - Higher the number of ranks, higher improvement gained by Hybrid MPI

Towards a Hybrid MPI Future

- Efficient use of Xeon Phi cores and memory channels
  - Throughput proportional to number of cores used
    - Ranks ↑ → Bandwidth ↑
  - Achieve higher throughput via balancing the communication load between the available cores
- Optimizing message matching
  - At peak 35% time spent on matching on coming receives
  - Efficient data structures and algorithms to reduce matching overhead
- Collectives and Inter-node implementation
  - Currently Hybrid MPI does not support collectives or native inter-node mode
  - Use available technologies (ie:- SCIF, IB, etc) to improve off Phi bandwidth and latency