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Asynchronism in MPI Intra-Node Communications

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Contents

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BACKGROUND & MOTIVATION

I/O Models

- Synchronous blocking I/O
  - Application blocks until the I/O system call is complete
- Synchronous nonblocking I/O
  - I/O command may not be satisfied immediately, requiring that the application makes calls to await completion

	Blocking	Nonblocking
Synchronous	Read/Write	Read/Write (O_NONBLOCK)
Asynchronous	I/O Multiplexing (Select/Poll)	Asynchronous I/O (AIO)

* Source: IBM Developer

I/O Models

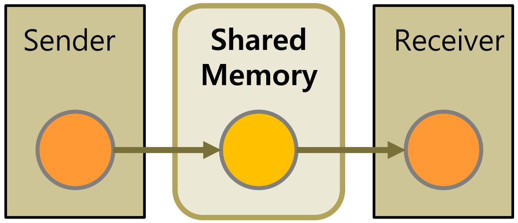
- Asynchronous blocking I/O
  - Application interrogates the readiness of multiple descriptors by using select/poll before I/O calls
- Asynchronous nonblocking I/O
  - Application can perform other processing while the background I/O operation completes

	Blocking	Nonblocking
Synchronous	Read/Write	Read/Write (O_NONBLOCK)
Asynchronous	I/O Multiplexing (Select/Poll)	Asynchronous I/O (AIO)

* Source: IBM Developer

Data Copies in MPI

- Shared memory channel
  - Moves messages from source to destination via a shared memory region
  - Small messages based on eager protocol



- Memory mapping channel
  - Directly moves messages from source to destination without intermediate copies by means of a kernel level support
  - Large messages based on rendezvous protocol
  - CMA, LiMIC2, XPMEM, …

CPU-based Data Movement

- Data copy operations in intra-node communications are performed by CPU
  - CPU resources are wasted for communication
  - CPU-based copying hinders overlapping of computation and communication

	Blocking	Nonblocking
Synchronous	CPU-based Data Movement	
Asynchronous		

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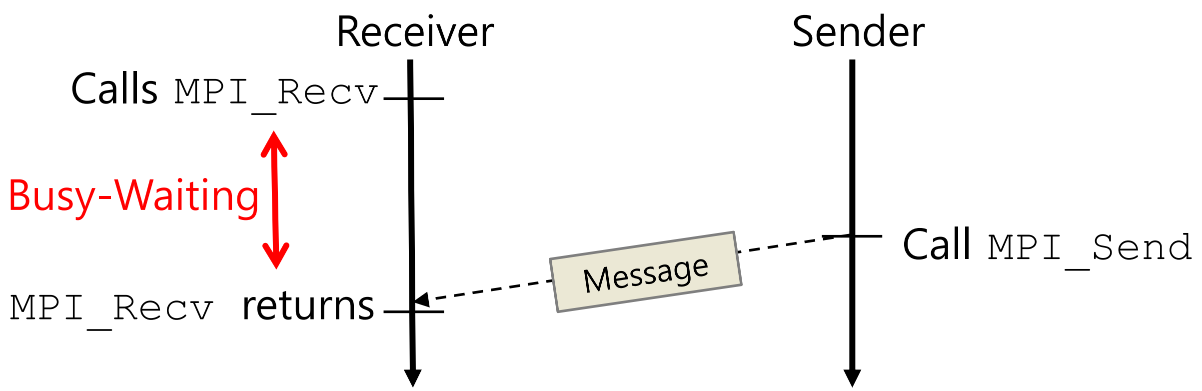
Our Goal #1

- Introducing asynchronism to data copy
  - Overlapping between computation and communication
  - Copy engine (CE)-based data movement
    - Asynchronous nonblocking data copy

	Blocking	Nonblocking
Synchronous	CPU-based Data Movement	
Asynchronous		CE-based Data Movement

Event Processing in MPI

- One-to-one mapping between processes and CPU cores
  - In HPC systems, the runtime solely dedicates a CPU core to each parallel process
  - Parallel programming libraries are optimized on the assumption that a parallel process occupies an entire CPU core
- MPI progress engine
  - Performs busy-waiting to check the completion of outstanding communications



Busy-Waiting-based Event Processing

- The longer the busy-waiting time, the higher the energy consumption
  - Nonuniformity of network latency
  - Asynchronous semantics in APIs
  - Load imbalance

	Blocking	Nonblocking
Synchronous		Busy-Waiting-based Event Processing
Asynchronous		

Our Goal #2

- Introducing asynchronism to progress engine
  - Energy efficiency
  - Blocking-based event processing
    - Asynchronous blocking progress engine

	Blocking	Nonblocking
Synchronous		Busy-Waiting-based Event Processing
Asynchronous	Blocking-based Event Processing	

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Asynchronism in MPI Intra-Node Communications

ASYNCHRONOUS NONBLOCKING DATA COPY

Copy Engines

- A special-purpose processor that can independently access memory and copy data
  - Does not cause cache pollution compared to the CPU-based memory copy
  - Examples
    - Intel Xeon (I/O Acceleration Technology)
    - AMD EPYC
- We can offload copy operations performed by CPU onto the copy engine
  - Can save CPU resources
  - Can improve overlapping of computation and communication

Related Work

- Exploiting I/OAT
  - [IPDPS07, Cluster07, ICPP09]
  - Additional process/thread that takes full charge of managing the copy engine for intra-node data movements and monopolizes a CPU core
- No support for collective communication
  - Only for point-to-point communication or one-sided communication

Asynchronous Nonblocking Data Copy

- We aim at exploiting copy engines for intra-node MPI blocking collective communications
  - MPI_Bcast
  - MPI_Gather
- Asynchronous nonblocking data copy
  - CE-based approach
  - CE-CPU Hybrid approach
  - Enhancement of CPU-based approach

Synchronous Blocking Semantics

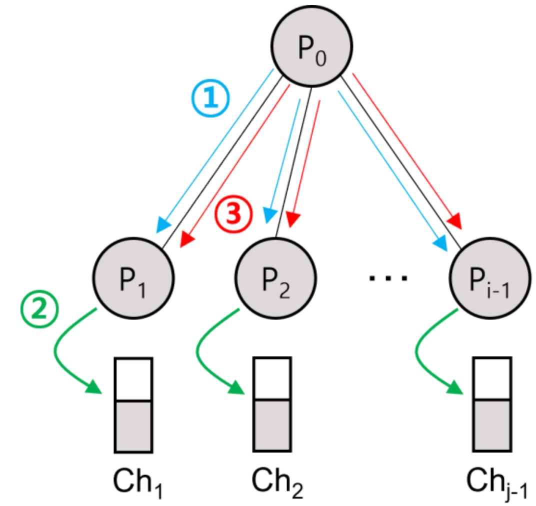
- Traditional collective interfaces
  - Do not return its control to user application until the collective communication is completed
  - Progress engine performs busy waiting to poll the completion or data copying to move data
  - No overlapping between computation and communication
- Our collective interfaces
  - Return asynchronously though the collective communication is not completed
  - Application can perform computation while the collective communication is in progress (by the copy engine)
  - Reserve synchronous blocking semantics by utilizing the memory protection mechanism (segmentation fault)

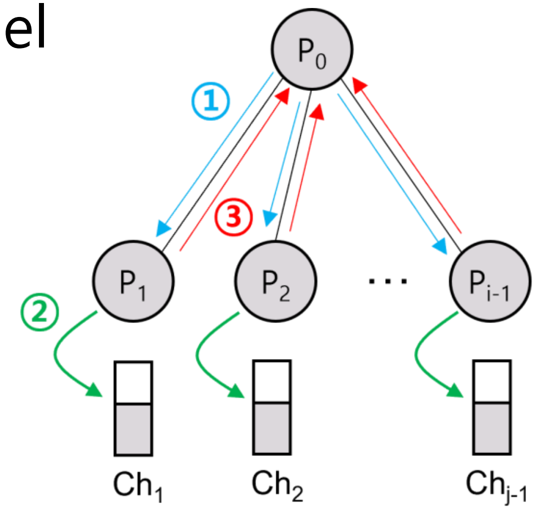
Core-to-Channel Mapping

- There can be multiple copy engines in the same node, and each copy engine provides several channels
  - Our experimental system
    - Two copy engines, each of which provides eight channels
    - The copy engine processes requests in channels in a round-robin fashion
- Core-to-channel mapping
  - In a round-robin manner for each NUMA node

Copy Engine (CE)-based Approach

- Step 1
  - Communication buffers are locked, and their descriptors (physical addresses of page frames and length) are sent to leaf processes
- Step 2
  - Leaf processes insert requests to channel
- Step 3
  - Copy engines move messages





CE-CPU Hybrid Approach

- Hybrid approach
  - Uses CPU to move data when lowering the overhead is more important than overlapping
  - Segmentation fault handler switches the copy device from copy engine to CPU
  - Virtual queues
    - We can neither preempt nor cancel the DMA request already submitted to a channel
    - Provide a mechanism that switches from the CE mode to the CPU mode in the middle of data movements
      - A DMA request for a collective communication is fragmented into several requests, each of which include vectors for only *n* pages
      - A callback function invoked whenever a fragmented request is completed moves fragmented requests in virtual queues to channels

Enhancement of CPU-based approach

- Existing design
  – Both memory mapping and copy operations are done on the receiver side

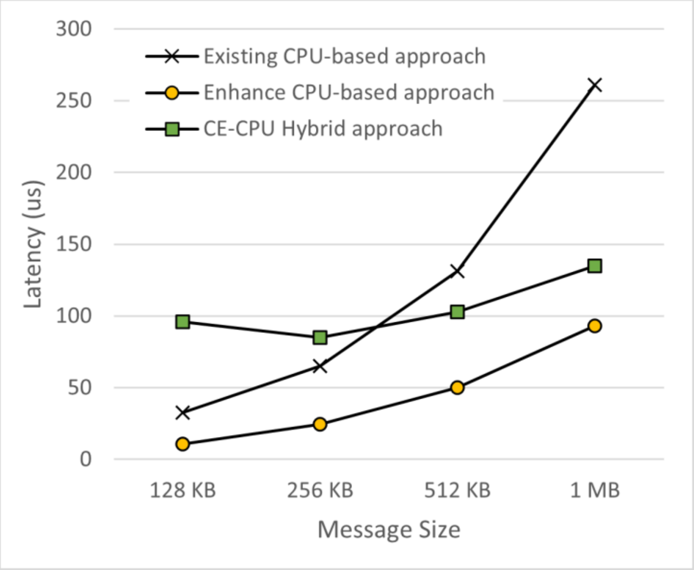
- New design
  – Segregates memory mapping and copy operations
  – The root process performs memory mapping, and the leaf processes perform data copy

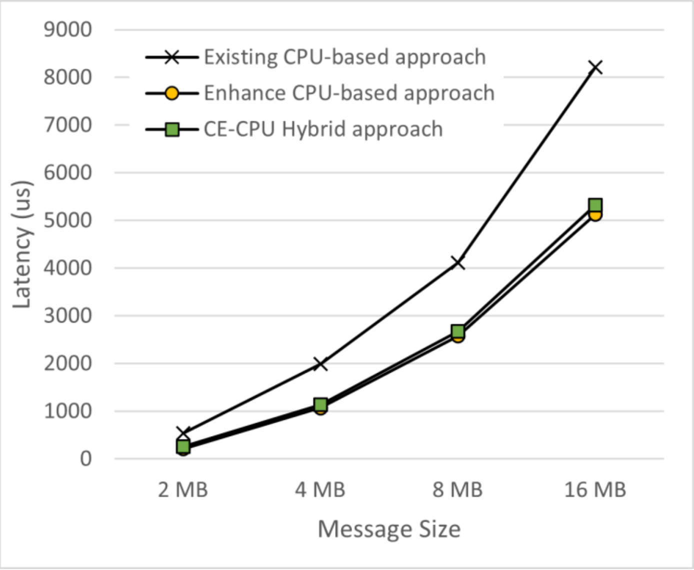
Performance Measurements

- Experiment system
  - NUMA-based multi-core system
    - Two Intel Xeon 3.10 GHz 10-core Haswell processors
    - DDR4 128 GB memory
    - Crystal Beach DMA v3.2 copy engine
  - Linux kernel version 5.3.7
  - Intel QuickData Technology Driver 5.00
- Comparisons
  - Default approach (MVAPICH2 version 2.3.7)
  - Enhanced CPU-based approach (MVAPICH2 version 2.3)
  - CE-CPU hybrid approach (MVAPICH2 version 2.3)

OSU Micro-Benchmark

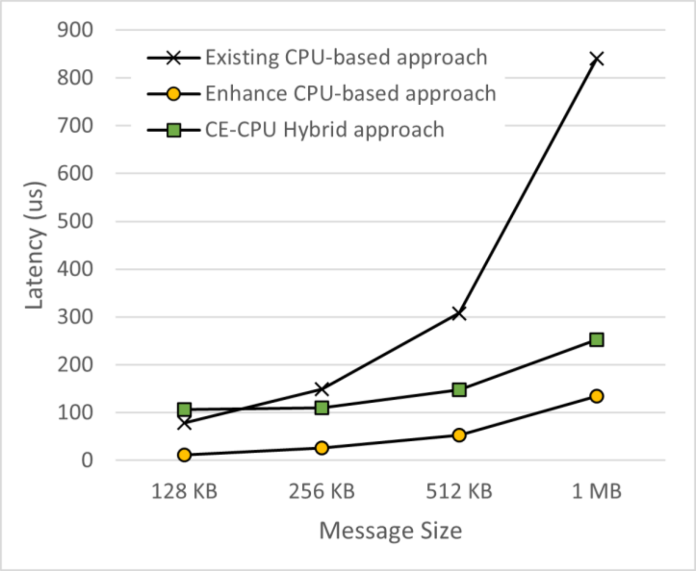
- MPI_Bcast
  - Enhanced CPU-based approach outperforms the existing CPU-based approach and reduces the latency of MPI_Bcast up to 67%

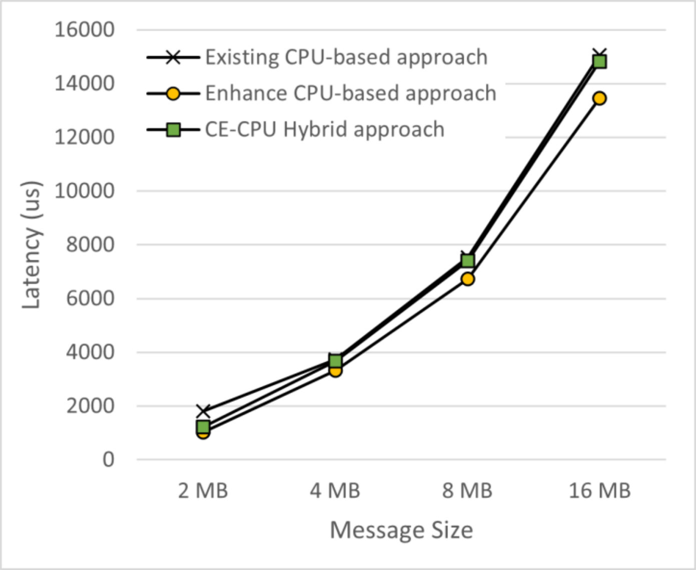




OSU Micro-Benchmark

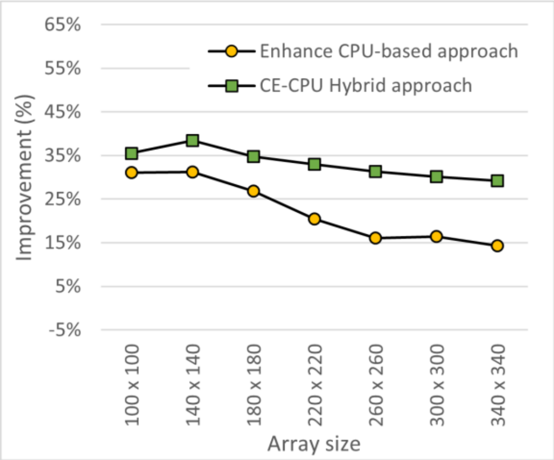
- MPI_Gather
  - Enhanced CPU-based approach reduces the latency of MPI_Gather up to 85%

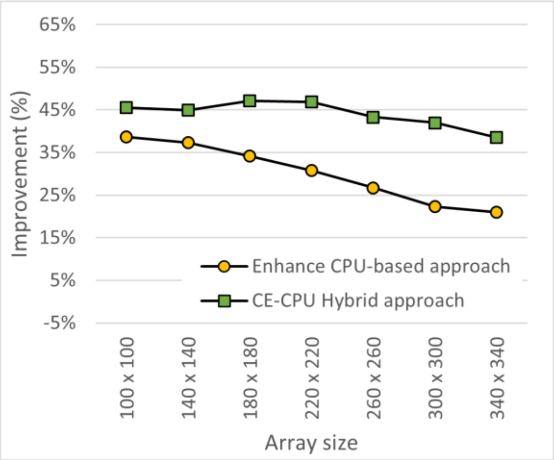


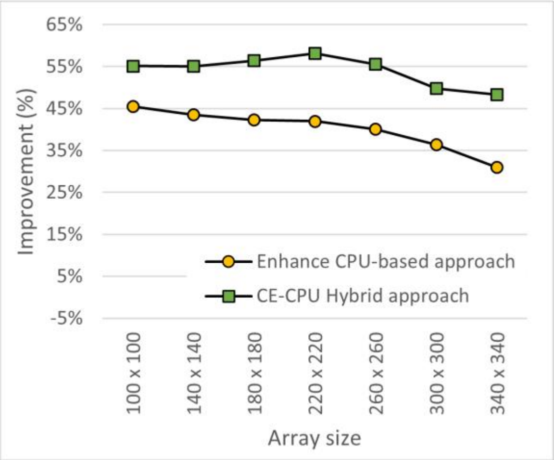


Overlapping with Computation

- MPI_Bcast
  - The enhanced CPU-based approach and the CE-CPU hybrid approach could reduce the overall execution time up to 45% and 58%, respectively
  - 20-process case with 4, 8, and 16 MB messages

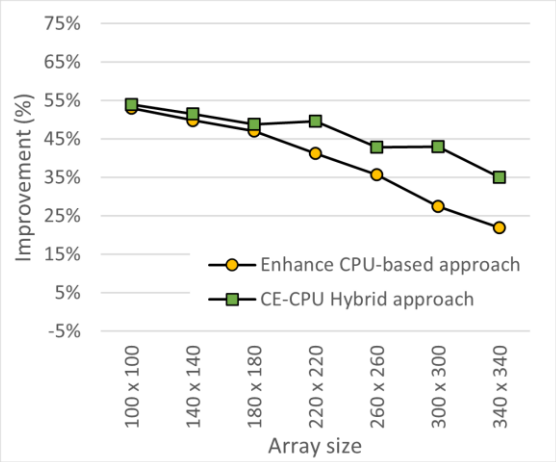


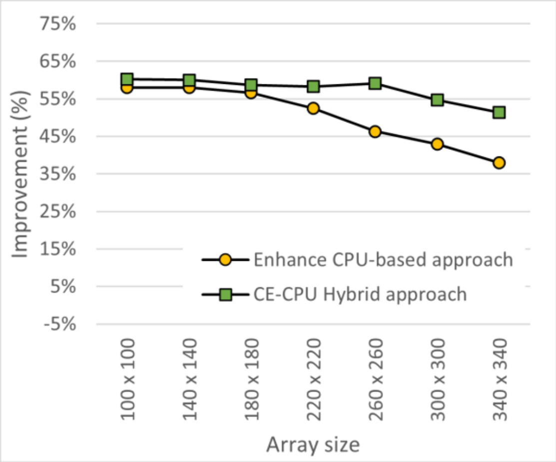


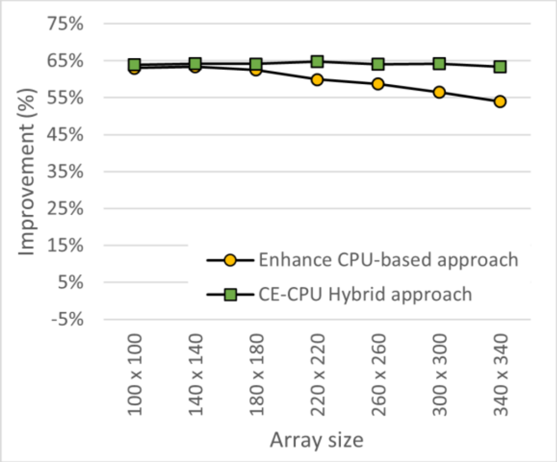


Overlapping with Computation

- MPI_Gather
  - The enhanced CPU-based approach and the CE-CPU hybrid approach could reduce the execution time up to 63% and 65%, respectively
  - 20-process case with 4, 8, and 16 MB messages







Asynchronism in MPI Intra-Node Communications

ASYNCHRONOUS BLOCKING PROGRESS ENGINE

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CPU Power Management States

- Dynamic Voltage and Frequency Scaling (DVFS)
  - Provides different levels of voltage and frequency for operating processors
  - P-states (ACPI)
    - P0: Maximum power and frequency
    - Pn: Less than P(n–1) voltage and frequency scaled

- Core-Idling
  - Turns off hardware components of idle cores
  - C-states (ACPI)
    - C0: Active
    - C1: Halt
    - C2: Stop-clock
    - C3: Sleep

Related Work

- Decision policies
  - EAM [SC'15]
    - Estimates the duration of MPI and communication phases based on temporal execution patterns
    - Interrupt-based core-idling
  - COUNTDOWN [ToC 2021]
    - Intercepts MPI calls and uses a time-out strategy for DVFS
    - Countdown Slack [TPDS 2020]
  - EAR/EARL [Cluster 2020]
    - Detects iterative regions and maintains application signatures by intercepting MPI calls
    - Decides the CPU frequency based on an energy model
- No support for core-idling on intra-node communication channels

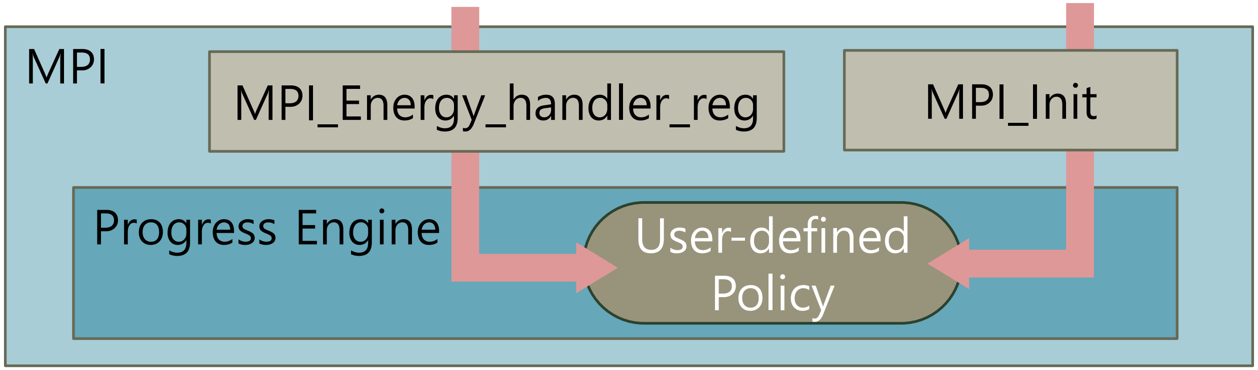
Asynchronous Blocking Progress Engine

- We aim to provide a framework that efficiently supports core-idling over multiple MPI communication channels
  - Intra-node communication channels
    - Shared memory
    - Memory mapping

- Asynchronous Blocking Progress Engine
  - Framework for energy-efficient MPI
  - Asynchronous blocking intra-node communication
  - Integration with blocking inter-node communication

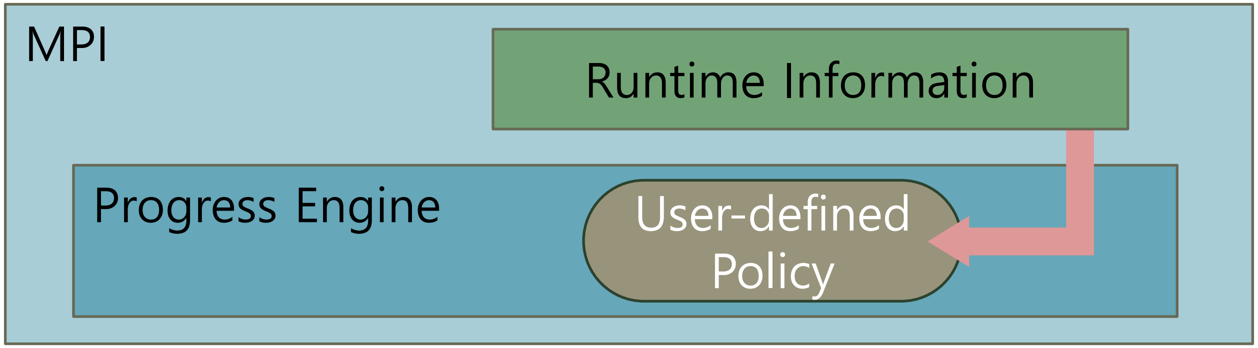
Framework for Energy Efficient MPI

- Interfaces
  - APIs
    - `MPI_Energy_handler_reg()`
      - `int *(enter_function) (MPI_Energy_Info*)`
    - `MPI_Energy_handler_dereg()`
    - Application can change the policy at runtime
  - Hooking of MPI calls
    - `MPI_Init()` and `MPI_Finalize()`
    - No application-level modification is required



Framework for Energy Efficient MPI

- Internal runtime information
  - Ranks
  - Communication channel
  - Message size
  - Number of busy-waiting iterations
  - Current busy-waiting time
  - Last busy-waiting time
  - …

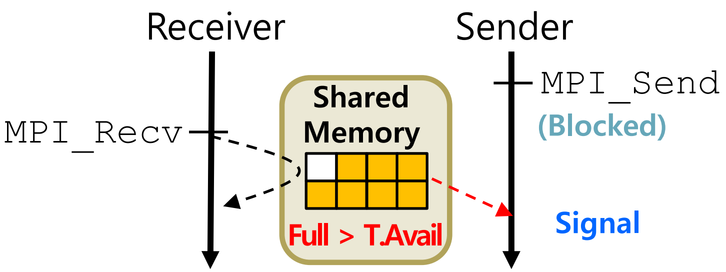


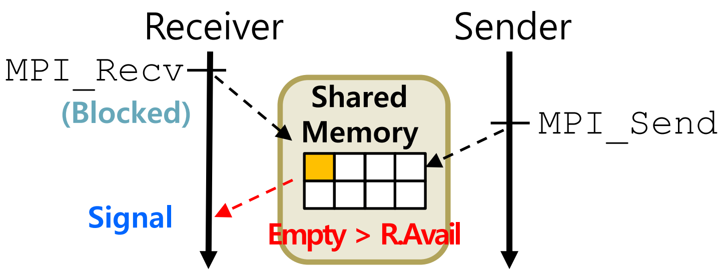
Signal-based Blocking Communication

- CPU dependent implementation
  - Assembly instructions (e.g., `mwait`)
- CPU independent implementation
  - Timers: only for coarse-grained controls
  - Semaphores: deadlock-prone
  - Signals: lossy
    - Easy to support callback functions
    - Flexible enough to support the inter-node communication channel
    - Able to leverage existing decision policies used in DVFS and core-idling approaches

Signaling Points

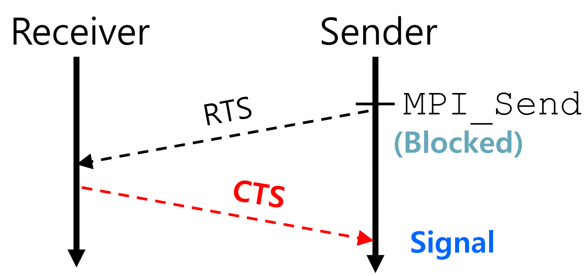
- Shared memory channel
  - When a shared buffer becomes available
  - When a new message is arrived

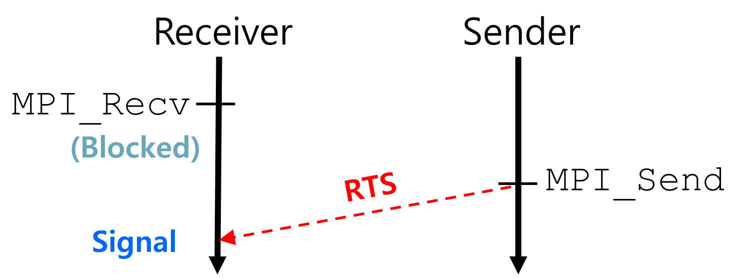


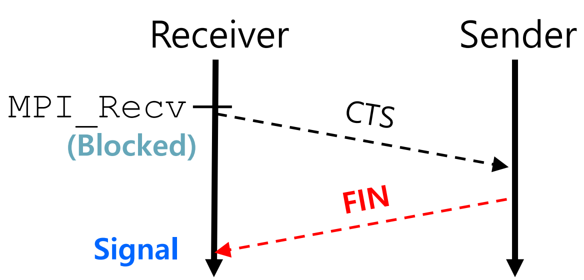


Signaling Points

- Memory mapping channel
  - When a control message of rendezvous protocol arrives

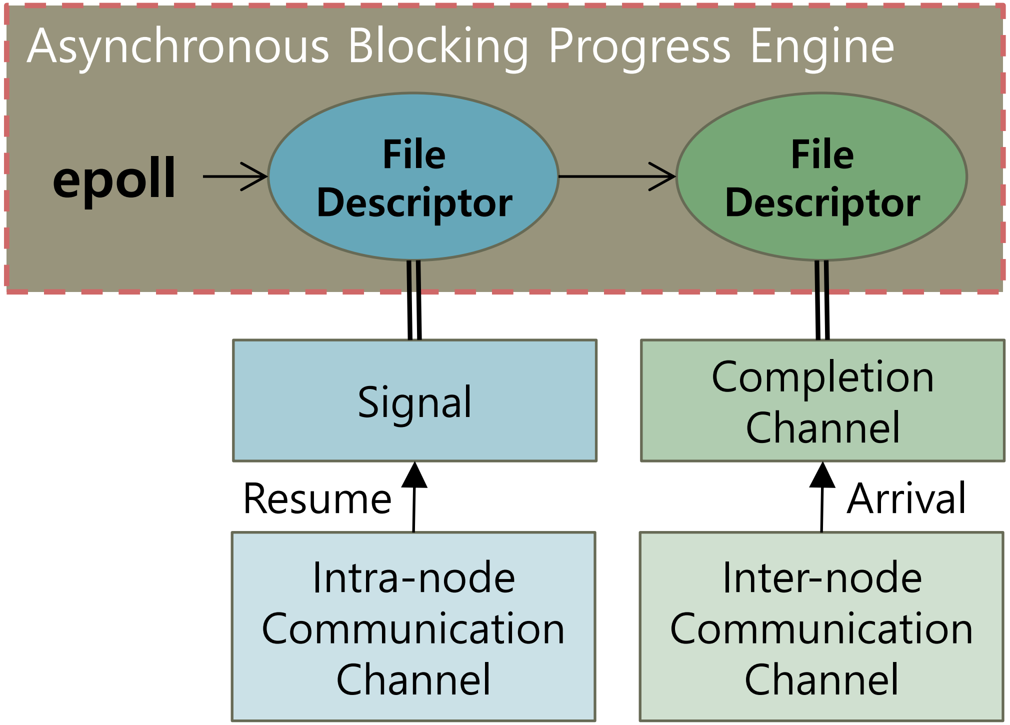






Integration with Blocking Inter-Node Communication

- Blocking inter-node communication
  - MV2_USE_BLOCKING
- `epoll`-based integration
  - File descriptors
    - Signal for intra-node communication
    - Completion channel for inter-node communication

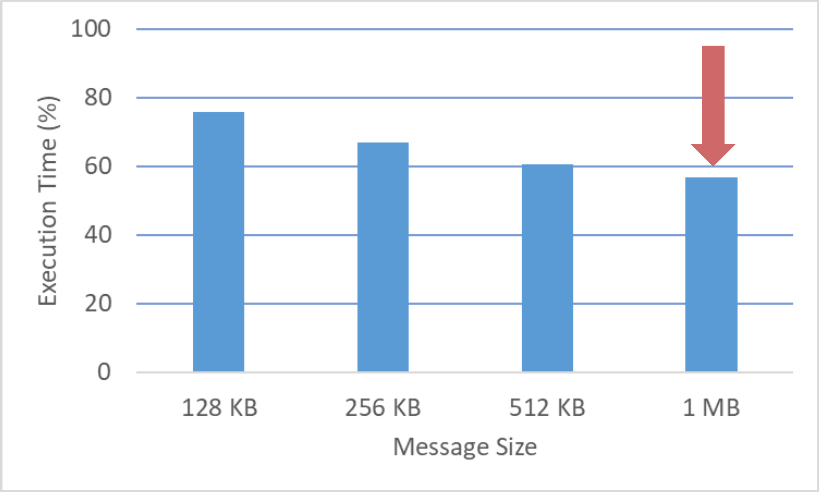


Performance Measurements

- Experiment system
  - Two ARM-based multi-core systems
    - Ampere eMAG 8180 (ARMv8) 3 GHz 32-core processor
    - DDR4 250 GB memory
  - NVIDIA ConnectX-5 InfiniBand adapter
  - Linux kernel version 5.4.0-156-generic
  - Wattman HPM-100A power meter
- Comparisons
  - Default blocking mode
    - MVAPICH2 version 2.3.7 with MV2_USE_BLOCKING
  - Our energy efficient framework
    - MVAPICH2 version 2.3.1

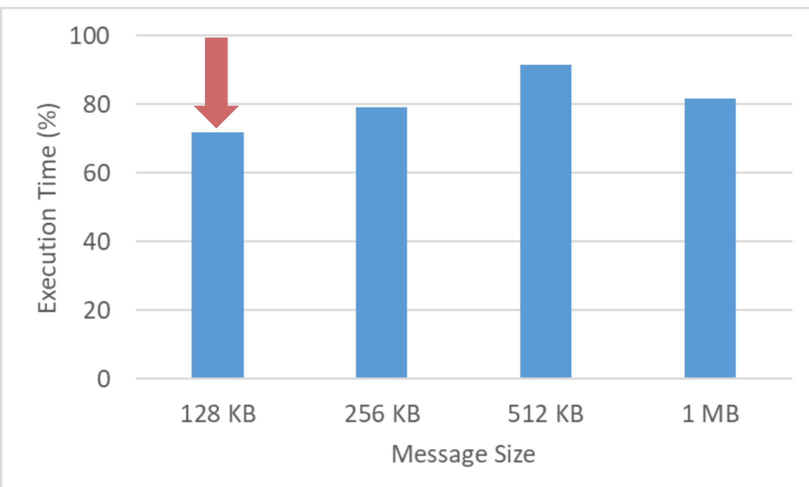
OSU Micro-Benchmark

- MPI_Alltoall
  - Execution time: 43.4% reduction (1 MB)
  - Energy consumption: 41.8% saving (1 MB)



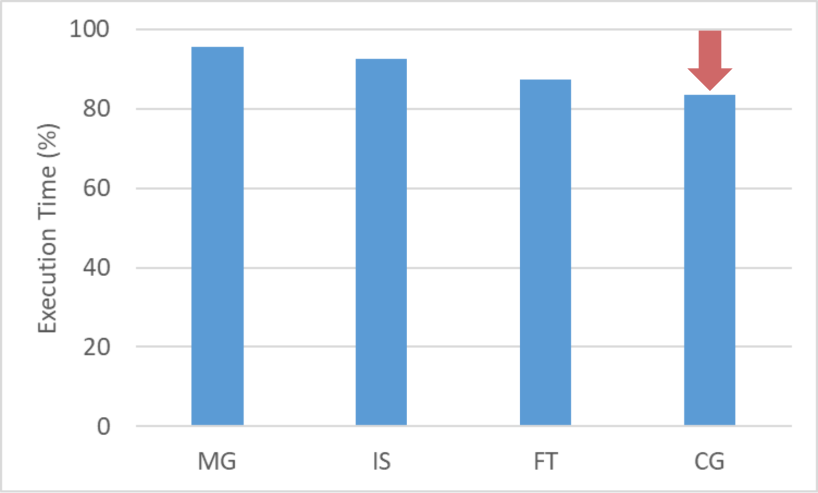
OSU Micro-Benchmarks

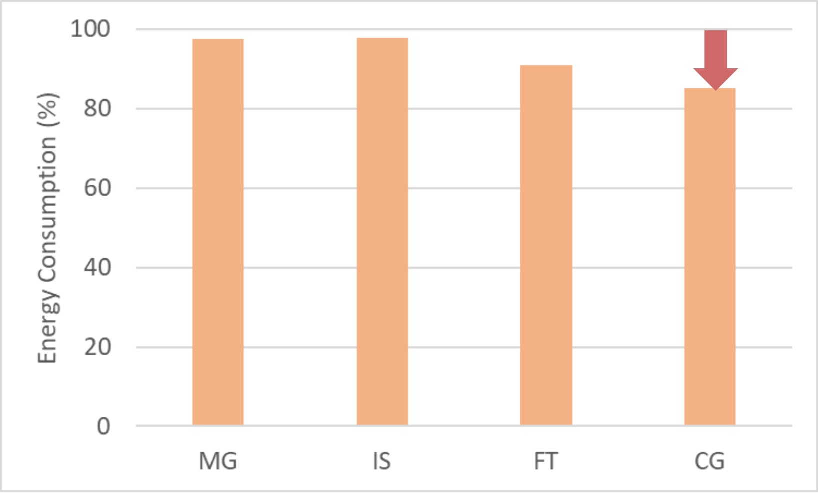
- MPI_Allreduce
  - Execution time: 28.1% reduction (128 KB)
  - Energy consumption: 28.9% saving (128 KB)



NAS Parallel Benchmarks

- Class C
  - Execution time: 16.5% reduction (CG)
  - Energy consumption: 14.9% saving (CG)





CONCLUDING REMARK

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Conclusions

- Asynchronous nonblocking data copy
  - A scheme to exploit multiple copy engines and CPUs for intra-node MPI collective communications
  - J.-Y. Cho, P.-R. Seo, and H.-W. Jin, “Exploiting Copy Engines for Intra-Node MPI Collective Communication,” The Journal of Supercomputing, May 2023
- Asynchronous blocking progress engine
  - A framework for better supports for energy-aware decision policies over multiple MPI communication channels
  - K.-W. Kim, H.-W. Jin, and E.-K. Byun, “Core-idling on MPI Intra-node Communication Channels for Energy Efficiency,” SC’21, Poster, November 2021

Future Work

- Asynchronous nonblocking data copy
  - Other collective calls
    - Blocking and nonblocking collective communications
  - Integration with inter-node communication
  - Measurement with real applications
- Asynchronous blocking progress engine
  - Various policies
  - Measurement with real applications