Optimized Non-contiguous MPI Datatype Communication for GPU Clusters: Design, Implementation and Evaluation with MVAPICH2

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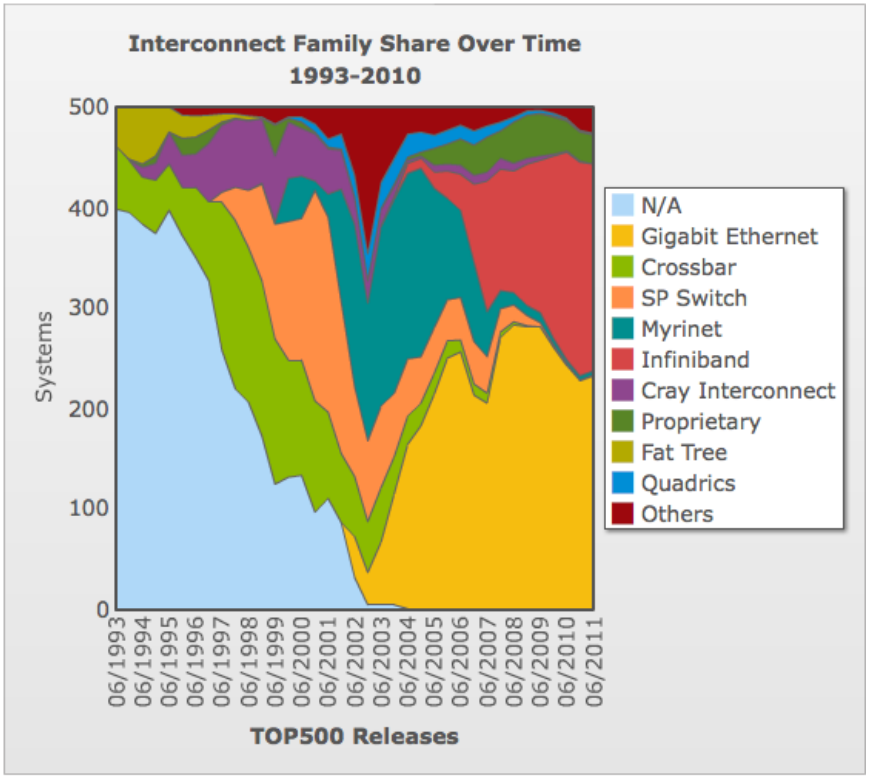
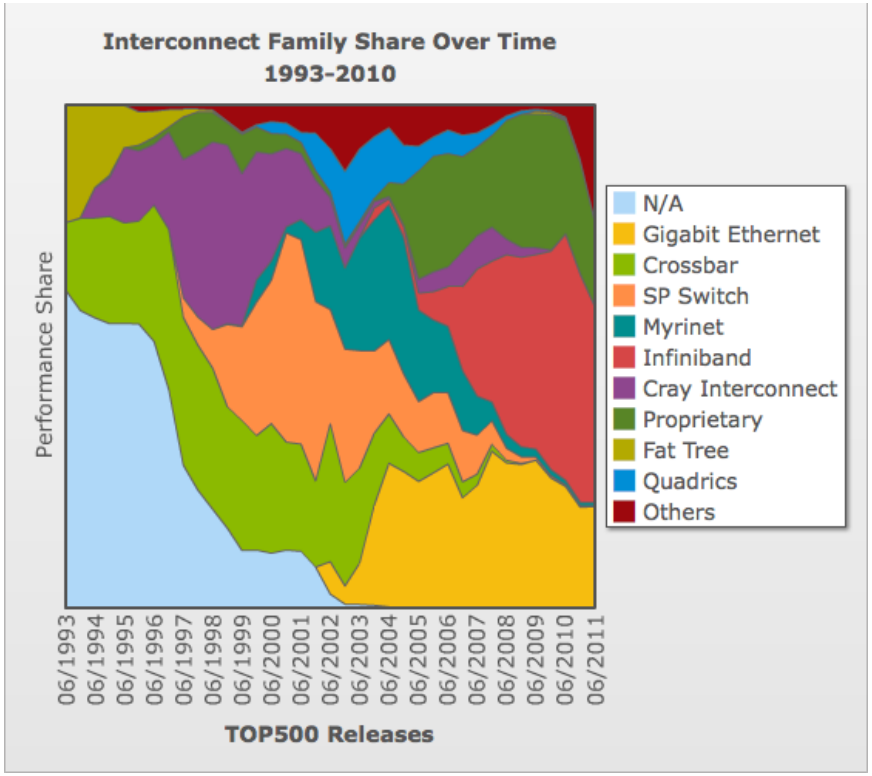
Outline

- Introduction
- Problem Statement
- Our Solution: MVAPICH2-GPU-NC
- Design Considerations
- Performance Evaluation
- Conclusion & Future Work

InfiniBand Clusters in TOP500



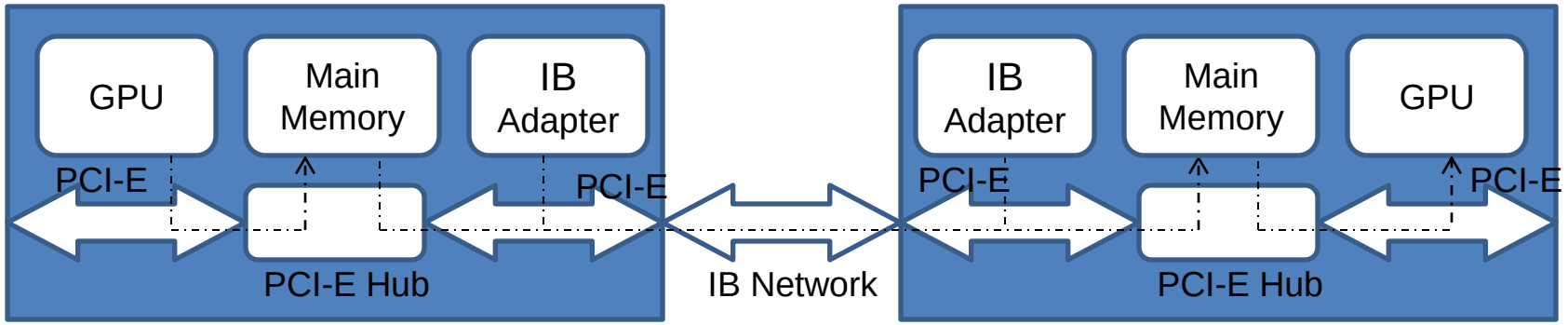


- Percentage share of InfiniBand is steadily increasing
- 41% of systems in TOP500 using InfiniBand (June '11)
- 61% of systems in TOP100 using InfiniBand (June '11)

Growth in GPGPUs

- GPGPUs are gaining significance on clusters for data-centric applications
  - Word Occurrence, Sparse Integer Occurrence
  - K-means clustering, Linear regression
- GPGPUs + InfiniBand are gaining momentum for large clusters
  - #2 (Tianhe-1A), #4 (Nebulae) and #5 (Tsubame) Petascale systems
- GPGPUs programming
  - CUDA or OpenCL + MPI
- *Big issues: performance of data movement*
  - *Latency*
  - *Bandwidth*
  - *Overlap*

Data Movement in GPU Clusters



- Data movement in InfiniBand clusters with GPUs
  - CUDA: Device memory → Main memory [at source process]
  - MPI: Source rank → Destination process
  - CUDA: Main memory → Device memory [at destination process]

MVAPICH/MVAPICH2 Software

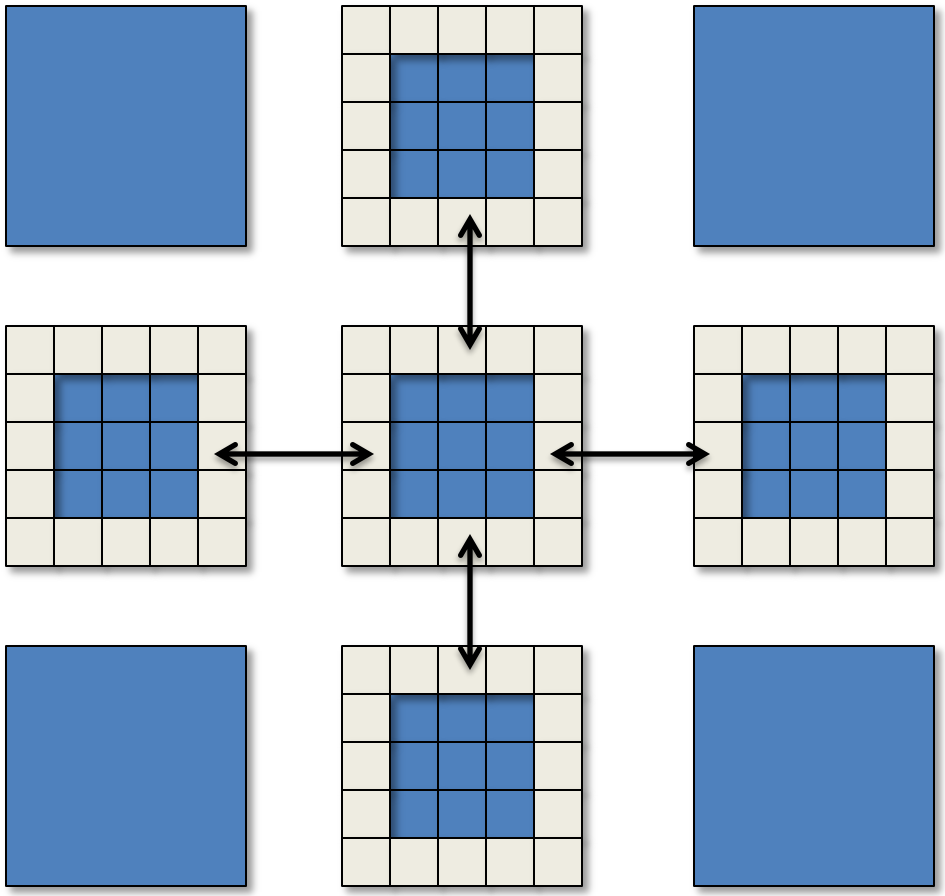
- High Performance MPI Library for IB and HSE
  - MVAPICH (MPI-1) and MVAPICH2 (MPI-2.2)
  - Used by more than 1,710 organizations in 63 countries
  - More than 79,000 downloads from OSU site directly
  - Empowering many TOP500 clusters
    - 5th ranked 73,278-core cluster (Tsubame 2.0) at Tokyo Institute of Technology
    - 7th ranked 111,104-core cluster (Pleiades) at NASA
    - 17th ranked 62,976-core cluster (Ranger) at TACC
  - Available with software stacks of many IB, HSE and server vendors including Open Fabrics Enterprise Distribution (OFED) and Linux Distros (RedHat and SuSE)
  - http://mvapich.cse.ohio-state.edu

MVAPICH2-GPU: GPU-GPU using MPI

- Is it possible to optimize GPU-GPU communication with MPI?
  - *H. Wang, S. Potluri, M. Luo, A. K. Singh, S. Sur, D. K. Panda, "MVAPICH2-GPU: Optimized GPU to GPU Communication for InfiniBand Clusters", ISC'11, June, 2011*
  - Support GPU to remote GPU communication using MPI
  - P2P and One-sided were improved
  - Collectives can directly get benefits from p2p improvement
- How to optimize GPU-GPU collectives with different algorithms?
  - *A. K. Singh, S. Potluri, H. Wang, K. Kandalla, S. Sur, D. K. Panda, "MPI Alltoall Personalized Exchange on GPGPU Clusters: Design Alternatives and Benefits", PPAC'11 with Cluster'11, Sep, 2011*
  - Support GPU to GPU Alltoall communication with Dynamic Staging mechanism
  - GPU-GPU Alltoall performance was improved
- How to handle non-contiguous data in GPU device memory?
  - *This paper!*
  - Support GPU-GPU non-contiguous data communication (P2P) using MPI
  - Vector datatype and SHOC benchmark are optimized

Non-contiguous Data Exchange

Halo data exchange



- Multi-dimensional data
  - Row based organization
  - Contiguous on one dimension
  - Non-contiguous on other dimensions
- Halo data exchange
  - Duplicate the boundary
  - Exchange the boundary in each iteration

Datatype Support in MPI

- Native datatypes support in MPI
  - improve programming productivity
  - Enable MPI library to optimize non-contiguous data transfer

At Sender:

```
MPI_Type_vector (n_blocks, n_elements, stride, old_type, &new_type);
MPI_Type_commit(&new_type);
…
MPI_Send(s_buf, size, new_type, dest, tag, MPI_COMM_WORLD);
```

- What will happen if the non-contiguous data is inside GPU device memory?

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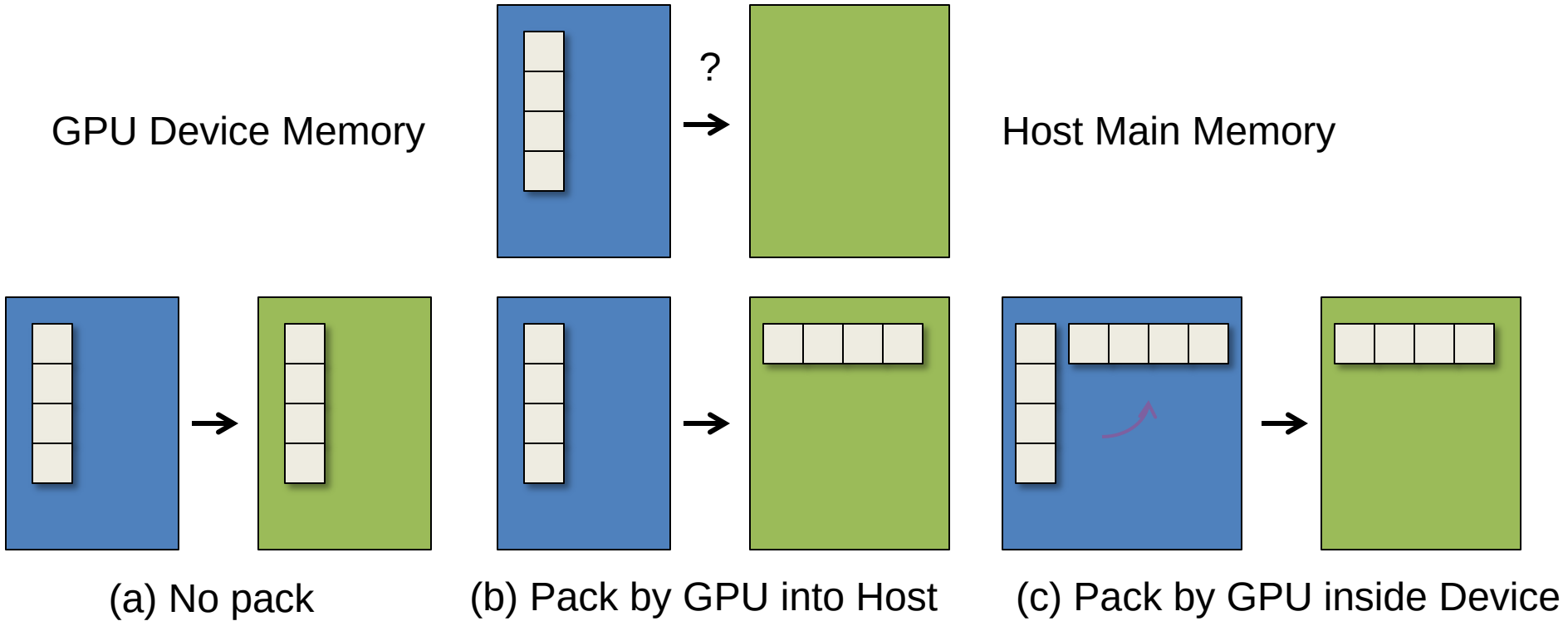
Problem Statement

- Non-contiguous data movement from/to GPGPUs
  - Performance bottleneck
  - Reduced programmer productivity
- Hard to optimize GPU-GPU non-contiguous data communication at the user level
  - CUDA and MPI expertise is required for efficient implementation
  - Hardware dependent characteristics, such as latency
  - Different choices of Pack/Unpack non-contiguous data, which is better?

Problem Statement (Cont.)



Which is better?

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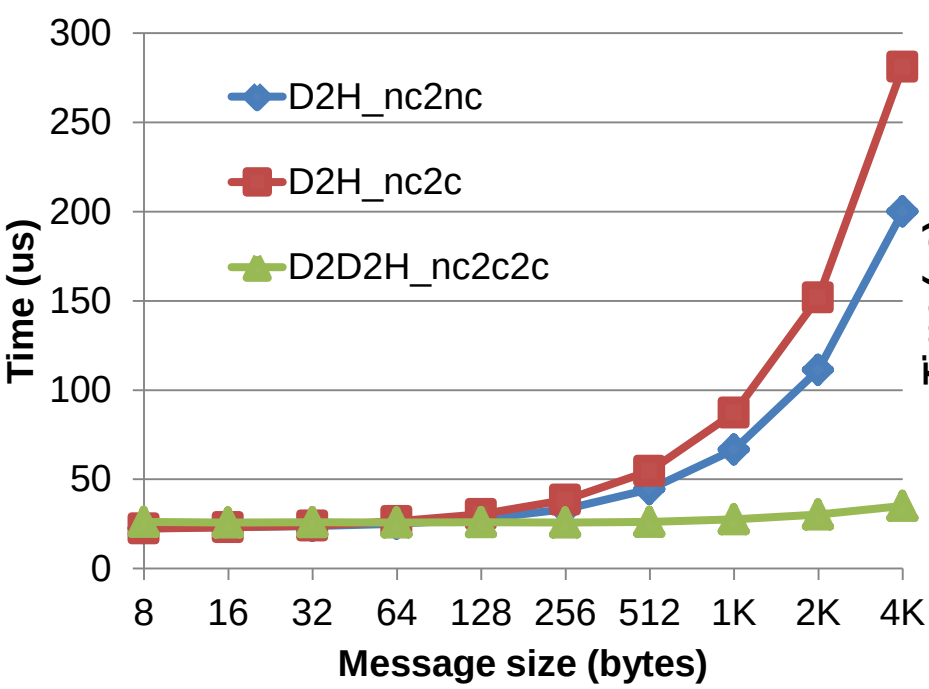
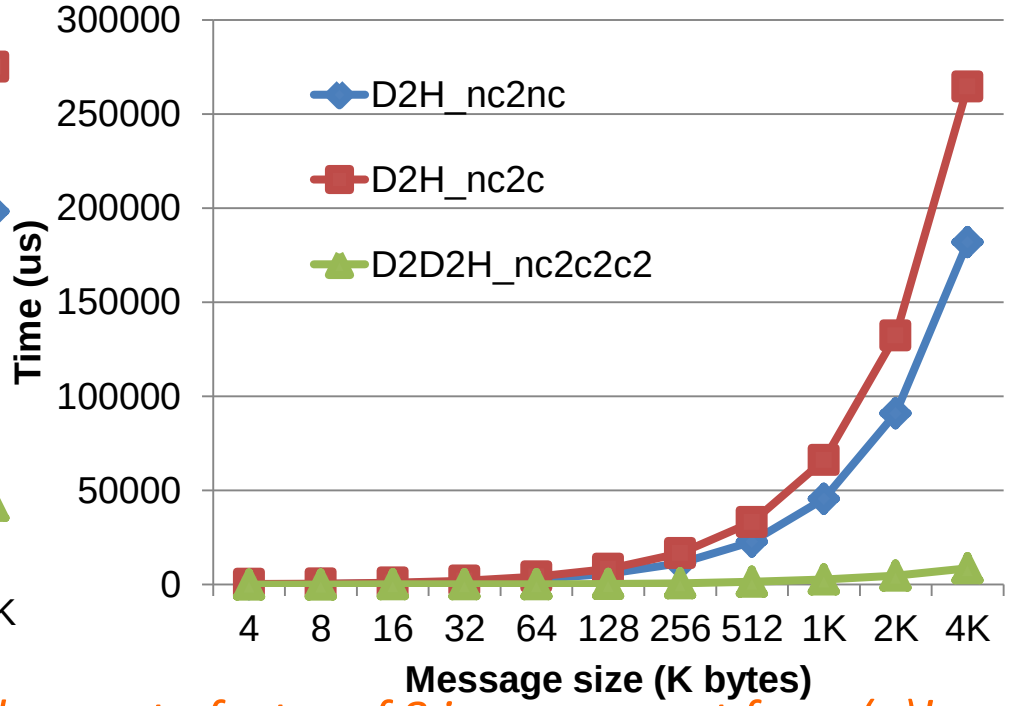
Performance for Vector Pack





(c) has up to factor of 8 improvement from (a)!

- Pack latency (similar for unpack)
  - (a) D2H_nc2nc: D2H, non-contiguous to non-contiguous. Pack by CPU later
  - (b) D2H_nc2c: D2H, non-contiguous to contiguous. Pack by GPU directly to host memory
  - (c) D2D2H_nc2c2c: D2D2H, non-contiguous to contiguous inside GPU

MVAPICH2-GPU-NC: Design Goals

- Support GPU-GPU non-contiguous data communication through standard MPI interfaces
  - e.g. MPI_Send / MPI_Recv can operate on GPU memory address for non-contiguous datatype, like MPI_Type_vector
- Provide high performance without exposing low level details to the programmer
  - offload datatype pack and unpack to GPU
    - Pack: pack non-contiguous data into contiguous buffer inside GPU, then move out
    - Unpack: move contiguous data into GPU memory, then unpack to non-contiguous address
  - pipeline data pack/unpack, data movement between device and host, and data transfer on networks
    - *Automatically* provides optimizations inside MPI library without user tuning

Sample Code - Without MPI Integration

- Simple implementation for vector type with MPI and CUDA
  - Data pack and unpack by CPU

```
MPI_Type_vector (n_rows, width, n_cols, old_datatype, &new_type);
MPI_Type_commit(&new_type);
```

At Sender:

```
cudaMemcpy2D(s_buf, n_cols * datasize, s_device, n_cols * datasize, width * datasize,
n_rows, DeviceToHost);
MPI_Send(s_buf, 1, new_type, dest, tag, MPI_COMM_WORLD);
```

At Receiver:

```
MPI_Recv(r_buf, 1, new_type, src, tag, MPI_COMM_WORLD, &req);
cudaMemcpy2D(r_device, n_cols * datasize, r_buf, n_cols * datasize, width * datasize,
n_rows, HostToDevice);
```

- *High productivity but poor performance*

Sample Code – User Optimized

- Data pack/upack is done by GPU without MPI data type support
- Pipelining at user level using non-blocking MPI and CUDA interfaces

At Sender:

```
for (j = 0; j < pipeline_len; j++)
    // pack: from non-contiguous to contiguous buffer in GPU device memory
    cudaMemcpy2DAsync(…);
while (active_pack_stream || active_d2h_stream) {
    if (active_pack_stream > 0 && cudaStreamQuery() == cudaSucess) {
        // contiguous data move from device to host
        cudaMemcpyAsync(…);
    }
    if (active_d2h_stream > 0 && cudaStreamQuery() == cudaSucess)
        MPI_Isend(….);
}
MPI_Waitall();
```

Good performance but poor productivity

Sample Code – MVAPICH2-GPU-NC

- MVAPICH2-GPU-NC: supports GPU-GPU non-contiguous data communication with standard MPI library
  - Offload data Pack and unpack to GPU
  - Implement pipeline inside MPI library

```
MPI_Type_vector (n_rows, width, n_cols, old_datatype, &new_type);
MPI_Type_commit(&new_type);
```

At Sender:

```
// s_device is data buffer in GPU
MPI_Send(s_device, 1, new_type, dest, tag, MPI_COMM_WORLD);
```

At Receiver:

```
// r_device is data buffer in GPU
MPI_Recv(r_device, 1, new_type, src, tag, MPI_COMM_WORLD, &req);
```

- *High productivity and high performance!*

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Design Considerations

- Memory detection
  - CUDA 4.0 feature *Unified Virtual Addressing (UVA)*
  - MPI library can differentiate between device memory and host memory without any hints from the user
- Overlap data pack/unpack with CUDA copy and RDMA transfer
  - Data pack and unpack by GPU inside device memory
  - Pipeline data pack/unpack, data movement between device and host, and InfiniBand RDMA
  - Allow for progressing DMAs individual data chunks

Pipeline Design

- Chunk size depends on CUDA copy cost and RDMA latency over the network
- Automatic tuning of chunk size
  - Detects CUDA copy and RDMA latencies during installation
  - Chunk size can be stored in configuration file (mvapich.conf)
- User transparent to deliver the best performance

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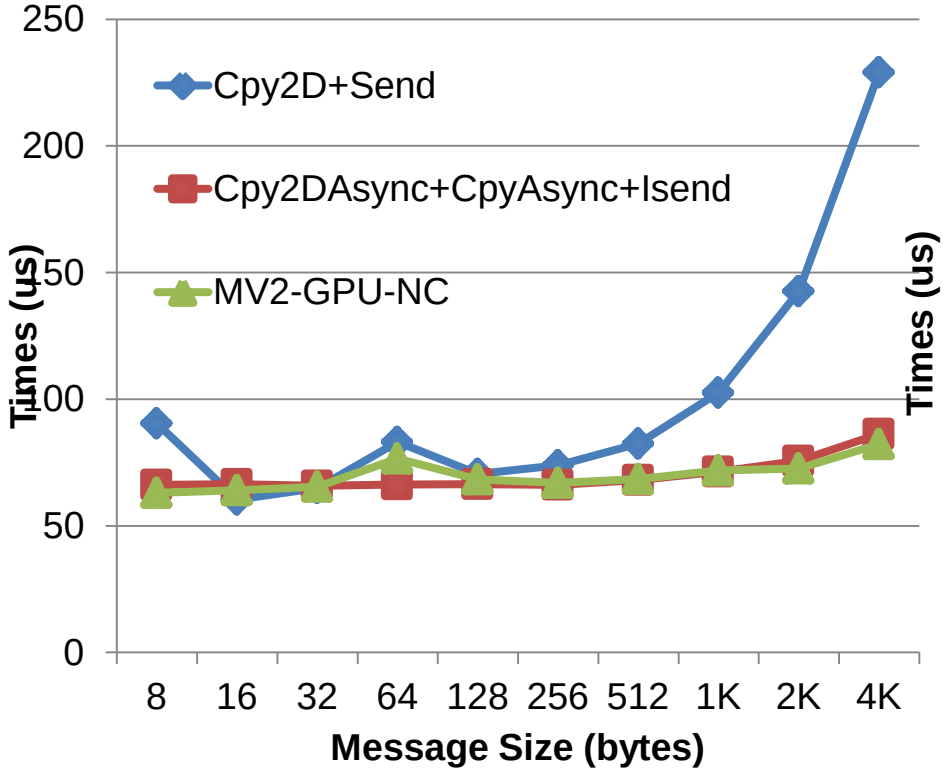
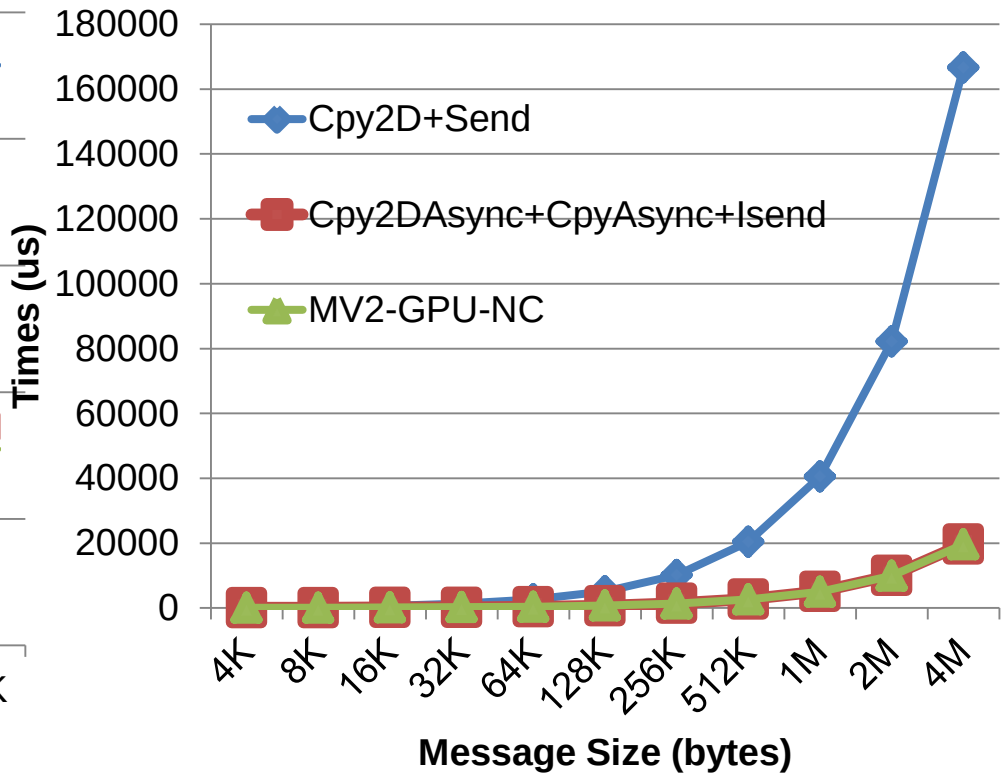
Performance Evaluation

- Experimental environment
  - NVIDIA Tesla C2050
  - Mellanox QDR InfiniBand HCA MT26428
  - Intel Westmere processor with 12 GB main memory
  - MVAPICH2 1.6, CUDA Toolkit 4.0
- Modified OSU Micro-Benchmarks
  - The source and destination addresses are in GPU device memory
- SHOC Benchmarks (1.0.1) from ORNL
  - Stencil2D: a two-dimensional nine point stencil calculation, including the halo data exchange
- Run one process per node with one GPU card (8 nodes cluster)

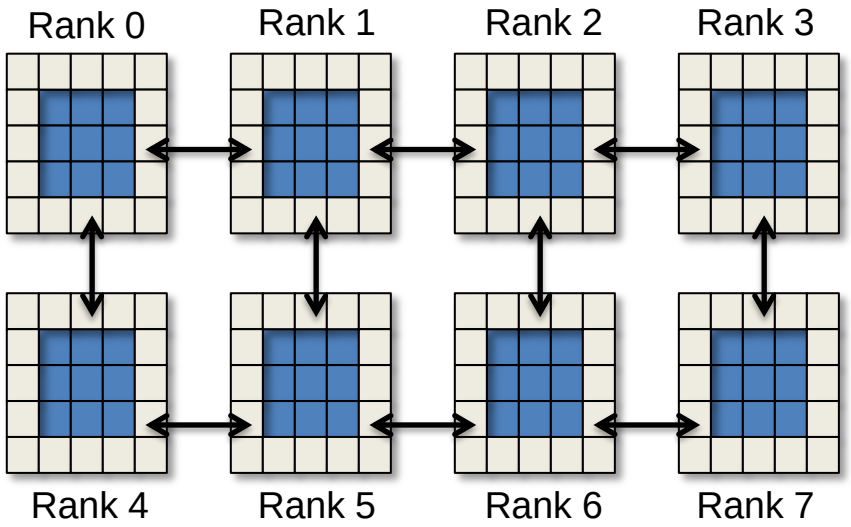
Ping Pong Latency for Vector

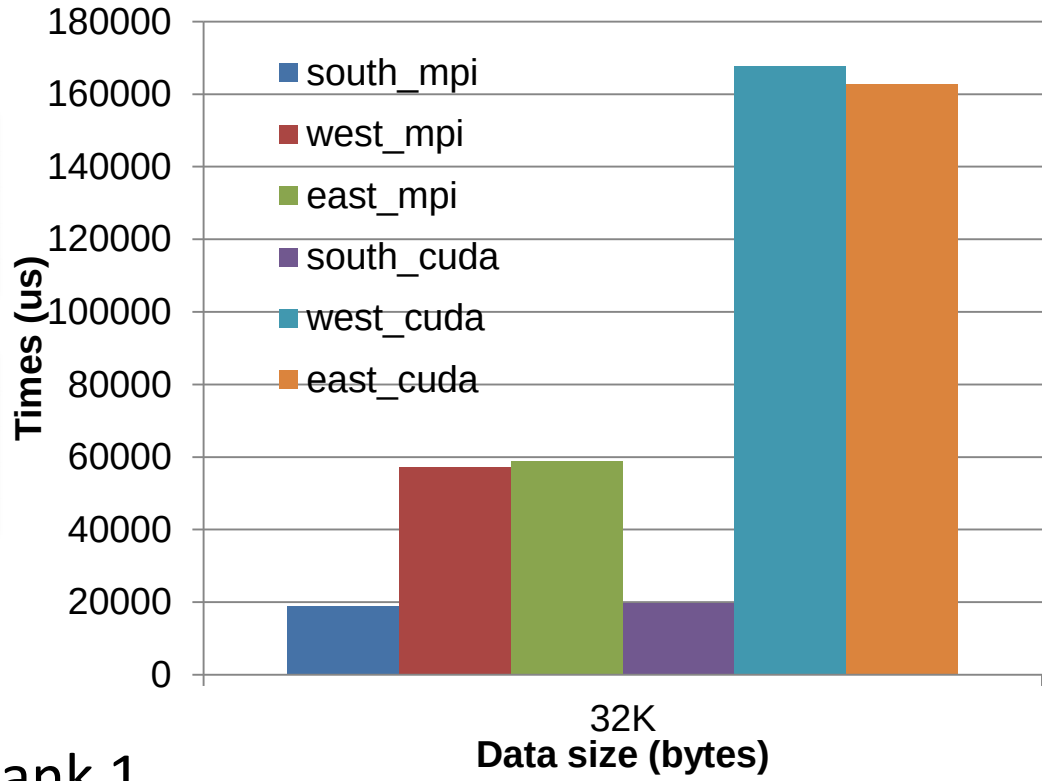




- MV2-GPU-NC
  - *88% improvement compared with Cpy2D+Send at 4MB*
  - *have the similar latency with Cpy2DAsync+CpyAsync+Isend, but much easier for programming*

Stencil2D Time Breakdown





- Time breakdown for process Rank 1
  - 2x4 process grid; 8K x 8K matrix; 32K bytes halo data for each dimension
  - Contiguous data exchange with Rank 5, non-contiguous data exchange with Rank 0 and Rank 2
- Non-contiguous data dominates data transfer time

Code Complexity Comparison

- MV2-GPU-NC uses GPU non-contiguous data address as parameters

	Stencil2D-Default	Stencil2D-MV2-GPU-NC
Function calls	MPI_Irecv: 4 MPI_Send: 4 MPI_Waitall: 2 cudaMemcpy: 4 cudaMemcpy2D: 4	MPI_Irecv: 4 MPI_Send: 4 MPI_Waitall: 2 cudaMemcpy: 0 cudaMemcpy2D: 0
Lines of code	245	158

- *36% code reduction in Stencil2D communication kernel!*

Comparing Median Execution Time

- Single precision
  - 1 x 8: only existing non-contiguous data exchange
  - 8 x 1: only existing contiguous data exchange
  - 2 x 4: 60% non-contiguous, 40% contiguous data exchange
  - 4 x 2: 40% non-contiguous, 60% contiguous data exchange

Process Grid (Matrix Size / Process)	Stencil2D-Default (sec)	Stencil2D-MV2-GPU-NC (sec)	Improvement
1 x 8 (64K x 1K)	0.547788	0.314085	42%
8 x 1 (1K x 64K)	0.33474	0.272082	19%
2 x 4 (8K x 8K)	0.36016	0.261888	27%
4 x 2 (8K x 8K)	0.33183	0.258249	22%

non-contiguous optimization in this paper

contiguous optimization in ISC'11 paper

both contiguous and non-contiguous optimizations

both contiguous and non-contiguous optimizations

Comparing Median Execution Time

- Double precision

Process Grid (Matrix Size / Process)	Stencil2D-Default (sec)	Stencil2D-MV2-GPU-NC (sec)	Improvement
1 x 8 (64K x 1K)	0.780297	0.474613	39%
8 x 1 (1K x 64K)	0.563038	0.438698	22%
2 x 4 (8K x 8K)	0.57544	0.424826	26%
4 x 2 (8K x 8K)	0.546968	0.431908	21%

- *MV2-GPU-NC:*
  - *Up to 42% improvement for Stencil2D with single precision data set;*
  - *Up to 39% improvement for Stencil2D with double precision data set;*

Conclusion & Future Work

- GPU-GPU non-contiguous P2P communication is optimized by MVAPICH2-GPU-NC
  - Support GPU-GPU non-contiguous p2p communication using standard MPI functions; improve the programming productivity
  - Offload non-contiguous data pack/unpack to GPU
  - Overlap Pack/Unpack, data movement between device and host, and data transfer on networks
  - get up to 88% latency improvement compared with without MPI level optimization for vector type
  - get up to 42% and 39% improvement compared with default implementation of Stencil2D in SHOC benchmarks

Conclusion & Future Work

- Future work
  - evaluate non-contiguous datatype performance with our design on larger scale GPGPUs cluster
  - improve more benchmarks and applications with MVAPICH2-GPU-NC
  - integrate this design into MVAPICH2 future releases

Thank You!

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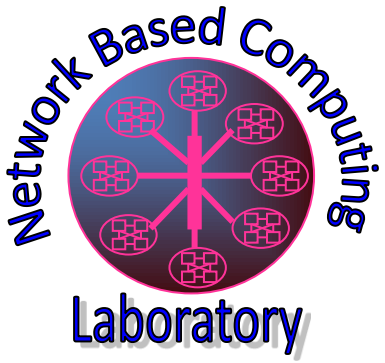

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