

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

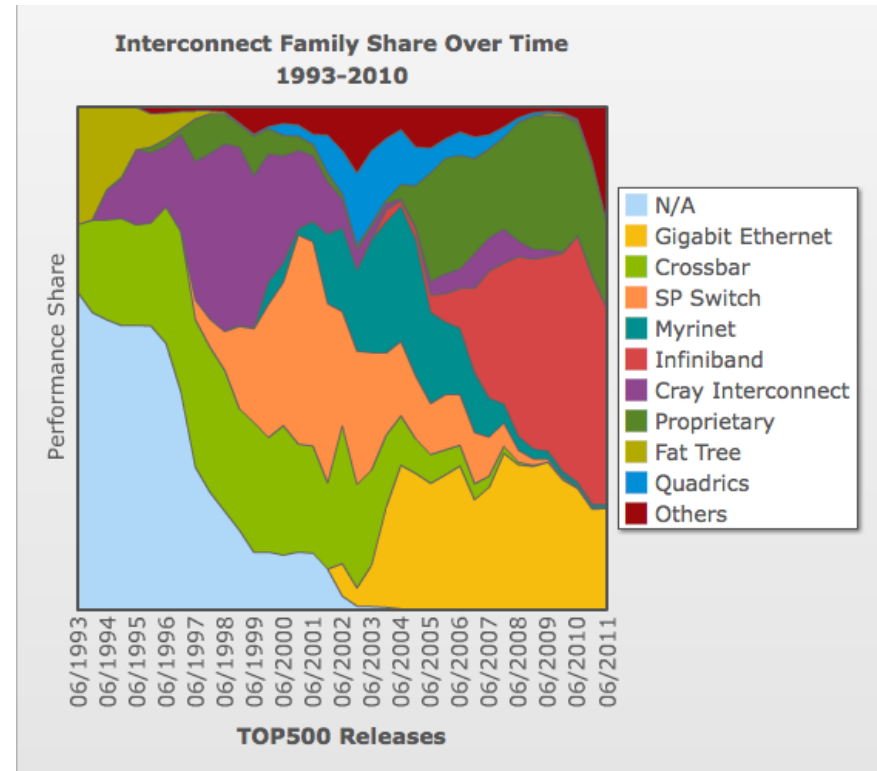
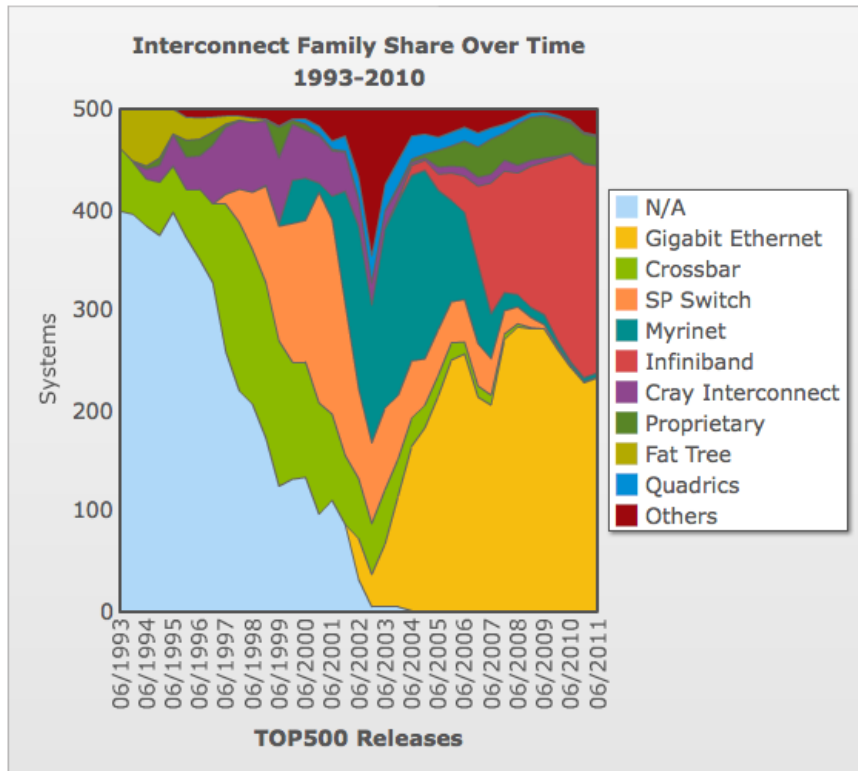
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Outline

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

InfiniBand Clusters in TOP500

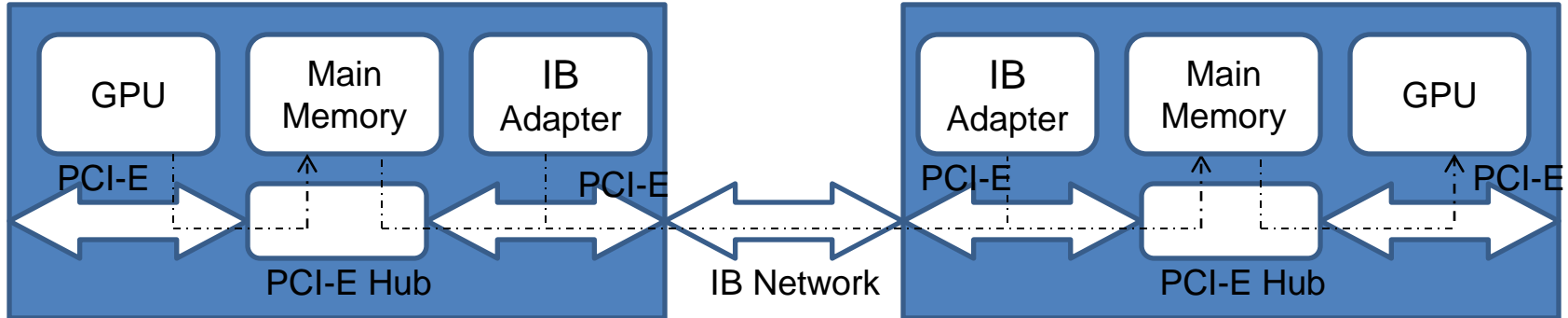


- Percentage share of InfiniBand is steadily increasing
- 41% of systems in TOP500 using InfiniBand (June '11)
- 61% of systems in TOP100 using InfiniBand (June '11)

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 \rightarrow Main memory [at source process]
 - **MPI:** Source rank \rightarrow Destination process
 - **CUDA:** Main memory \rightarrow Device memory [at destination process]

MVAPICH/MVAPICH2 Software

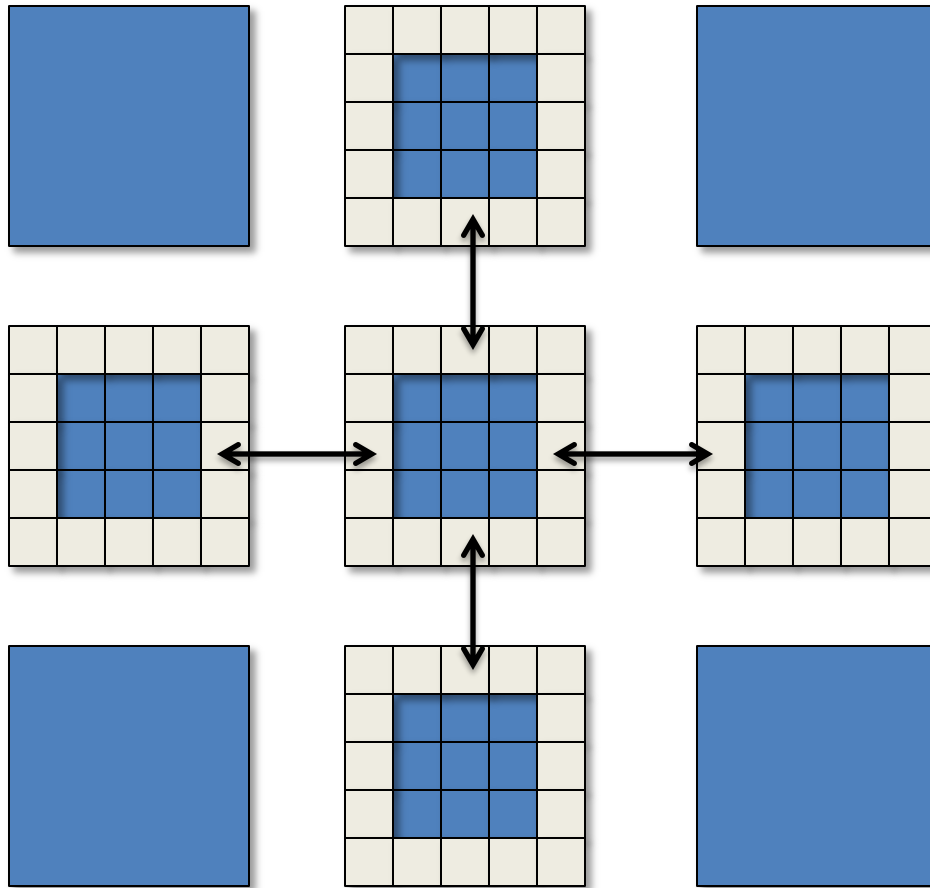
- High Performance MPI Library for IB and HSE
 - MVAPICH (MPI-1) and MVAPICH2 (MPI-2.2)
 - Used by more than 1,710 organizations in 63 countries
 - More than 79,000 downloads from OSU site directly
 - Empowering many TOP500 clusters
 - 5th ranked 73,278-core cluster (Tsubame 2.0) at Tokyo Institute of 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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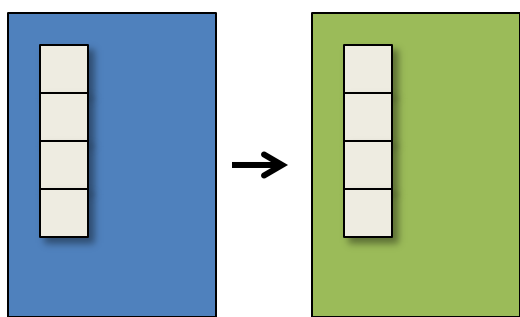
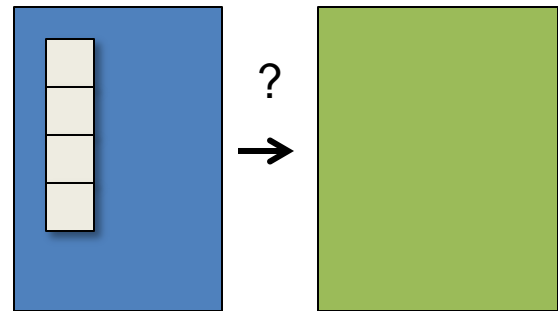
Problem Statement

- 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?

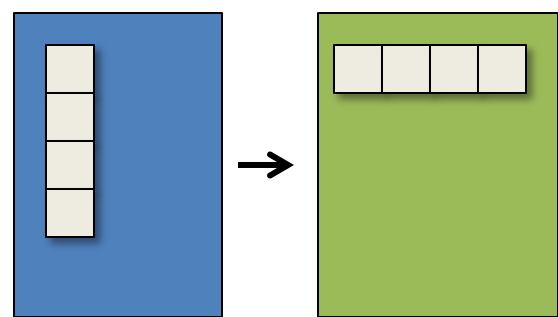
Problem Statement (Cont.)

GPU Device Memory

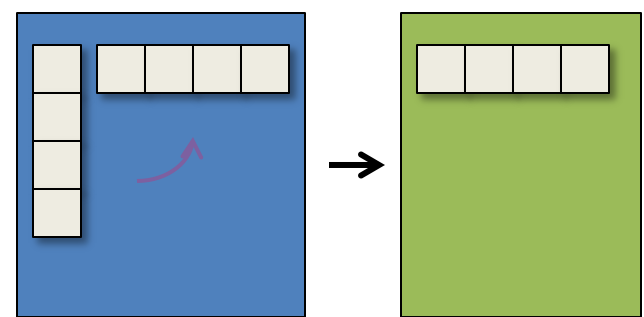
Host Main Memory



(a) No pack



(b) Pack by GPU into Host



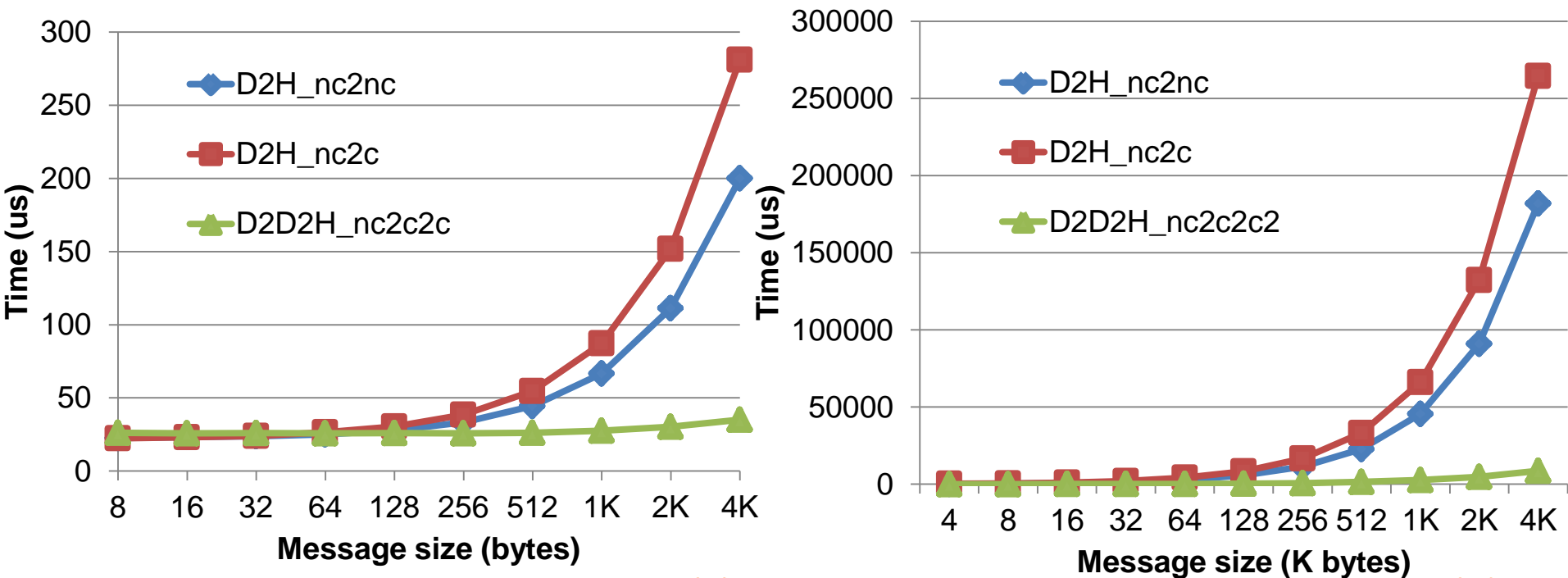
(c) Pack by GPU inside Device

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/unpack 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() == cudaSuccess) {
        // contiguous data move from device to host
        cudaMemcpyAsync(...);
    }
    if (active_d2h_stream > 0 && cudaStreamQuery() == cudaSuccess)
        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

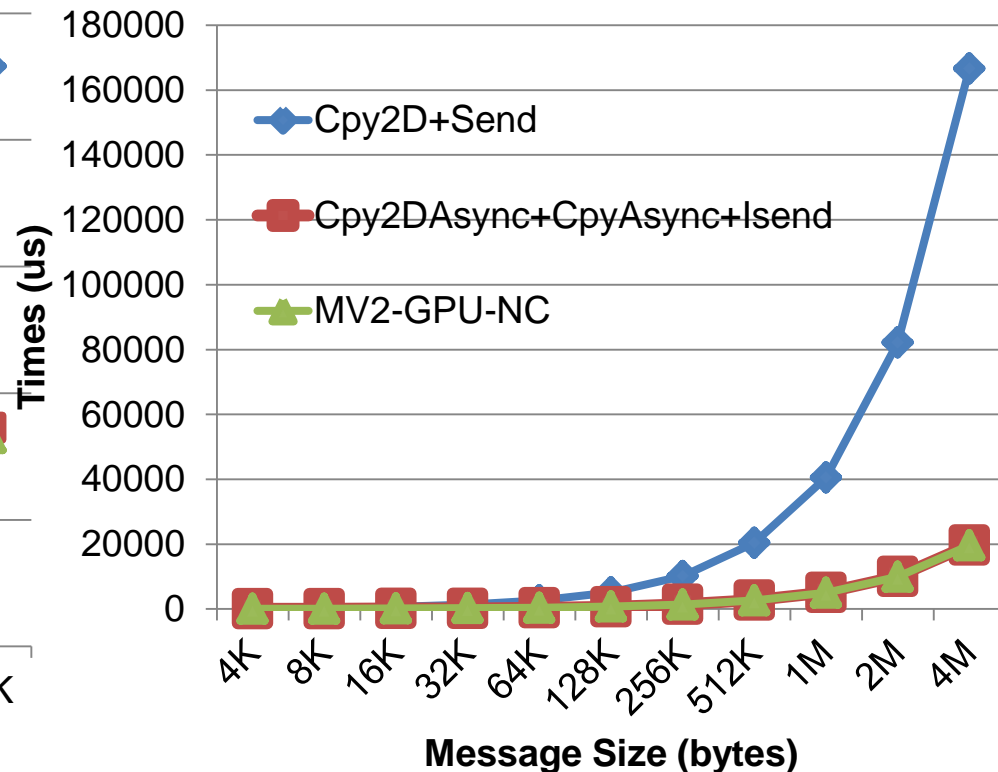
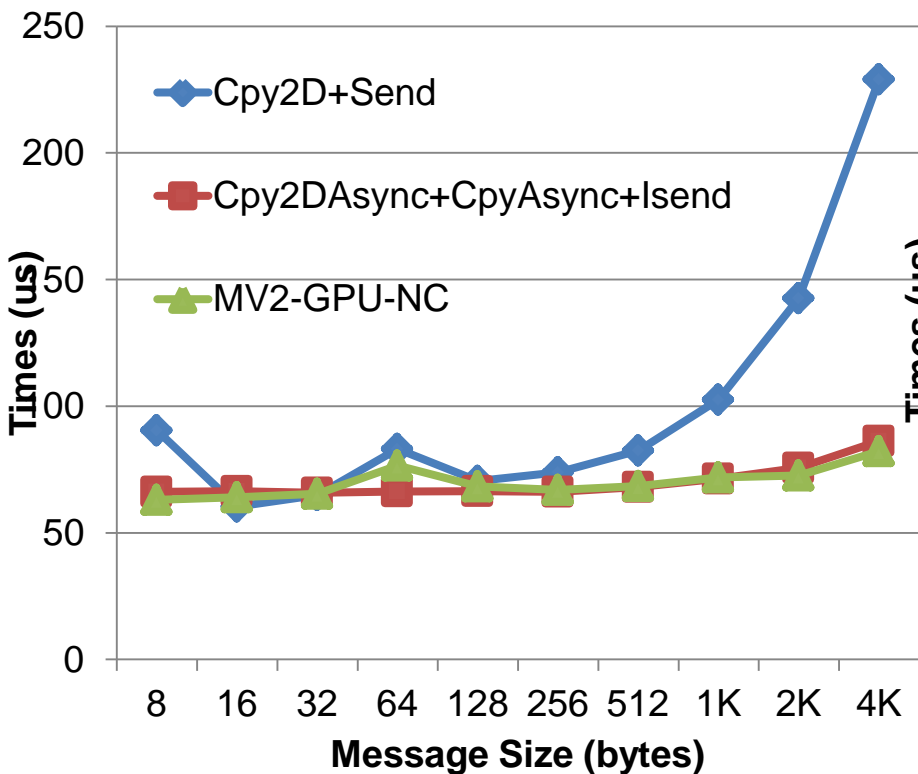
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Performance Evaluation

- 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)

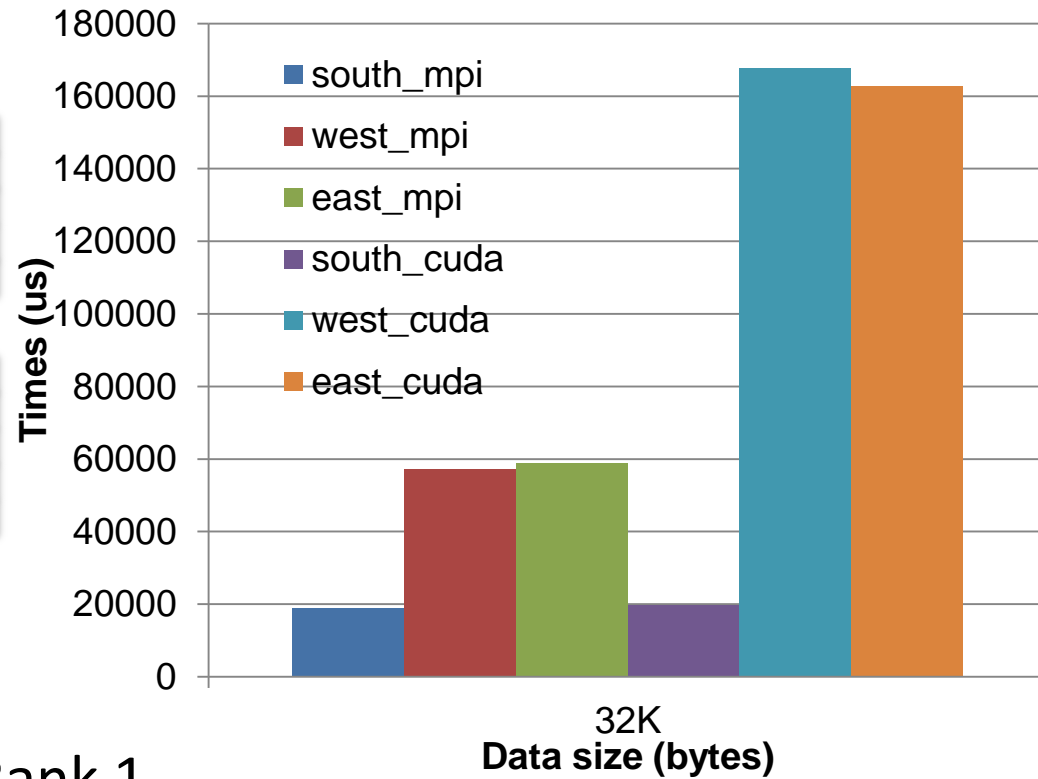
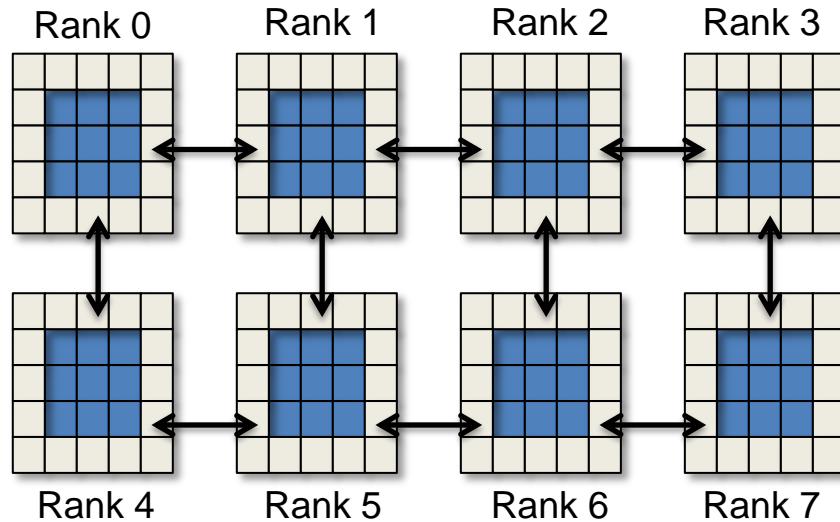
Ping Pong Latency for Vector



- **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)	Improvem ent
1 x 8 (64K x 1K) <i>non-contiguous optimization in this paper</i>	0.547788	0.314085	42%
8 x 1 (1K x 64K) <i>contiguous optimization in ISC'11 paper</i>	0.33474	0.272082	19%
2 x 4 (8K x 8K) <i>both contiguous and non-contiguous optimizations</i>	0.36016	0.261888	27%
4 x 2 (8K x 8K) <i>both contiguous and non-contiguous optimizations</i>	0.33183	0.258249	22%

Comparing Median Execution Time

- Double precision

Process Grid (Matrix Size / Process)	Stencil2D- Default (sec)	Stencil2D-MV2-GPU- NC (sec)	Improvem ent
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

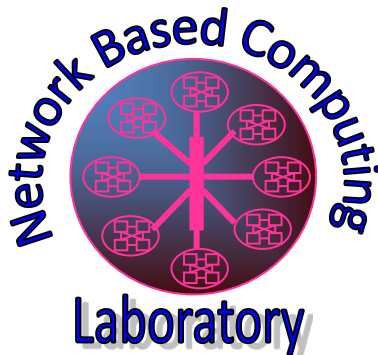
Conclusion & Future Work

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

Thank You!

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<http://nowlab.cse.ohio-state.edu/>

MVAPICH Web Page

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