Optimization 2: Communication Optimization

Osamu Tatebe
tatebe@cs.tsukuba.ac.jp
Faculty of Engineering, Information and Systems / Center for Computational Sciences,
University of Tsukuba

Agenda

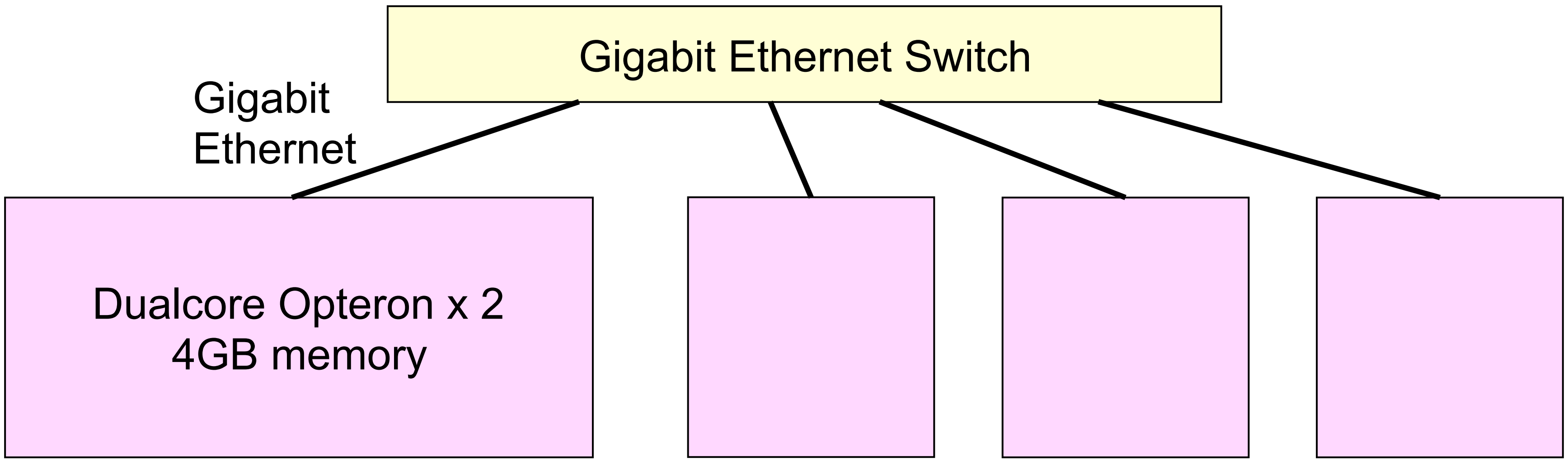
- Basic communication performance
  - Point-to-point communication
  - Collective communication
- Profiling
- Communication optimization technique
  - Communication reduction
  - Communication latency hiding
  - Communication blocking
  - Load balancing
  - Collective communication

Basic Performance

- Performance for basic communications **should be understood** to optimize communication
  - Understand performance in various communication patterns
  - Decide the block size of communication blocking
  - Improve the performance communication library compared with the peak network performance

PC Cluster Platform [P1]

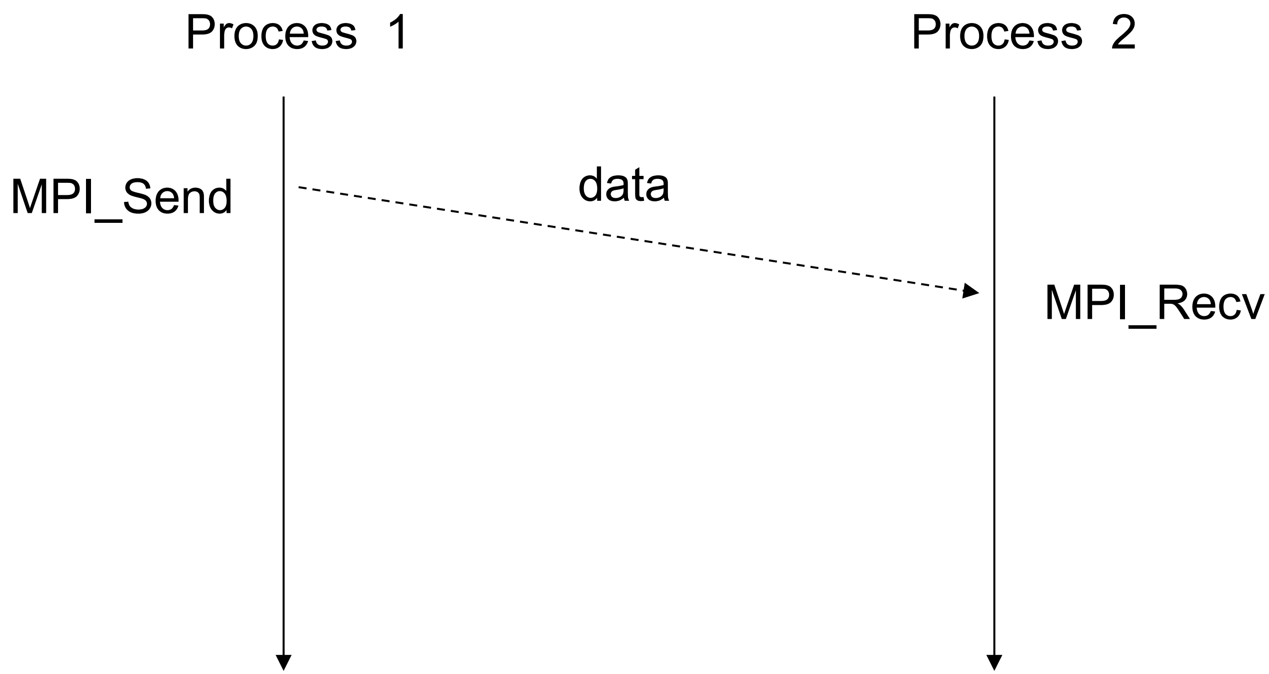
- 4 cluster nodes
  - 2.6GHz Dualcore Opteron x 2 sockets (4 cores)
  - 4GB memory
  - Linux 2.6.18-1.2798.fc6
  - OpenMPI 1.1-7.fc6
- Connected by Gigabit Ethernet
  - Theoretical peak in TCP is 949 Mbps (= 113.1 MB/sec)



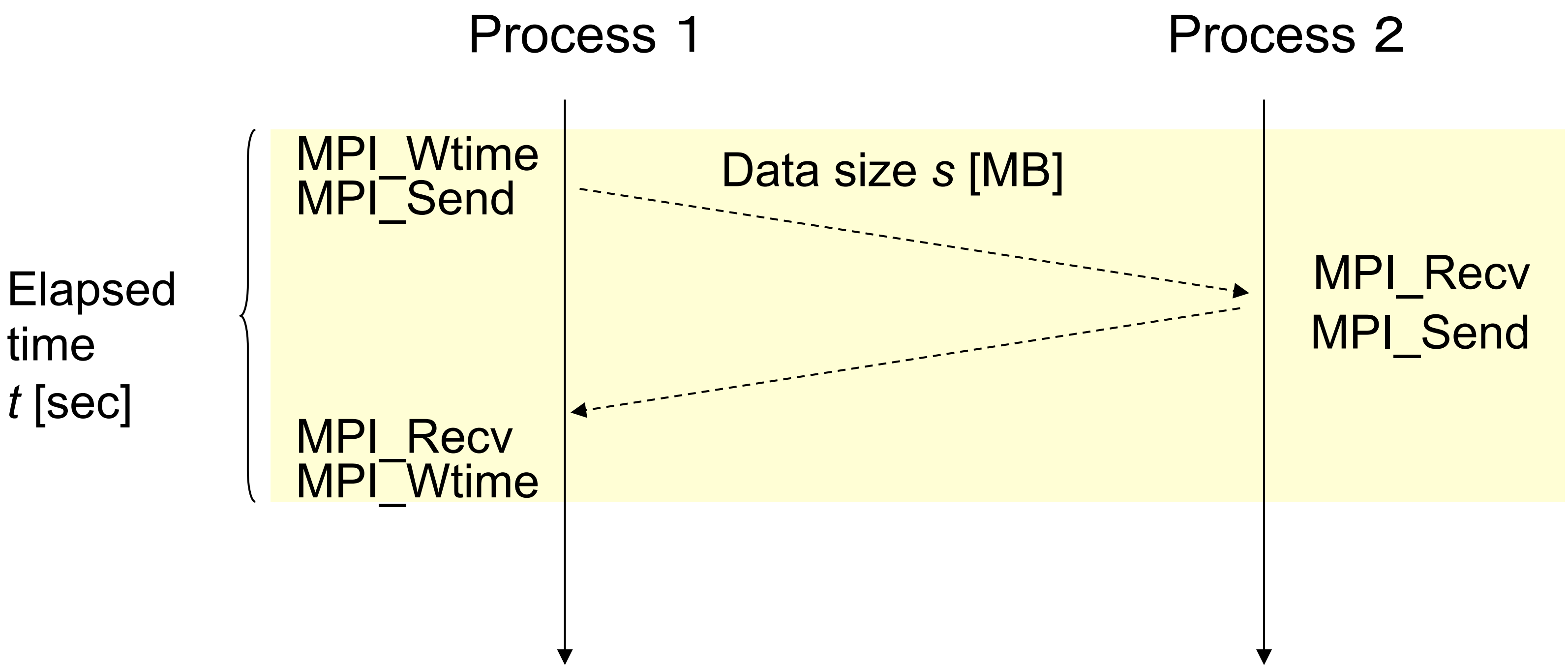
PC Cluster Platform [P2]

- T2K Tsukuba 4 nodes
  - 2.3GHz Quadcore Opteron x 4 sockets (16 cores)
  - 32GB memory
  - MVAPICH2
- Connected by 4xDDR Infiniband (multirail)
  - Theoretical peak is 8 GB/sec (= 64 Gbps)
- No memory location optimization

Performance of point-to-point communication



PingPong Benchmark (1)

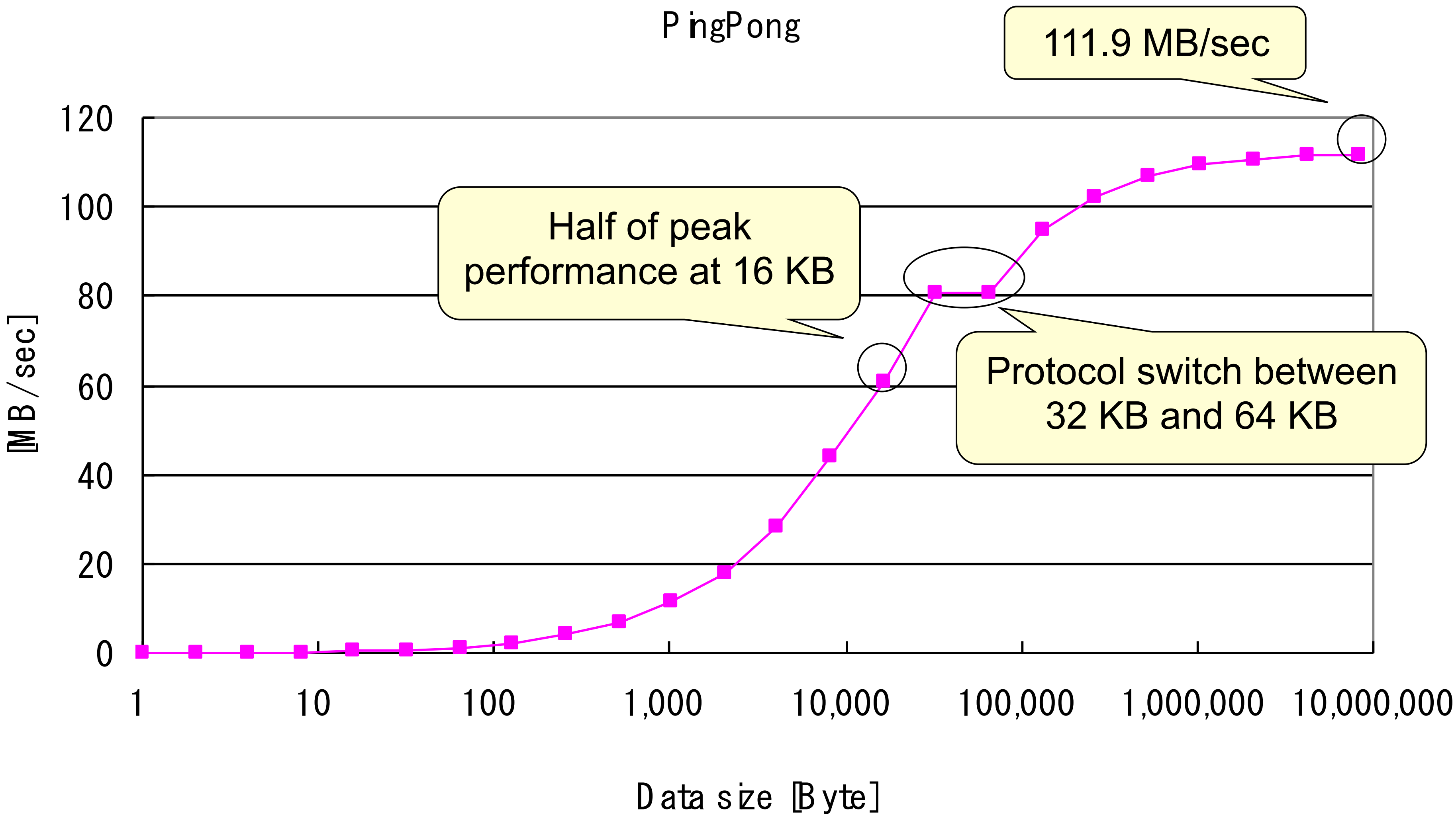


Network bandwidth $s/t/2$ [MByte/sec]

PingPong Benchmark (2)

```
for (s = 1; s <=P MAX_MSGSIZE; s <<= 1) {
    t = MPI_Wtime();
    for (i = 0; i < ITER; ++i)
        if (rank == 0) {
            MPI_Send(BUF, s, MPI_BYTE, 1, TAG1, COMM);
            MPI_Recv(BUF, s, MPI_BYTE, 1, TAG2, COMM, &status);
        } else if (rank == 1) {
            MPI_Recv(BUF, s, MPI_BYTE, 0, TAG1, COMM, &status);
            MPI_Send(BUF, s, MPI_BYTE, 0, TAG2, COMM);
        }
    t = (MPI_Wtime() – t) / 2 / ITER;
    if (rank == 0)
        printf("%d %g %g\n", s, t, s / t); // size, time, bandwidth
}
```

[P1] PingPong Benchmark



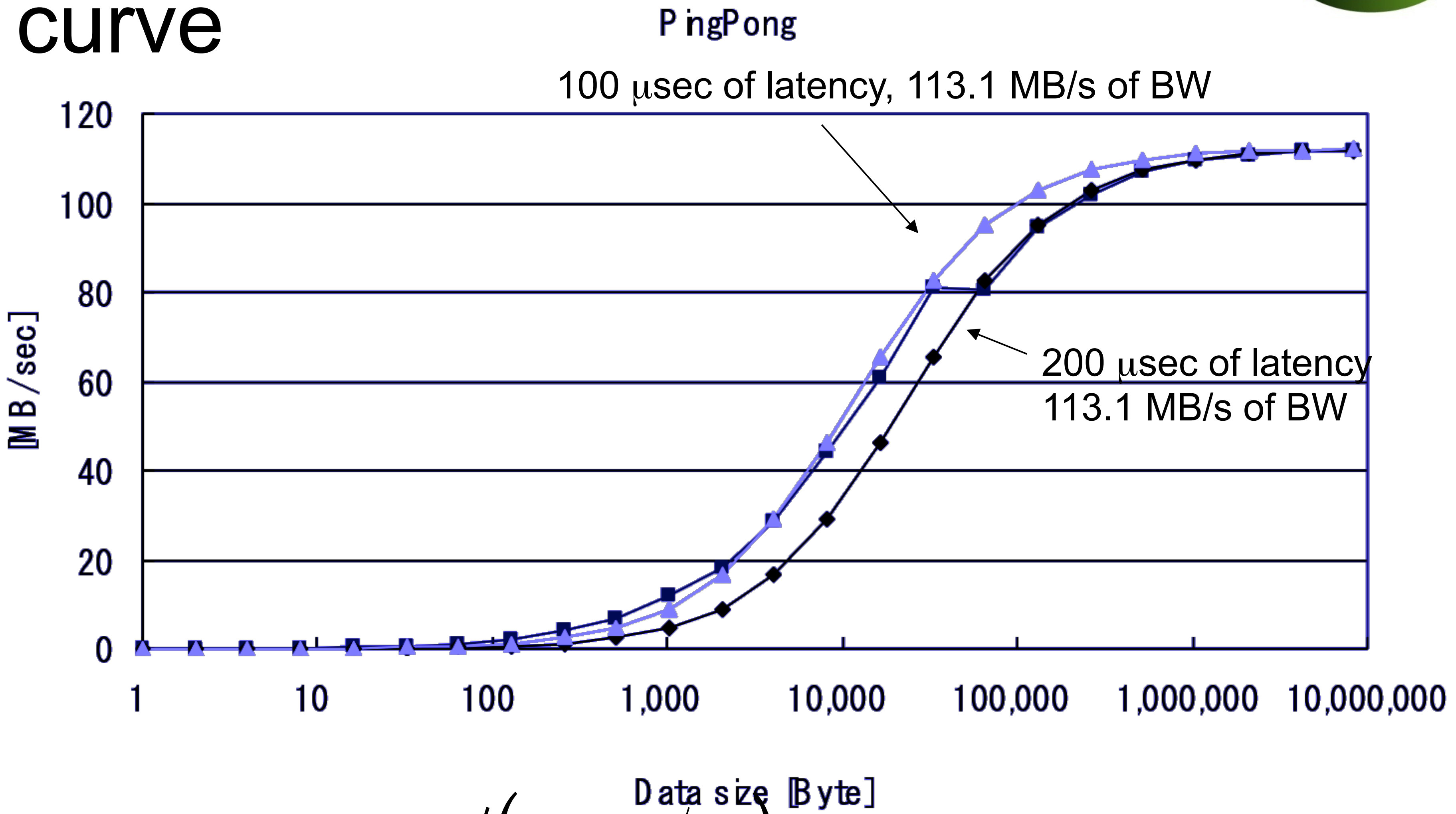
Protocol of point-to-point communication

- Eager protocol (1-way protocol)
  - for relatively small size of messages
  - A sender sends both the message header and the message body (data, payload) at the same time
  - It can reduce the communication latency, but incurs copy overhead at the receiver
- Rendezvous protocol (3-way protocol)
  - for larger size of message
  - A sender sends the message header, and waits for the acknowledgement
  - The sender sends the message body
  - It can achieve good communication bandwidth by reducing the copy overhead, but has longer latency than the eager protocol

Protocol of point-to-point communication (continued)

- MPI selects one of several protocols according to the message size
- It is visible if we carefully measure the performance with various message size
- Most MPI allows for users to specify the threshold of the message size for the protocol switch to optimize the communication performance

[P1] Comparison with theoretical curve



Theoretical curve $s/(L+s/B)$

$$N_{half} = BL$$

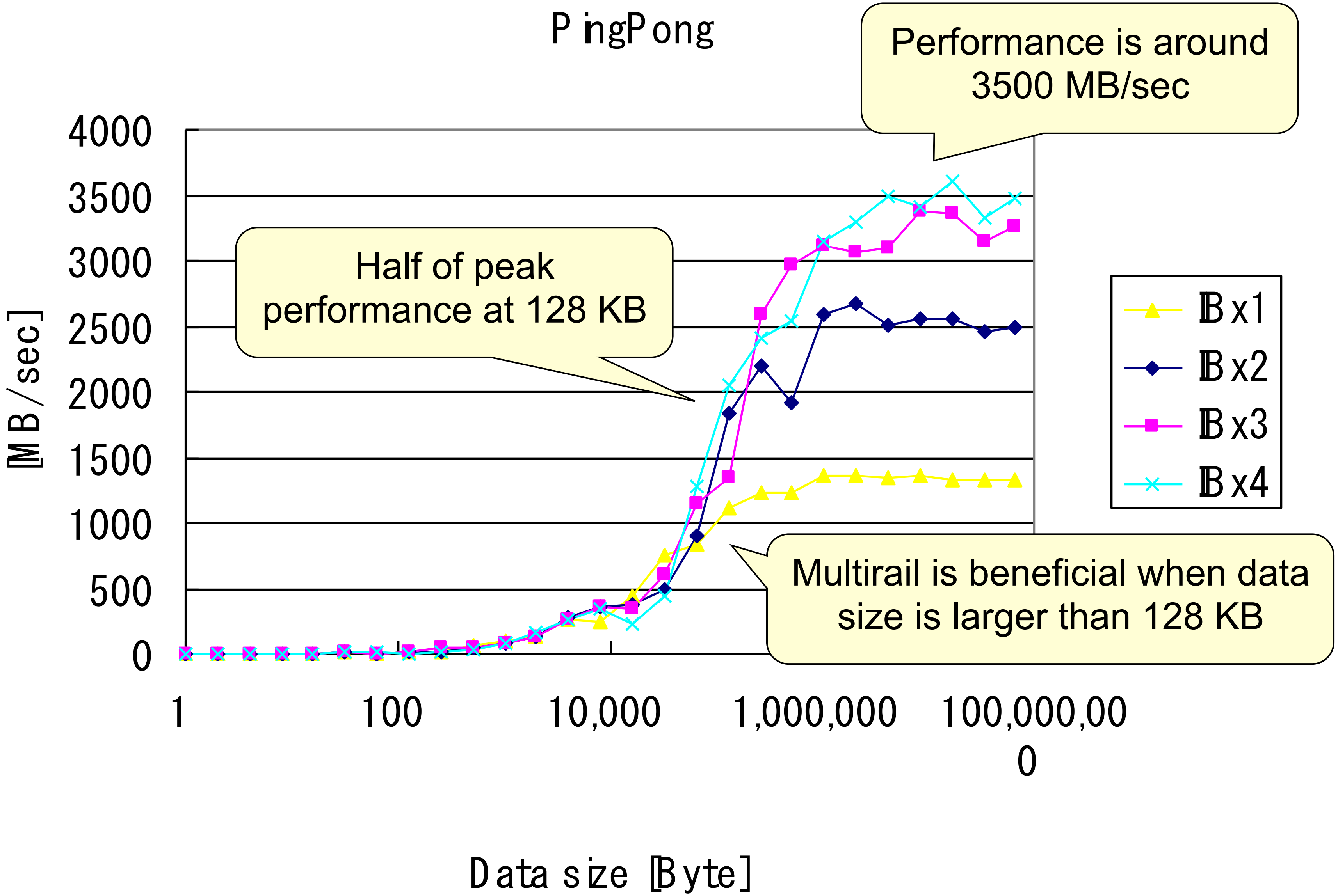
L latency B bandwidth

[P1] PingPong Benchmark Summary

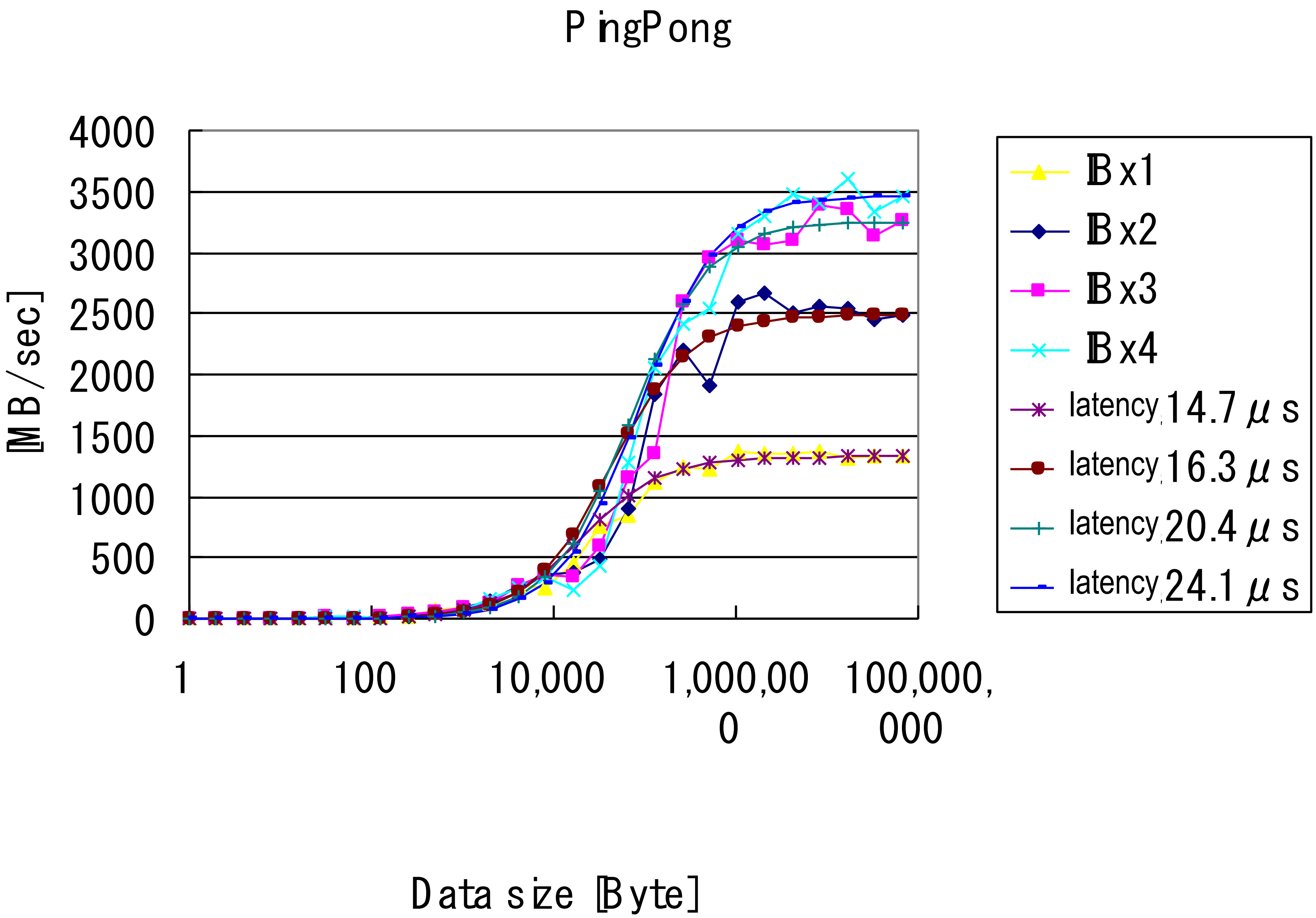
- Larger data size gets better performance
- Cf. theoretical peak is 113.1 MB/sec
- More than half → 16 KB or larger
- More than 90% of peak → 512 KB or larger

- Performance follows the curve of 100μsec latency in short message, and follows the curve of 200μsec latency in long message
  - Although latency of 1-byte PingPong is 563 μsec

[P2] PingPong Benchmark



[P2] Comparison with theoretical curve



[P2] PingPong Benchmark Summary

- Larger data size gets better performance

#IB	1	2	3	4
BW[MB/s]	1366	2674	3256	3468
Latency[μsec]	14.7	16.3	20.4	24.1
N_{half}[KB]	20	42	68	86

- Performance follows the curve of around 20μs latency in both short and long messages

Intel® MPI Benchmark

- Basic MPI Benchmark Kernel
- MPI1
  - PingPong
  - PingPing

  Single Transfer

  - Sendrecv
  - Exchange*

  Parallel Transfer

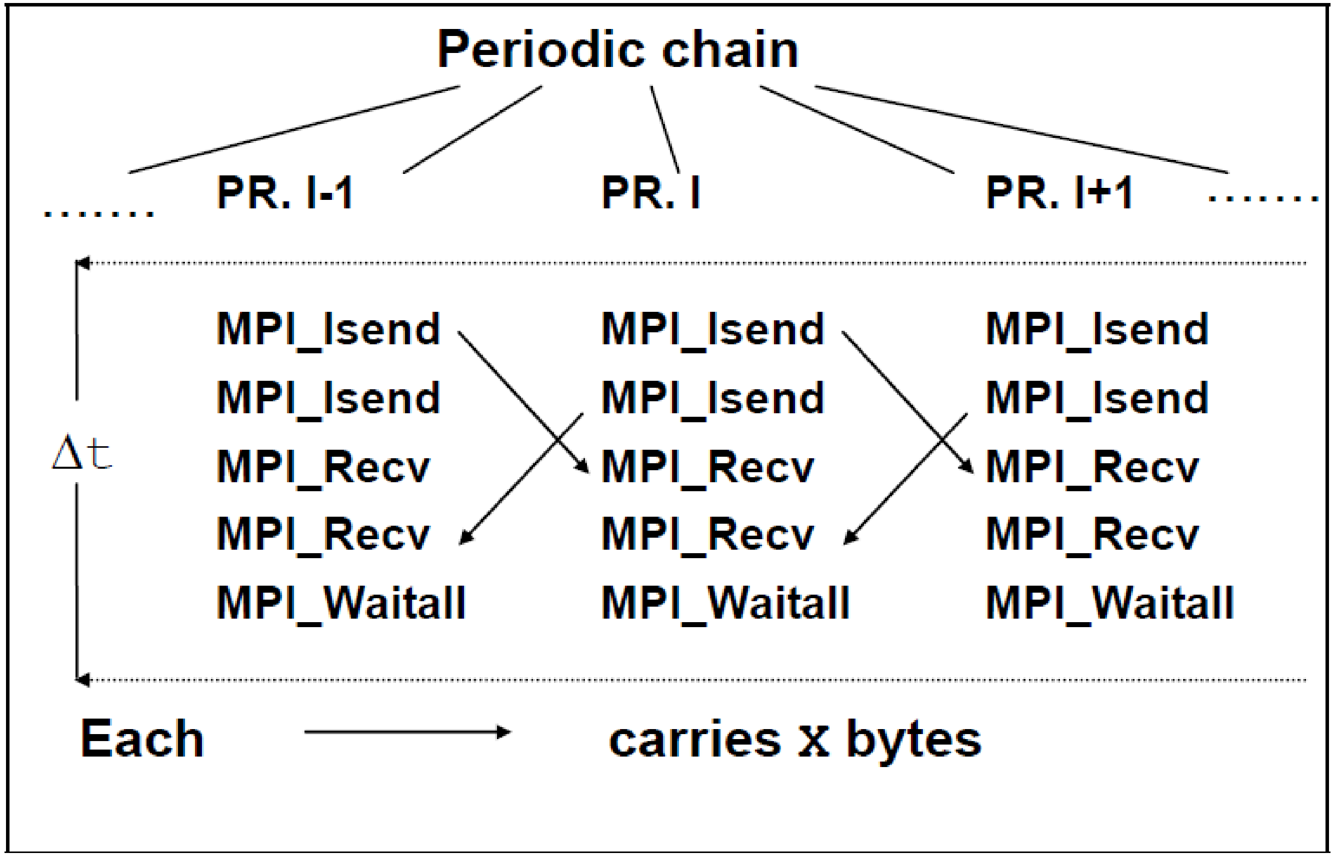
  - Bcast
  - Allgather
  - Allgatherv
  - Alltoall*
  - Alltoallv*
  - Reduce
  - Reduce_scatter
  - Allreduce*
  - Barrier

  Collective

  - Multiple version that executes above in parallel
- EXT
  - Window
  - Unidir_Put
  - Unidir_Get
  - Bidir_Get
  - Bidir_Put
  - Accumulate
- IO
  - S_{Write,Read}_{indv,expl}
  - P_{Write,Read}_{indv,expl,shared,priv}
  - C_{Write,Read}_{indv,expl,shared}

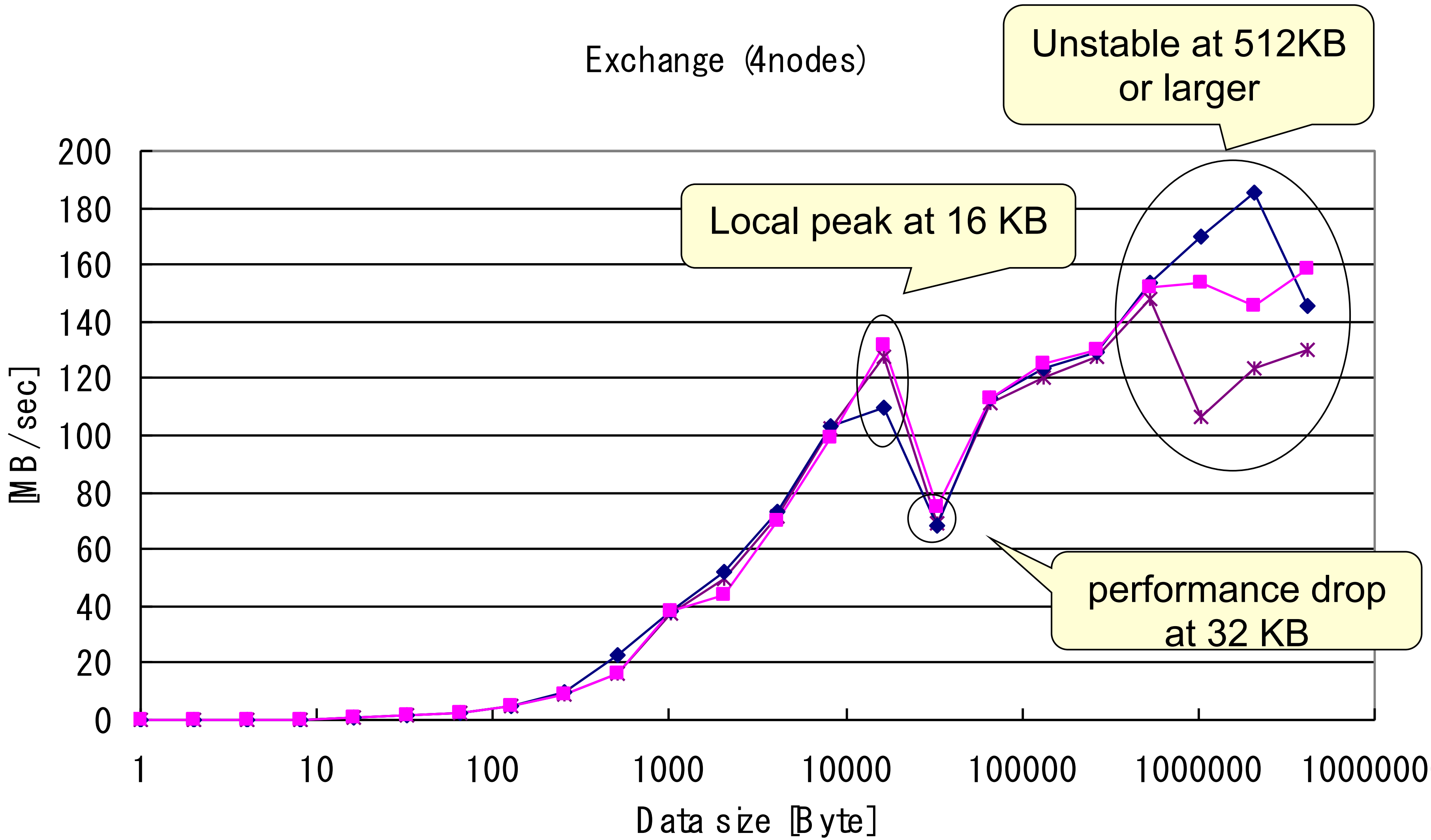
Exchange Pattern

- Communication pattern to exchange border elements



*From Intel MPI Benchmarks Users Guide and Methodology Description

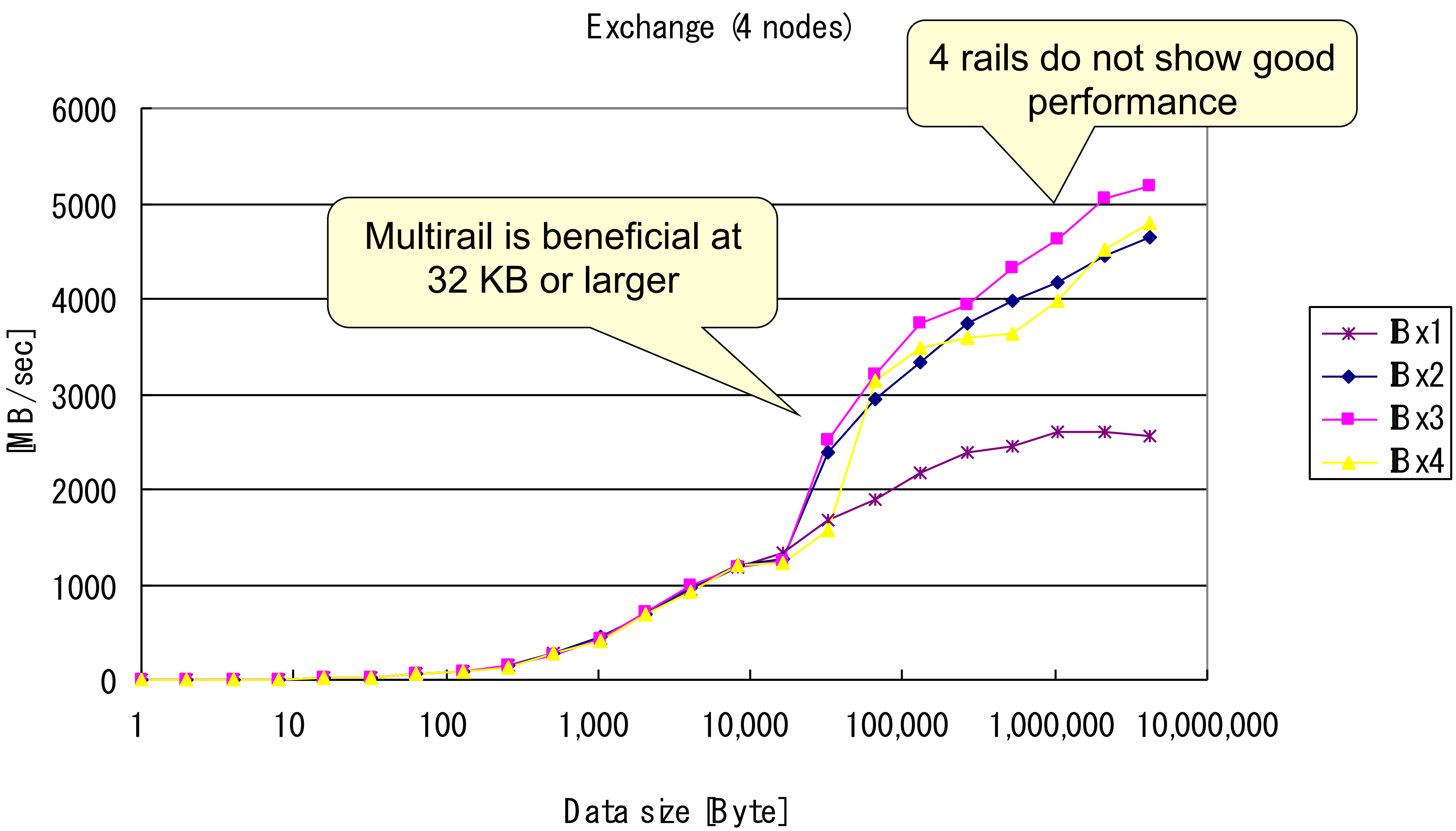
[P1] Exchange (4 nodes) [3 trials]



[P1] Exchange (4 nodes) Summary

- Basically larger data size gets better performance except around 32 KB
- Cf. Theoretical peak is 2*113.1 = 226.2 MB/sec
- More than half → 16KB and 128 KB or larger
  - Less than half at 32 KB and 64 KB
- Unstable at 512 KB or larger

[P2] Exchange (4 nodes)



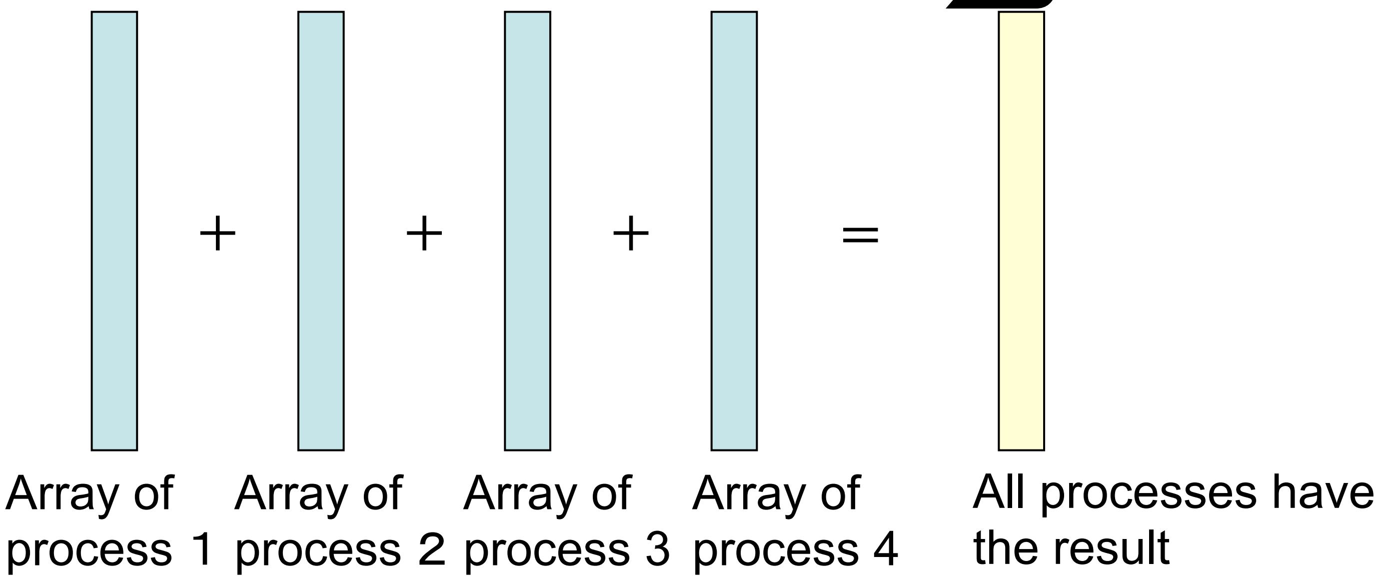
[P2] Exchange Summary

- Larger data size gets better performance
- Multirail is beneficial at 32 KB or larger
- 4 rails do not show good performance
- Performance is stable
  - Infiniband does not drop packets

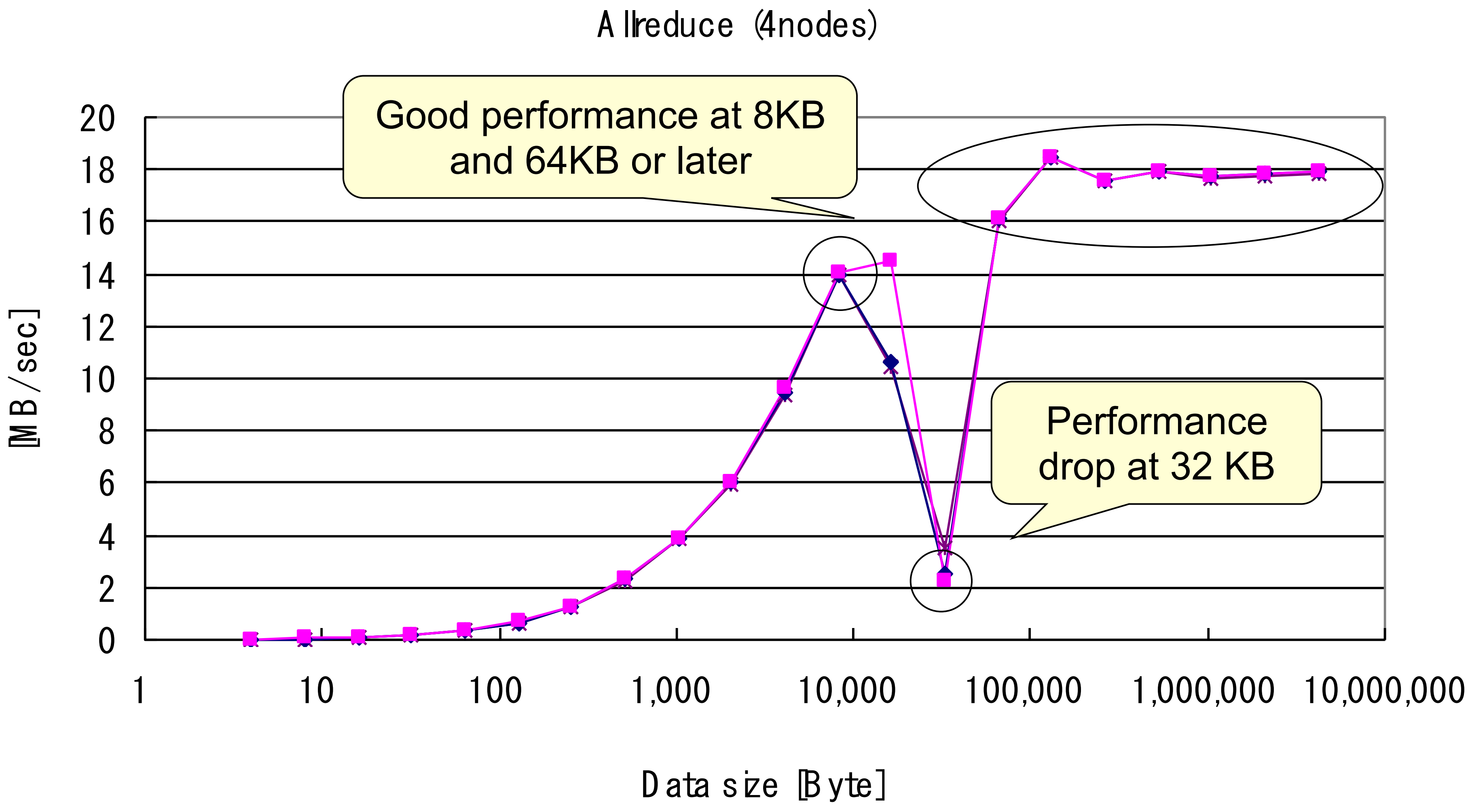
Allreduce

- Do specified operation (sum, max, logical and/or, …) among arrays of each process, and store the result in all processes
- Example of MPI_SUM

$$x_1 + x_2 + x_3 + x_4 = \sum_{i=1}^{4} x_i$$



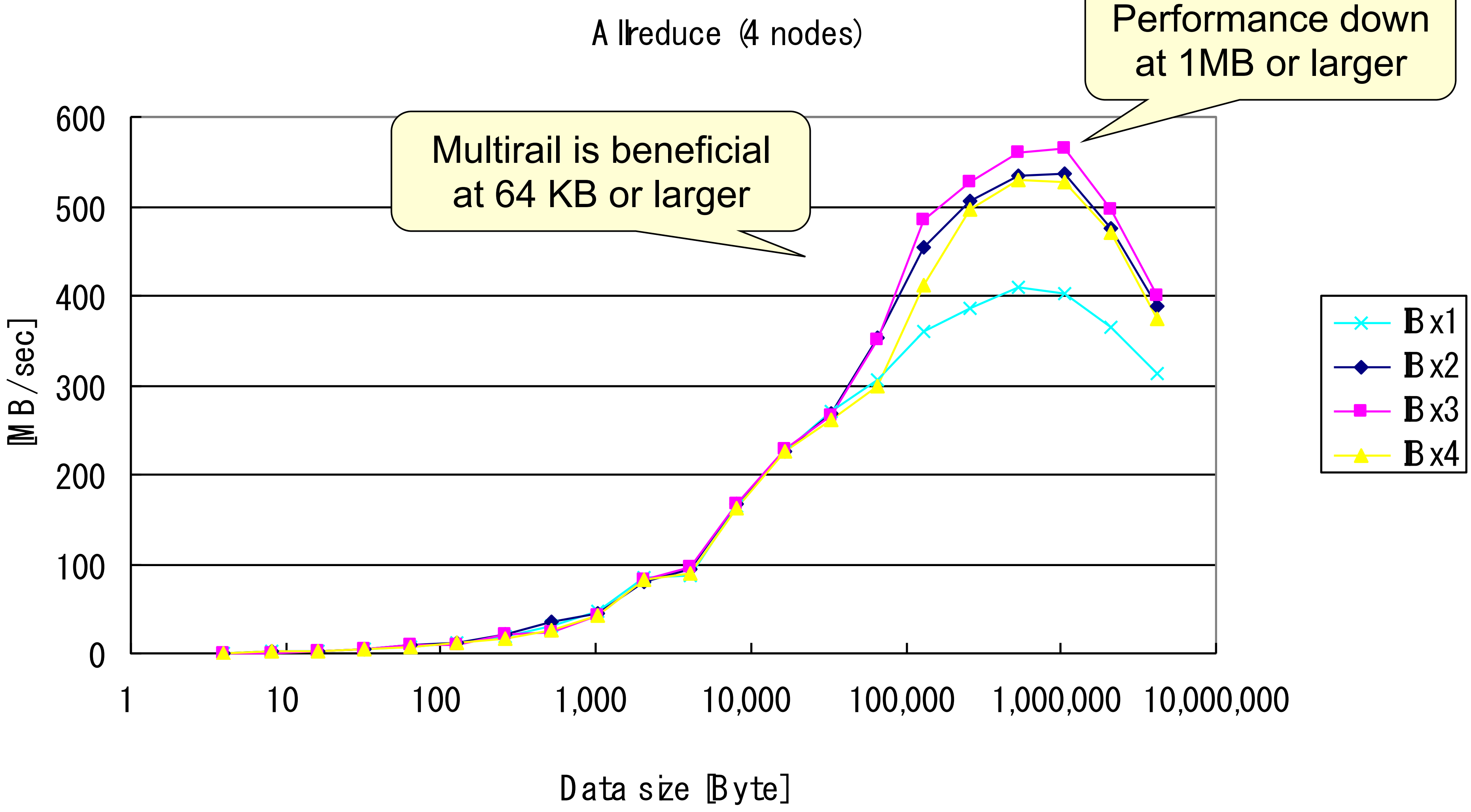
[P1] Allreduce (4 nodes)
[data size / time]



[P1] Allreduce Summary

- Basically larger data size gets better performance except around 32 KB
- Good performance is achieved at 8 KB and 64 KB or larger

[P2] Allreduce (4 nodes)
[data size / time]

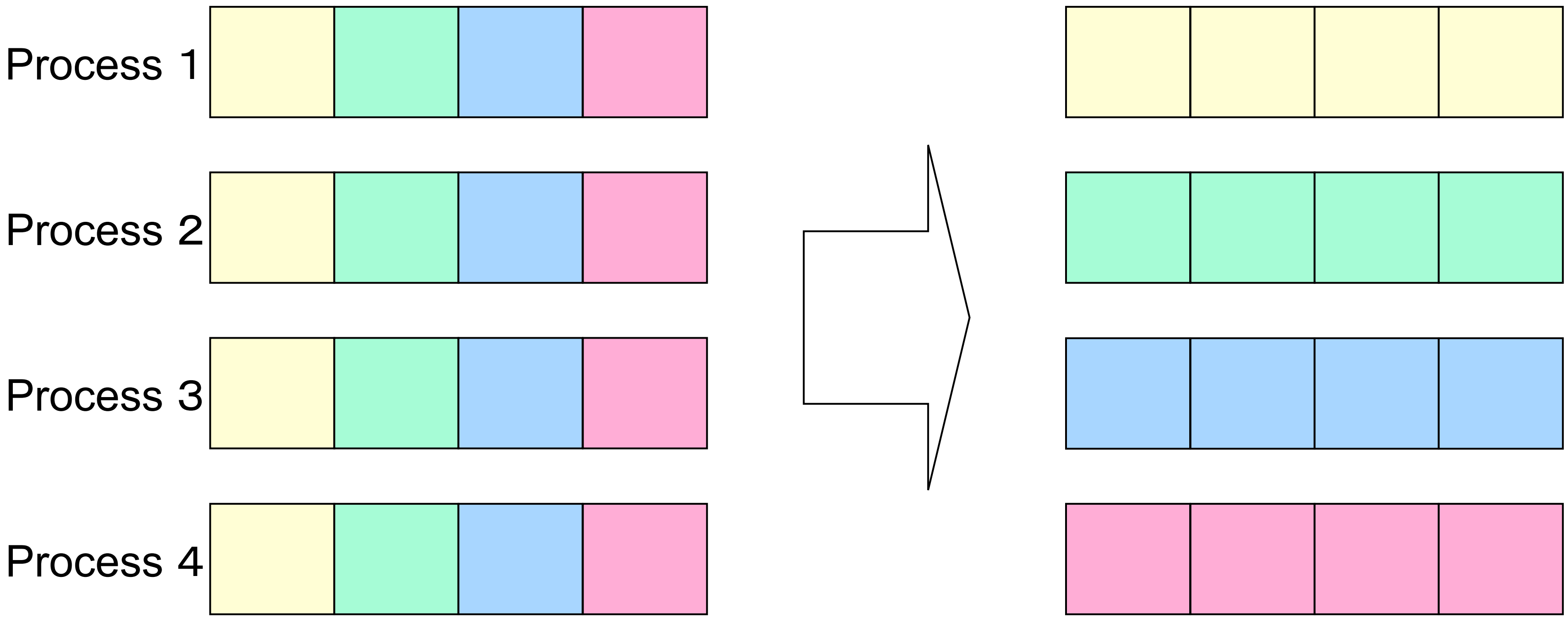


[P2] Allreduce Summary

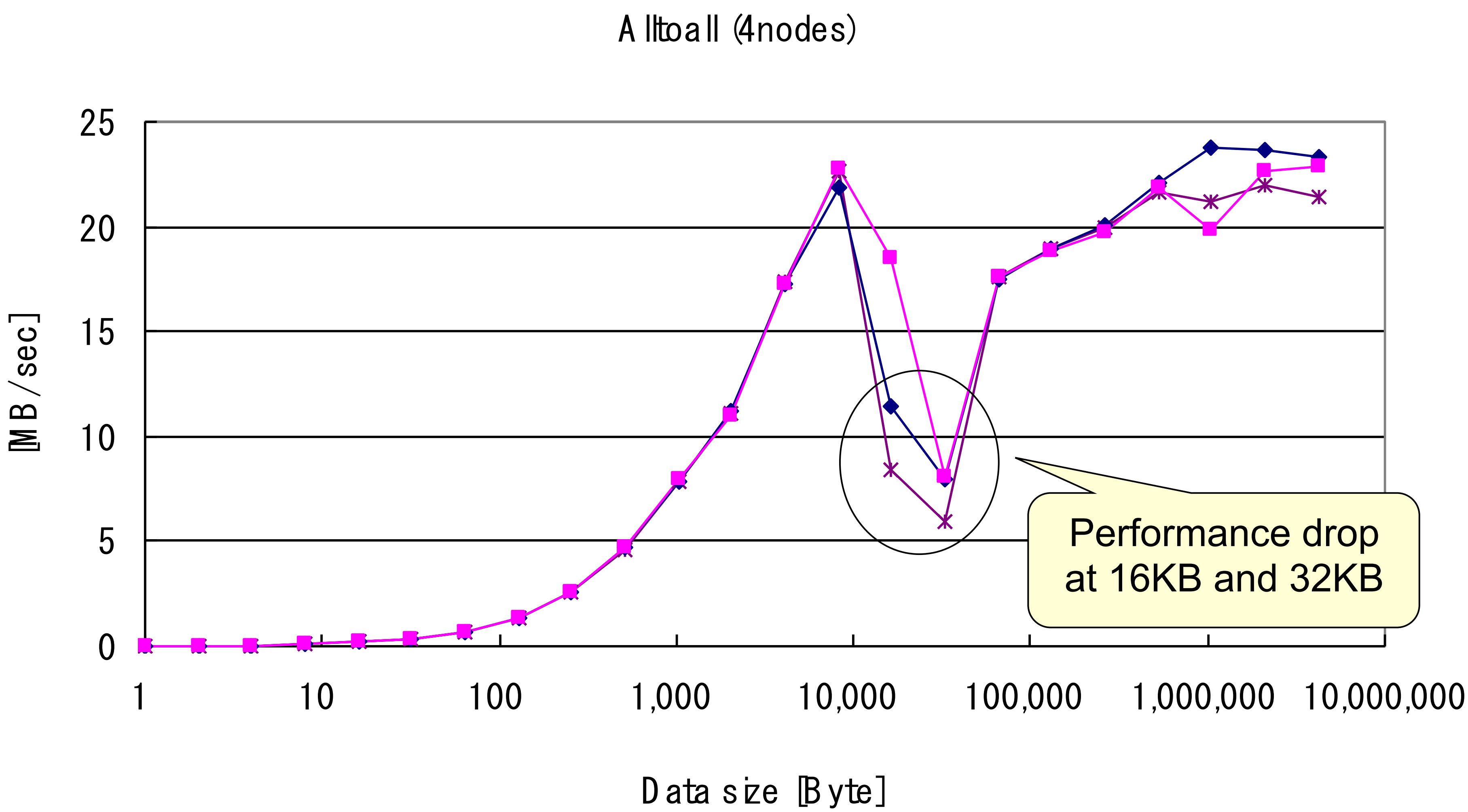
- Larger data size gets better performance until 1 MB
  - Performance deteriorates when data size is larger than 1 MB
- Multirail is beneficial at 64 KB or larger
- 4 rails do not show good performance

Alltoall

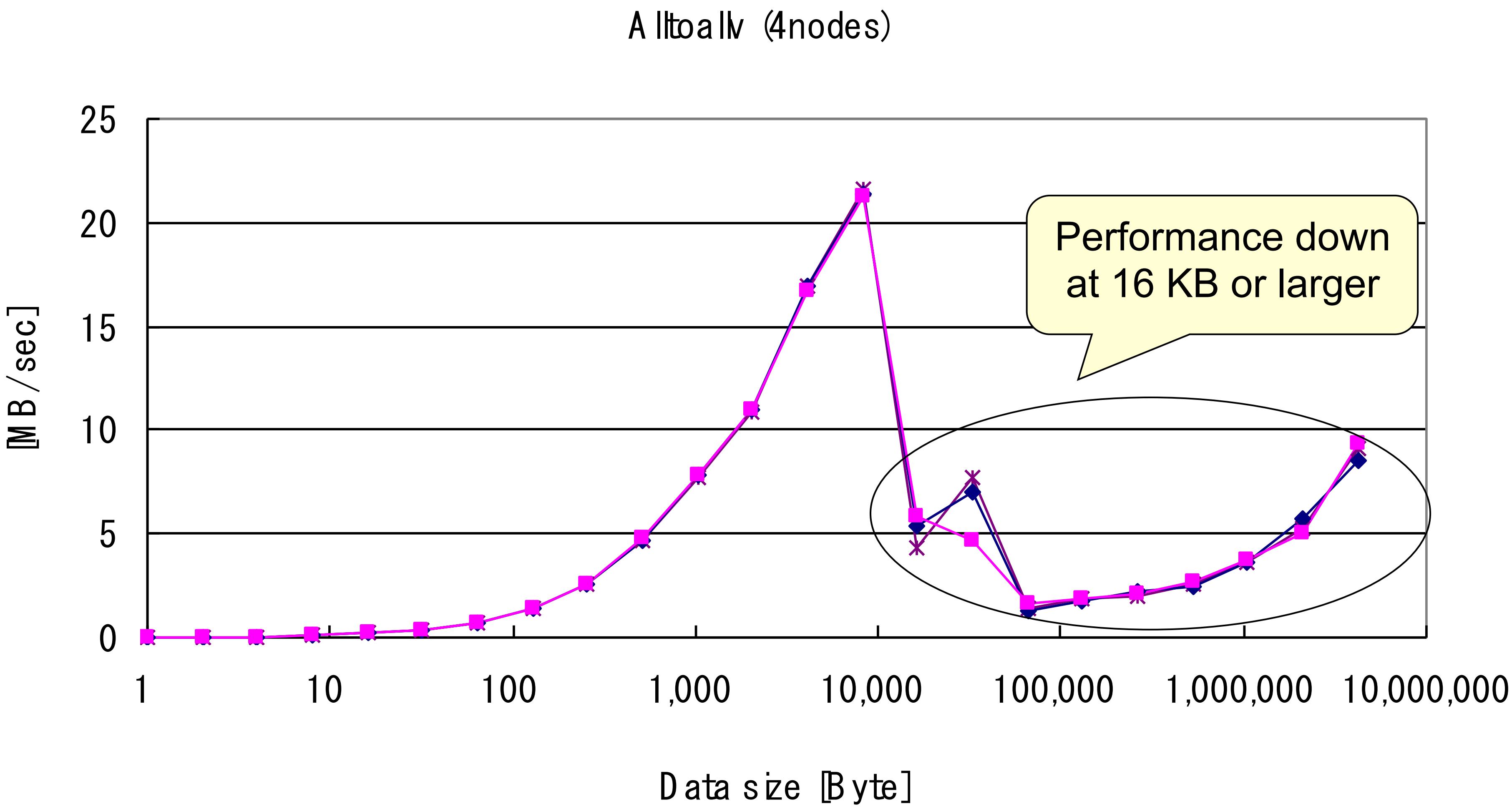
- Collective communication in matrix transpose pattern



[P1] Alltoall [data size / time]



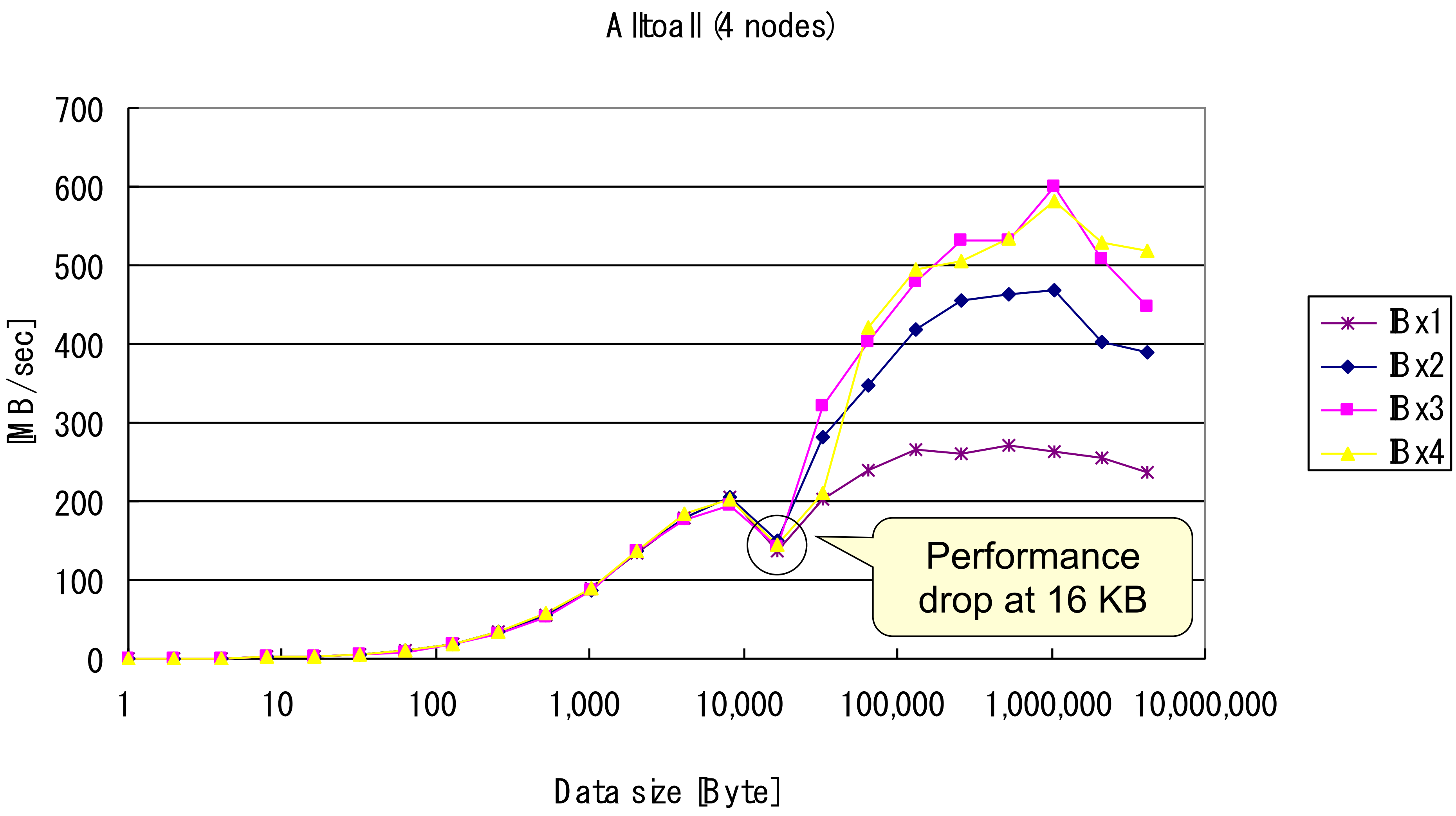
[P1] Alltoallv [data size / time]



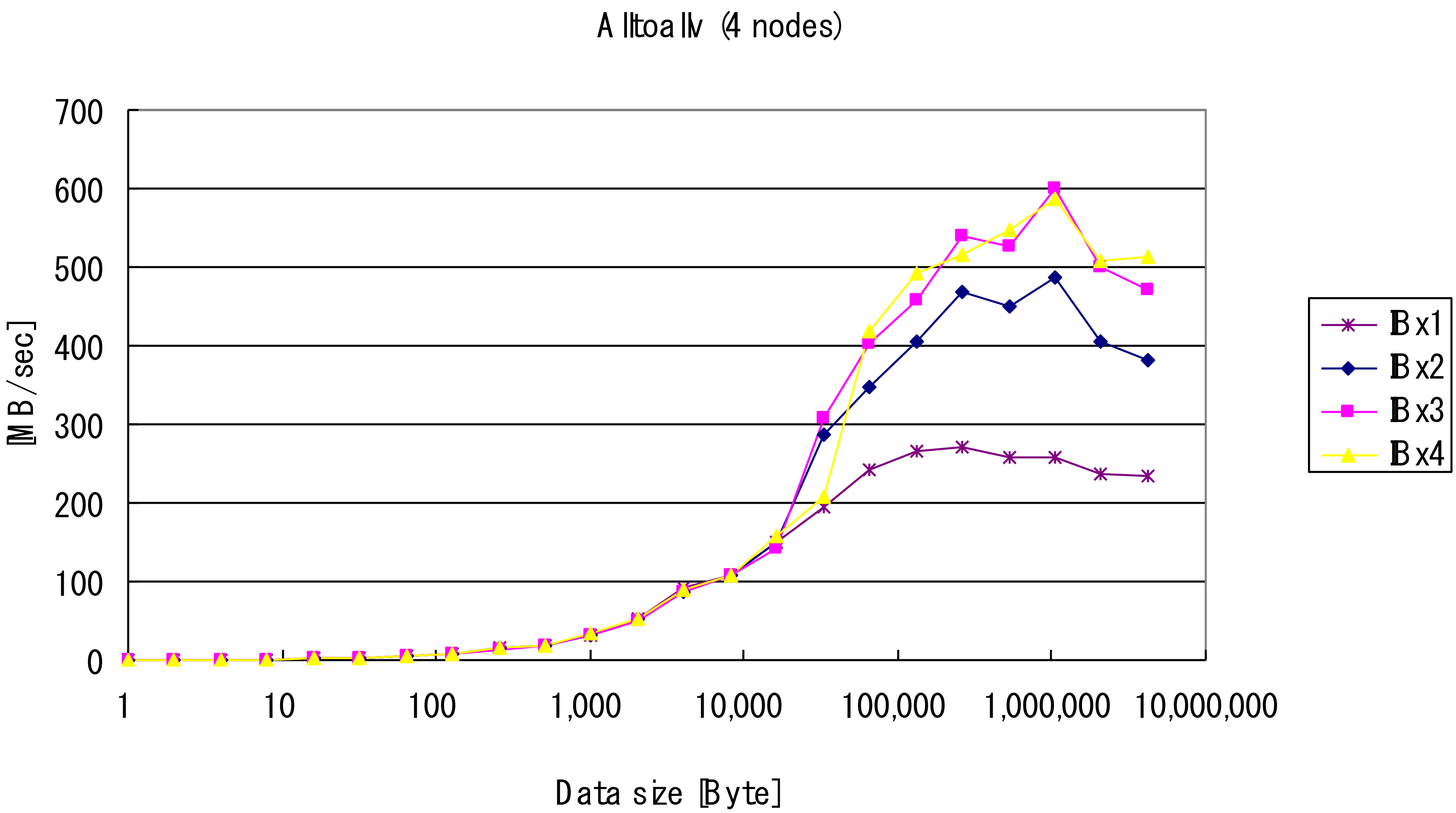
[P1] Alltoall(v) Summary

- Alltoall basically performs better as data size is larger except between 16 KB an 32 KB
  - Performs good at 8 KB and 64 KB or larger
  - Same behavior as allreduce
- Alltoallv shows quite bad performance at 16 KB or larger
  - Excessive memory copy?
  - Not enough optimized?

[P2] Alltoall [data size / time]



[P2] Alltoallv [data size / time]



[P2] Alltoall(v) Summary

- Both Alltoall and Alltoallv perform better as data size is larger
  - Alltoall performance drops at 16KB
- Multirail is beneficial at 32KB or larger

Multirail solution

- Multi-rail (or “binding”) solution theoretically improves the performance in bandwidth, but the latency is not improved
- For large size of messages, it works in most of cases
- When the number of bound links increases, the efficiency typically goes down
- Several use cases of multirail. If you have four links bound:
  - Use them as a single channel logically
  - Use them as two sets of 2-rail binding
  - Use them as four sets of single channel
- Most MPI libraries that support multirail provide the feature to control “how many links are bound” by user
- There is no generic best usage, and it depends on the behavior of application

Profiling

- Understand the behavior of programs
  - Frequently called functions
  - Time-consumed functions
  - Call tree
  - Memory usage of functions, …
- Understand the most time-consumed code
- Understand synchronization and load imbalance in parallel programs

Profiler is required not to change the behavior of parallel program so much

Communication profiling by users

- Users insert an instrumenting code at the point of interest by themself
- Put “wall clock measuring” (ex. MPI_Wtime, gettimeofday()) before and after to measure time of a certain block
  - for each MPI function
  - for some important blocks
- The accuracy of measuring “ticks” depends on the system

```
double t1, t;

t1 = MPI_Wtime();
MPI_Allgather(....);
t = MPI_Wtime() – t1;
```

- It is easy, but there are more sophisticated tools

tlog – time log

- Light-weight profiling library by Prof. Sato at University of Tsukuba
  - 16 B of memory space for each event
- 9 kinds of single events and 9 kinds of interval events
  - It can be extended since event number field is 8 bit
- Record the elapsed time in seconds from tlog_initialize
  - Time difference among processes is measured in tlog_initialize
  - Recorded time is "absolute" time in parallel processes relative to tlog_initialize
- Temporal URL for download
  - http://www.ccs.tsukuba.ac.jp/workshop/HPCseminar/2011/software/tlog-0.9.tar.gz

tlog – major API

void tlog_initialize(void)
    initializes the tlog environment. It should be called after MPI_Init

void tlog_log(int event)
    records a log of the specified event

void tlog_finalize(void)
    outputs the logs to trace.log. It should be called before MPI_Finalize()

```
tlog_initialize();
…
tlog_log(TLOG_EVENT_1_IN);
/* EVENT 1 */
tlog_log(TLOG_EVENT_1_OUT);
…
tlog_finalize();
```

Example - cpi.c

- Test program that computes π

```
MPI_Init(&argc, &argv);
tlog_initialize();
tlog_log(TLOG_EVENT_1_IN);
MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
tlog_log(TLOG_EVENT_1_OUT);
/* compute mypi (partial sum) */
tlog_log(TLOG_EVENT_2_IN);
MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);
tlog_log(TLOG_EVENT_2_OUT);
if (rank == 0) /* display the result */
tlog_log(TLOG_EVENT_1_IN);
MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
tlog_log(TLOG_EVENT_1_OUT);
tlog_finalize();
MPI_Finalize();
```

Example – compilation of cpi

- How to link tlog library

```
% mpicc -O -o cpi cpi.c -ltlog
```

- How to install tlog library and tlogview

```
% ./configure
% make
% sudo make install
```

Example to install in /usr/local

Example – output of cpi

```
$ mpiexec -hostfile hosts -n 4 cpi
adjust i=1,t1=0.011781,t2=0.011886,t0=0.011769,diff=6.7e-05
adjust i=2,t1=0.012911,t2=0.013015,t0=0.012877,diff=8.8e-05
adjust i=3,t1=0.014441,t2=0.014548,t0=0.014392,diff=0.000115
adjust i=1,t1=0.01623,t2=0.016335,t0=0.016285,diff=-2e-06
adjust i=2,t1=0.017314,t2=0.017418,t0=0.017367,diff=-2e-06
adjust i=3,t1=0.018401,t2=0.018504,t0=0.018454,diff=2.5e-06
tlog on ...
Process 0 on exp0.omni.hpcc.jp
pi is approximately 3.1416009869231249, Error is 0.0000083333333318
wall clock time = 0.000213
tlog finalizing ...
Process 3 on exp3.omni.hpcc.jp
Process 1 on exp1.omni.hpcc.jp
Process 2 on exp2.omni.hpcc.jp
tlog dump done ...
```

measurement of time difference among nodes (output in debug mode)

output in debug mode

Output of program

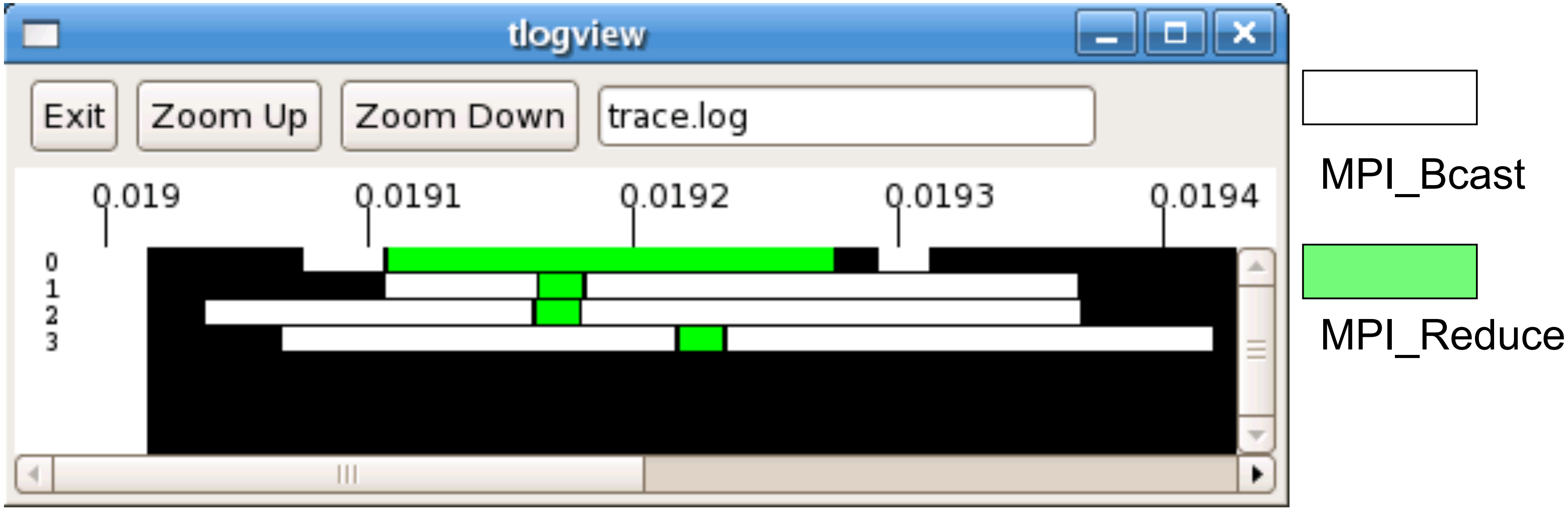
output in debug mode

Profiling result of cpi (1)

- tlogview – visualization tool for tlog output

```
% tlogview trace.log
```

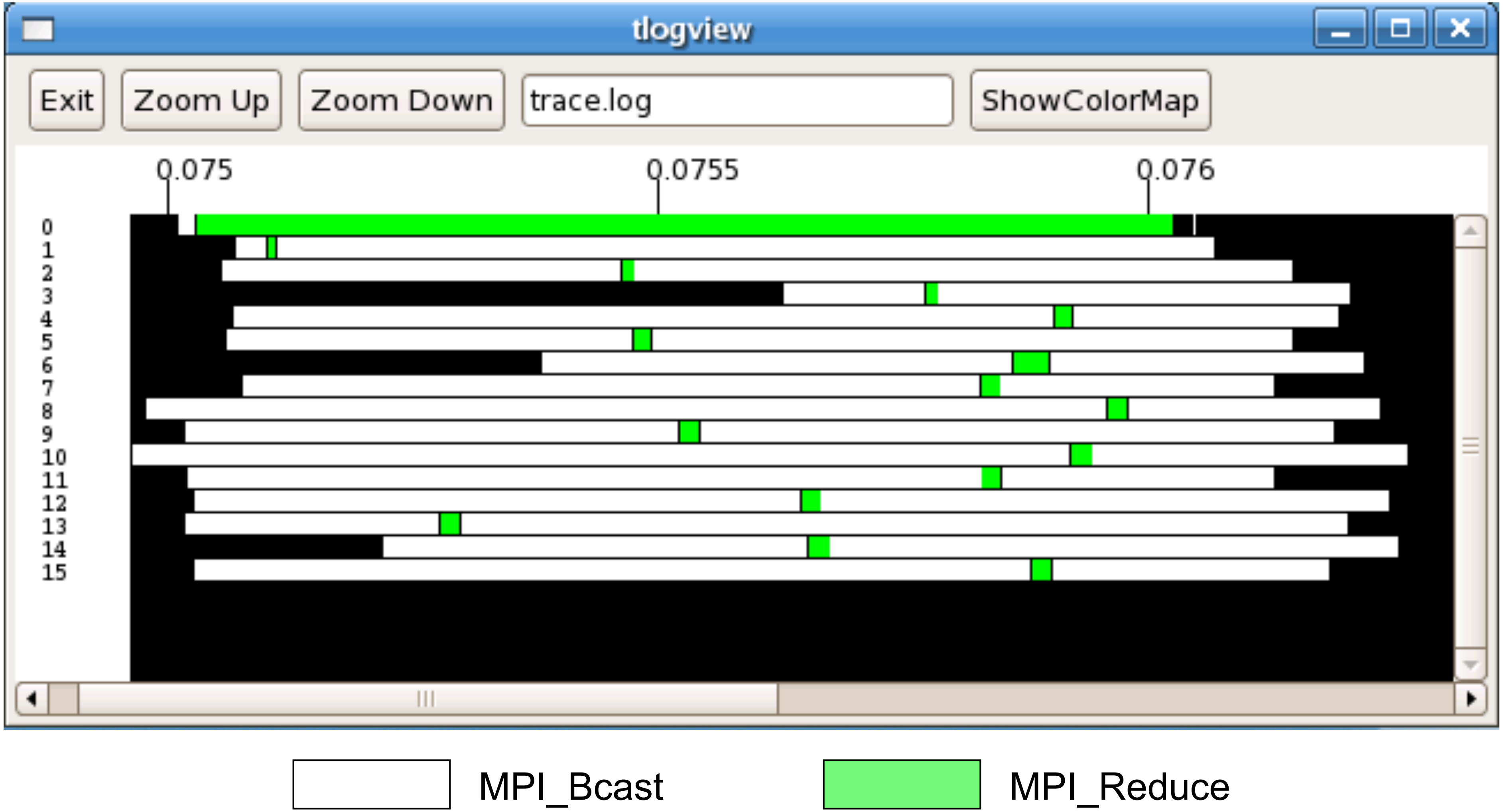
- Profiling example when using 4 processes



Elapsed time from tlog_initialize in seconds
(adjusted using the time difference among nodes)

Profiling result of cpi (2)

- Profile example when using 16 processes



Communication optimization

- Communication reduction*
- Load balancing*
- Communication blocking
  - Basically larger data size is better performance
- Communication latency hiding for short message communication
  - Overlapping computation and communication
  - Pipeline execution

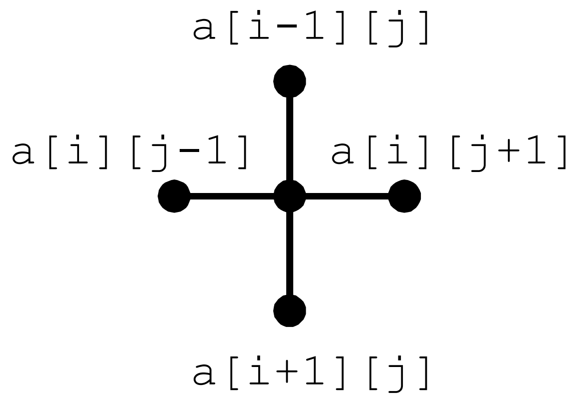
Communication blocking

- Data size is a major factor for communication performance
- Communication blocking enlarges the data size by aggregating the communication data
  - Block distribution of data
  - Aggregation of multiple iterations

Example of communication blocking – Jacobi method

- Solving a sparse matrix that arises when discretizing 2D Poisson equation in 5 point stencil

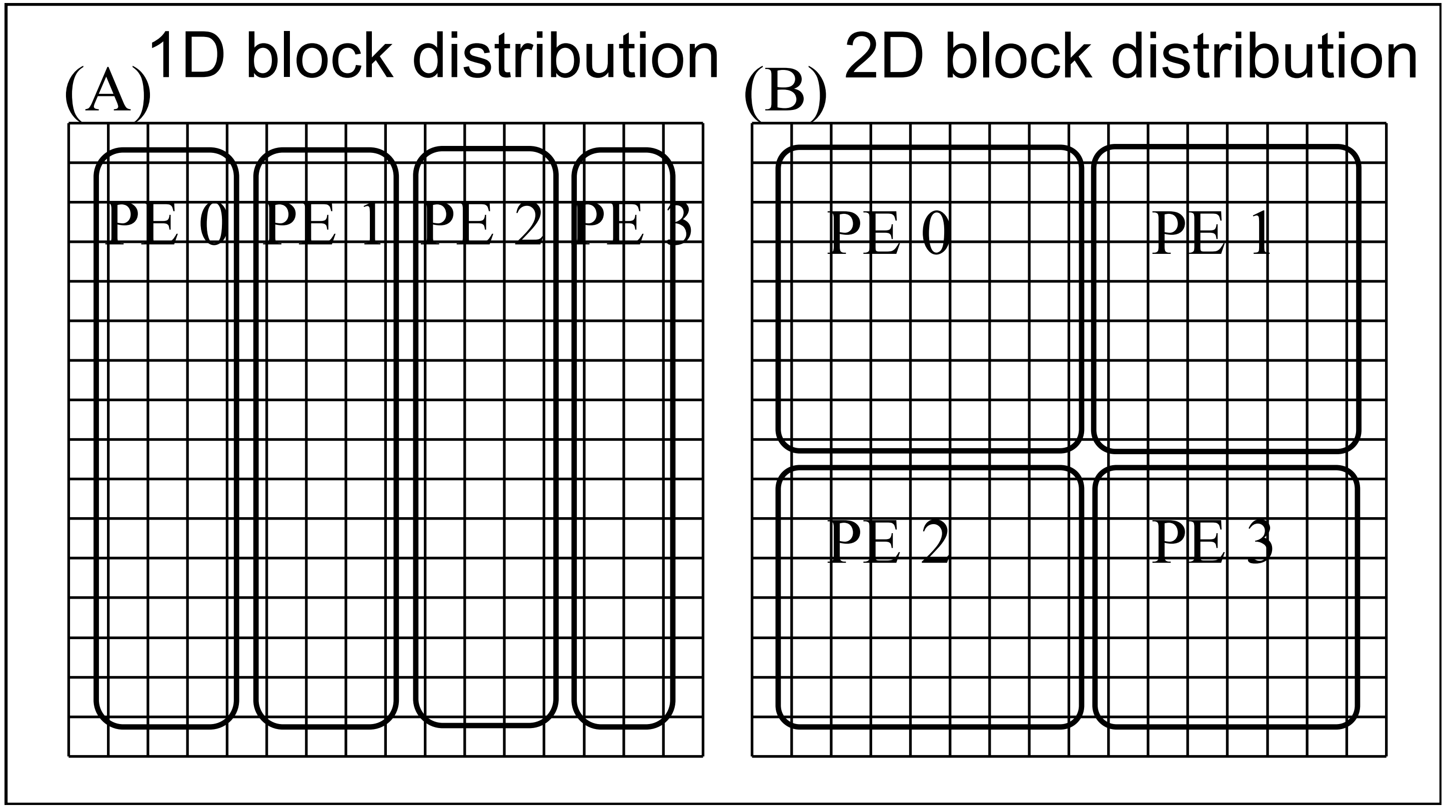
```
jacobi() {
  while (!converge) {
    for(i = 1; i < N - 1; ++i)
      for(j = 1; j < N - 1; ++j)
        b[i][j] = .25 *
              (a[i - 1][j] + a[i][j - 1]
               + a[i][j + 1] + a[i + 1][j]);
    /* convergence test */
    /* copy b to a */
  }
}
```



Data dependency

*In fact, not to use Jacobi method but RB-SOR etc.

Block distribution of data

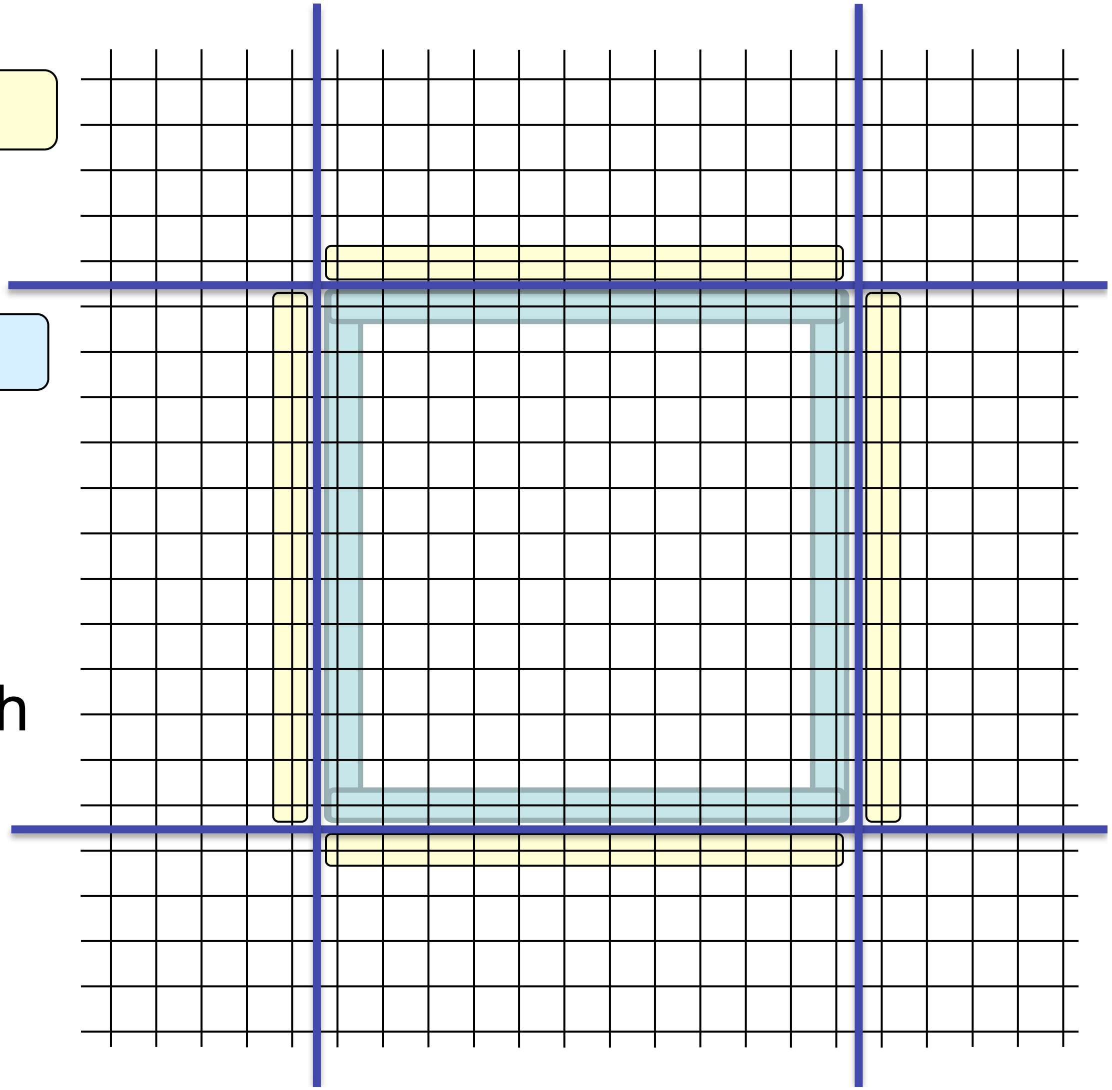


- Block distribution of data enlarges the communication data size
  - In case of 1D n
  - In case of 2D $n/\sqrt{p}$

Communication of shadow region (boundary region)

- To update the boundary [light blue box], data of [yellow box] is required
- To update the boundary [yellow box], data of [light blue box] is required

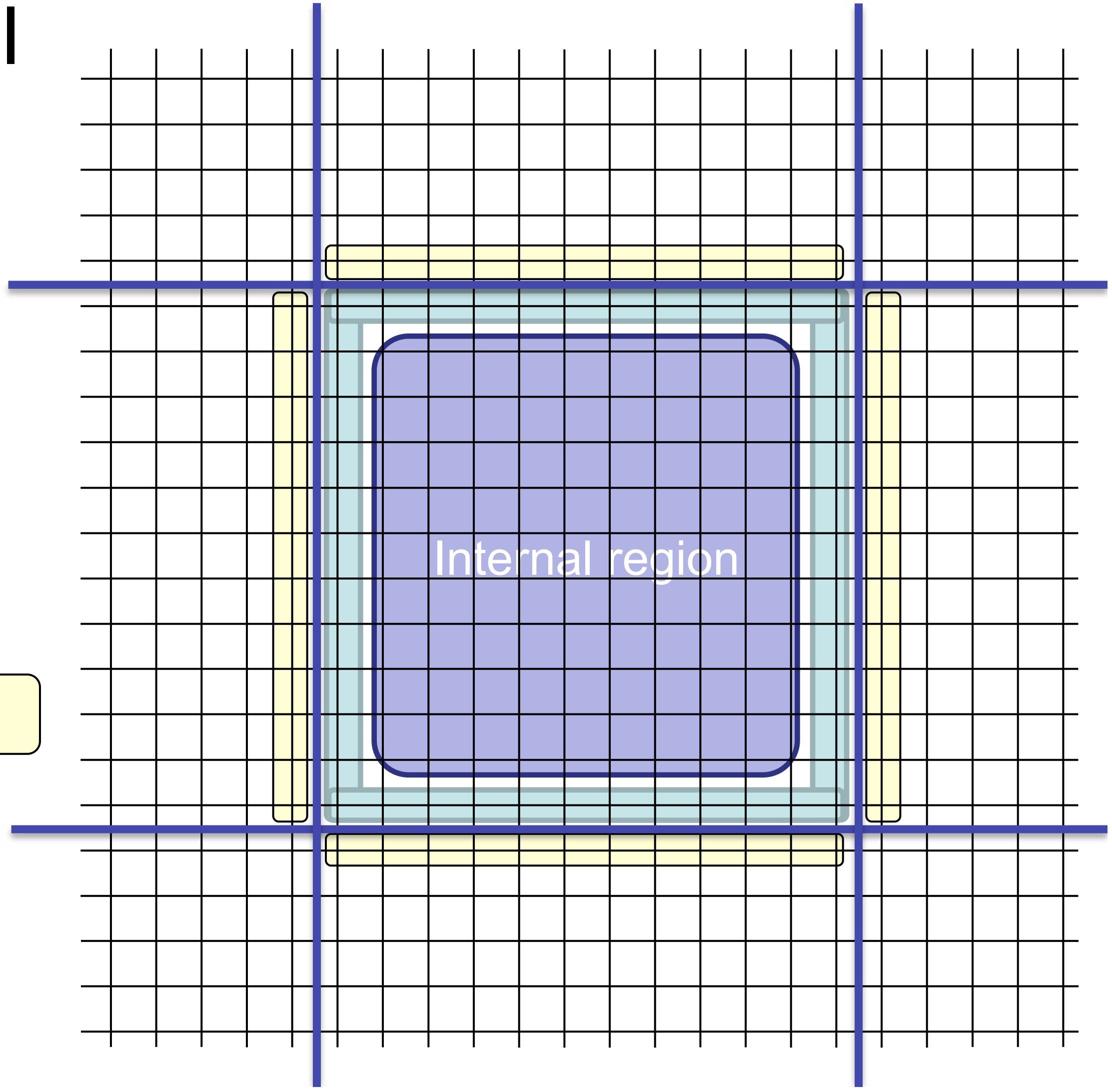
1. Exchange [yellow box] and [light blue box]
2. Update all data in each process



Overlapping computation and communication

- To update internal region, data of ▢ is not required

1. Send data of ▢
2. Update internal region
3. Receive data of ▢
4. Update boundary region ▢

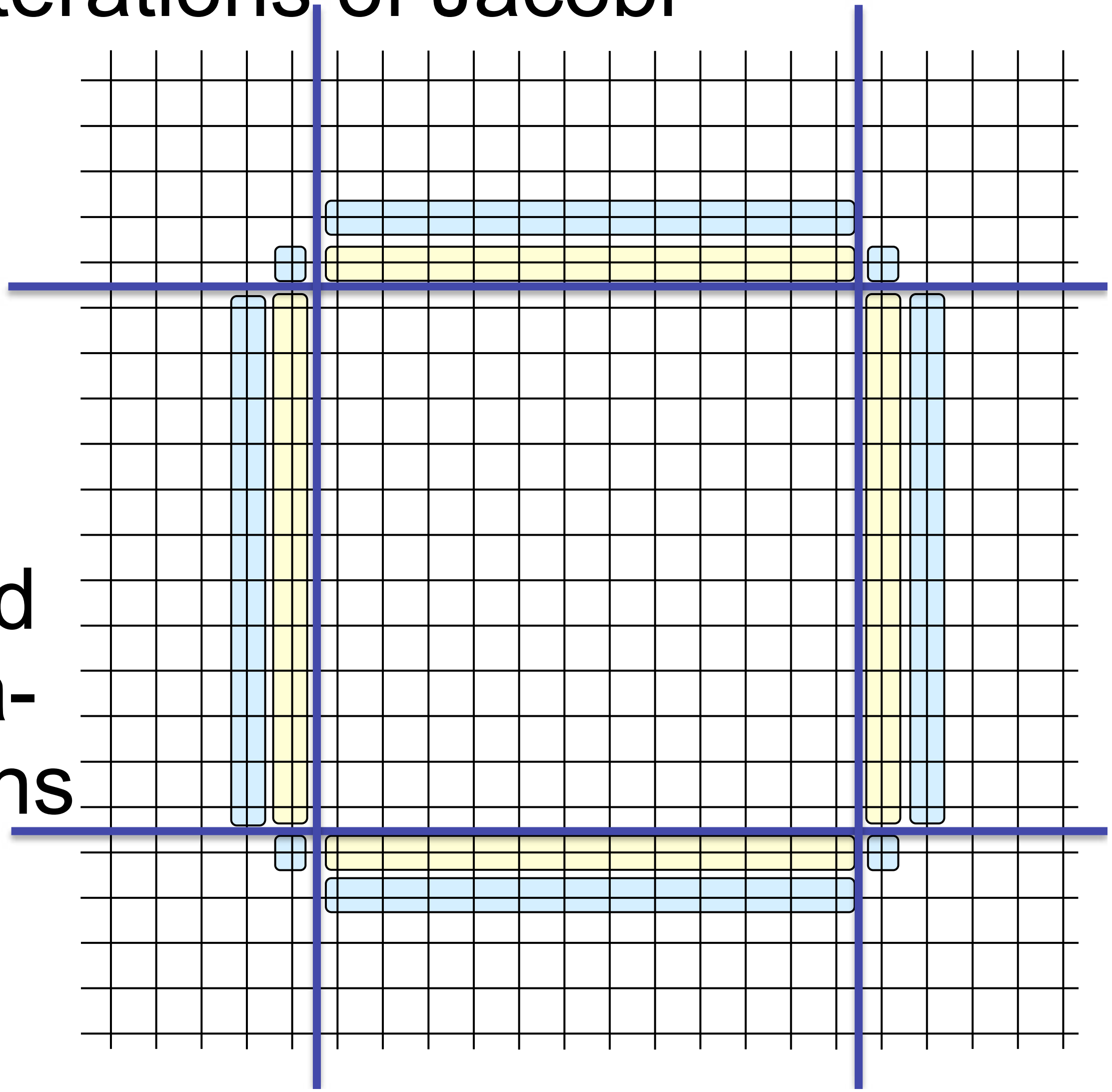


Overlapping computation and communication (2)

- MPI_Isend(, …, &req[0])
- MPI_Irecv(, …, &req[1])
- Calculation in internal region
- MPI_Waitall(2, req, status)
- Calculation on boundary region

Communication aggregation of multiple iterations

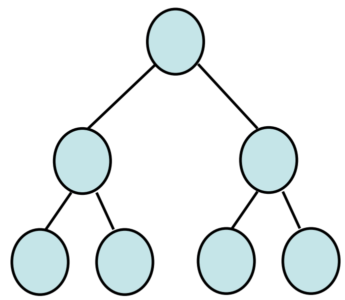
- Aggregation of 2 iterations of Jacobi method
- The first iteration requires
- Next iteration requires
- Transferring and enables calculation of two iterations
  - In 1D $2n$
  - In 2D $2n/\sqrt{p}$



Hand-made collective communication

- Usually, you should use collective communication on proprietary hardware system (such as MPP)
- On some cluster systems with open source MPI libraries, it may provide better performance by performing a set of point-to-point communication instead of collective communication library
- It depends on the application behavior, system hardware and library, so you need to examine it with practical data

Example: All-to-All (1) (repeating broadcast)



- All nodes transfer the same size of message to all other nodes with each other
- 1-to-all broadcast can be performed with the binary-tree algorithm, which requires

$$T = (a + s / b)\log_2 P$$

a: latency *b*: throughput *s*: message size *P*: # of processors

- If repeating 1-to-all broadcast *P* times, communication time is

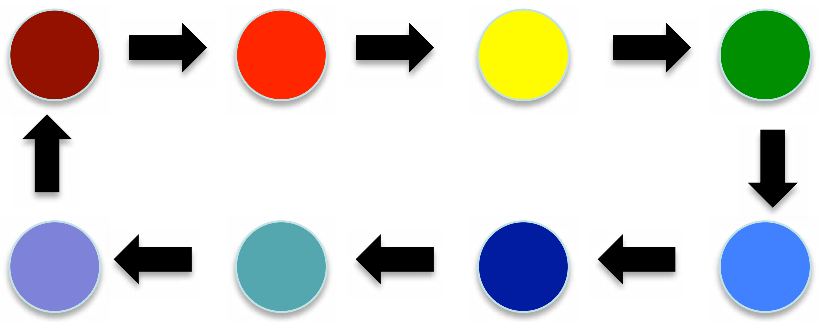
$$T = P((a + s / b)\log_2 P) = aP\log_2 P + (s / b)P\log_2 P$$

Example: All-to-All (2) (ring algorithm)

- Making a “ring” of nodes, and each node sends a message to the neighbor while receiving a message from the other neighbor
  ⇒ “bucket relay” manner, and time is

$$T = (P-1)(a + s/b) = (P-1)a + (P-1)(s/b) \approx Pa + P(s/b)$$

  ⇒ it reduces the time to ***$1/\log_2 P$*** apprximately
- Reason: all processors always send/receive something at any time



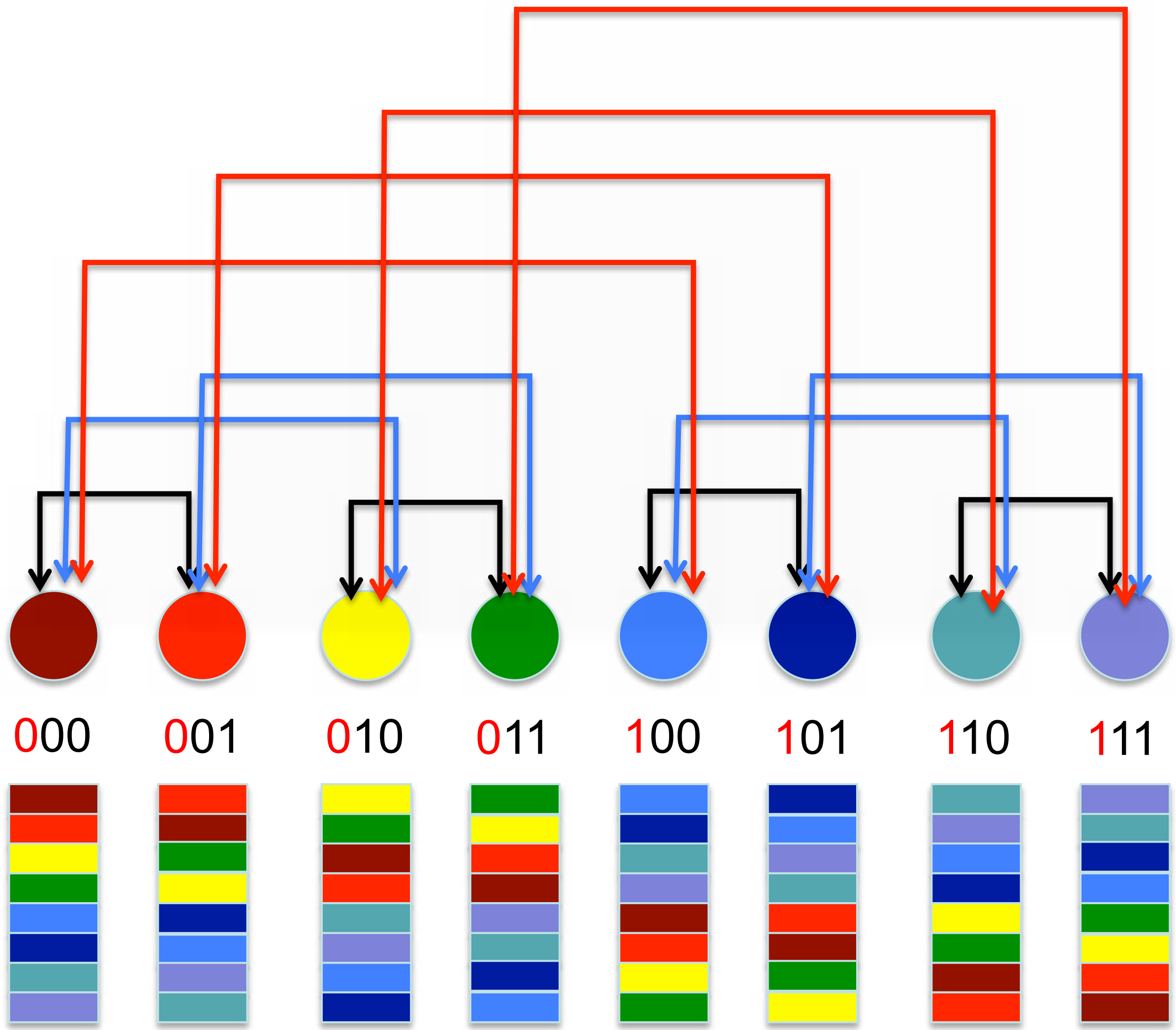
Example: All-to-All (3) (pairwise exchange in butterfly algorithm)

- More sophisticated algorithm for all-to-all
  - Let consider the node address in binary number
  - At first, all nodes exchange a message with nodes where the node address differs in the lowest significant bit (right most bit) changing 0⇔1
    ex) 000⇔001 010⇔011 100⇔101 110⇔111
  - After that, all nodes exchange a message currently hold in the node (including its own one and received so far) with nodes where the node address differs in the 2nd lowest significant bit changing 0⇔1
    ex) 000⇔010 001⇔011 100⇔110 101⇔111
  - Repeat them for $log_2 P$ times, finally all nodes have all messages from all other nodes
  - Total communication time is

$$T = \sum_{i=0}^{\log_2 P - 1} (a + 2^i s/b) = a \log_2 P + (P-1)(s/b) \approx a \log_2 P + P(s/b)$$

  - Here, the total data amount to send is the same with "bucket relay" algorithm, but the number of message is reduced
    ⇒ larger average message size to enhance the sustained bandwidth

Pairwise exchange in butterfly network for all-to-all



- The amount of data transfer in total is the same as p-time broadcast algorithm
- The number of messages is reduced
  ⇒ average message size is increased
  ⇒ more efficient
- However, message transfer distance is more far
  ⇒ not good for mesh/torus network

Collective communication library vs hand-made methods

- The best way for collective communication depends on the algorithm and system configuration (network topology, hardware, system size, buffer size, etc.), then it is difficult to determine the best algorithm for all systems
- An MPI library is equipped with one fixed algorithm (ordinarily), and it may not fit to the target system
- While you try the collective communication routines provided by the system, you might find more efficient algorithm with peer-to-peer communication with system configuration aware ones
  ⇒ not guaranteed to work well in any case

Summary

- Basic communication performance
  – Point-to-point communication
  – Collective communication
- profiling
- Communication optimization
  – Communication reduction
  – Communication latency hiding
  – Communication blocking
  – Load balancing
  – Collective communication