Throughput Studies on the InfiniBand Interconnect via All-to-All Communications

REU Site: Interdisciplinary Program in High Performance Computing

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Abstract

Distributed-memory clusters are the most important type of parallel computer, and they dominate the TOP500 list. The InfiniBand interconnect is the most popular network for distributed-memory compute clusters. Contention of communications across a switched network that connects multiple compute nodes in a distributed-memory cluster may seriously degrade performance of parallel code. This contention is maximized when communicating large blocks of data among all parallel processes simultaneously. This communication pattern arises in many important algorithms such as parallel sorting. The cluster tara in the UMBC High Performance Computing Facility (HPCF) with a quad-data rate InfiniBand interconnect provides an opportunity to test if the capacity of a switched network is a limiting factor in algorithmic performance. We find that we can design a test case involving increasing usage of memory that does not scale any more on the InifiniBand interconnect, thus becoming a limiting factor.

1 Introduction

The TOP500 list at `www.top500.org` of the world's most powerful supercomputers is updated every June and November. For many years by now, the list has been dominated by distributed-memory clusters. The high-performance InfiniBand interconnect is the most popular network for distributed-memory compute clusters. It connects the parallel processes that are run on several nodes in the cluster. Information transferred among nodes may stress communication across the network, both in relation to the size of the data being sent and the number of nodes being considered. As communication increases, contention along the system will stress the network due to the massive transfer of data among compute nodes. At significantly high levels of contention, the network will eventually fail to process inter-node communication efficiently. This work studies this effect by creating the maximum possible contention by simultaneous communication among all processes, created by All-to-All communication commands. These commands are integral to many parallel algorithms and thus a relevant test case.

To accomplish sufficient inter-node stress within the network in an algorithmically realistic way, our team implemented a parallel sorting function which transfers the local portion of a user-defined number of n pieces of data among the p processes. Before the communications, each node holds a portion of an array of data that is sorted locally, but may contain portions that should reside on other processes. Using All-to-All commands, each individual node sends the appropriate portions of data to all other nodes in the network simultaneously, thus maximizing inter-node communication stress. Our results show that, for constant *global* memory, as the number of processes increase, speed improves as the network contention decreases under All-to-All communication. Alternately, for constant *local* memory, as the number of processes increase, speed deteriorates as the network contention increases under All-to-All communication. This test case demonstrates that stress on the InfiniBand network can be created and will limit the scalability of parallel algorithms that use All-to-All communications as building blocks.

Section 2 specifies the details of the computational hardware, in particular of the InfiniBand interconnect, used in the studies. Section 3 explains the design of the sorting algorithm as algorithmic motivation for the All-to-All communications as well as the design of the sample data that results in the maximum contention of the communications. Then, Section 4 collects all results for the experiments with constant *global* memory and constant *local* memory, and Section 5 summarizes the conclusions.

2 Background

2.1 Computational Environment and InfiniBand Interconnect

The studies were performed on the cluster tara in the UMBC High Performance Computing Facility (HPCF). All details of the cluster tara and in particular about its InfiniBand interconnect are posted on the webpage `www.umbc.edu/hpcf`. Various performance studies using tara are available as technical reports, for instance [3] that compares performance by two implementations of MPI. Following [3], we use the MPI implementation MVAPICH2.

The cluster tara has 86 nodes, comprising 82 compute nodes, 2 develop nodes, 1 user node, and 1 management node. Each node has two quad-core Intel Nehalem X5550 processors (2.66 GHz, 8192kB cache) and 24 GB of local memory. All components of tara are connected by a quad-data rate InfiniBand interconnect.

InfiniBand is a connection that allows for high-speed data transfers from computers to input/output devices [4]. It is a switched fabric communication link, meaning that it connects the nodes to each other via switches. In computer networks, switches receive data sent from one device and direct the data to only the device(s) which is (are) meant to receive the data [4]. This allows for more secure and potentially faster data transfers between multiple devices. Using the InfiniBand communication network, there is very low latency (1.2 μs to transfer a message between two nodes), and wide bandwidth up to 3.5 GB (28 Gb) per second.

It is intuitive to hypothesize that as the number of processes on which a parallel job is run increases, the communication between processes will become slower and may bottleneck

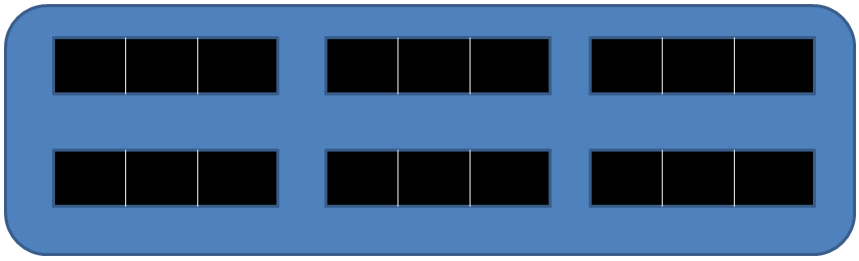


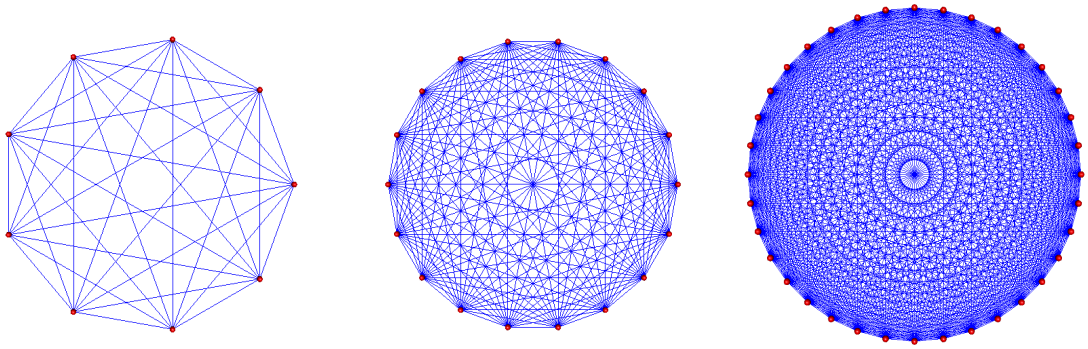
Figure 2.1: Schematic of leaf module with 18 ports.

because more processes need to communicate with each other than when the number of processes is small. However, many times, commercial manufacturers attempt to avoid this occurrence by using methods such as virtual channels and adaptive routing. Adaptive routing, as apposed to merely routing, allows nodes to reroute the path that data is sent based on network fluctuations, such as congestion at one node. When a problem is encountered while transferring data, information is sent to the appropriate nodes, and new paths to send data that avoid problem areas are created [4]. Virtual channels were created in order to alleviate the deadlock issue, and also decrease network latency and throughput. Though these methods are commonly used in parallel computing technology to solve many communication issues that arise, their effects on performance have not been rigorously studied. Therefore, it is difficult to determine when inter-job communication will become a performance issue. Our experiments study this issue. In order to study the effects of inter-job communication on job performance, our team implemented a sort algorithm which requires communication between all parallel processes.

2.2 Leaf Modules

The InfiniBand switch in the cluster tara has six leaf modules, each with 18 ports. Two leaf modules currently have complete sets of 18 compute nodes attached to them. Specifically, one leaf module connects the nodes n37 through n54, while another leaf module connects nodes n55 through n72. We can control the choice of leaf module by explicitly requesting nodes for our jobs by name. The remaining leaf modules contain other nodes that are not part of the partition of compute nodes (such as the develop nodes or components of the storage system) or have a defective node among its connections. Therefore, in this study, our team focuses on how contention is effected both within one leaf module and contention over two leaf modules. Considering this network contention provides insight into whether parallel algorithms that send large blocks of data via All-to-All communications result in contention first over two leaf modules or whether there is contention using nodes located within just one leaf module. More importantly, our conclusions answer the question regarding whether implementation of parallel code requiring All-to-All communications of large data seriously degrades performance.

The 18 ports in one leaf module are arranged evenly in two rows of ports; that is, nine ports are located in the first row and nine nodes are located in a second row. Each of the nine ports are separated in three groups of three ports, as shown in the schematic picture



$N = 9$ $N = 18$ $N = 36$

Figure 3.1: Network schematics for All-to-All communication between $N = 9, 18, 36$ nodes.

in Figure 2.1. Our team studied contention by running several tests by requesting specific nodes, starting with three nodes that form one group on the leaf module, then testing nine nodes or one row in the leaf module, and finally extending this process to the whole leaf module with 18 nodes, and then across two leaf modules with 36 nodes. This setup allows us to see if contention problems can be linked to communication within the leaf module or communication between leaf modules of parallel code.

3 Methodology

3.1 All-to-All Communications

An All-to-All communication simultaneously sends and receives data between all parallel processes in one call. Since is it eventually not possible to have physical cable connections between all possible pairs of ports in the InfiniBand switch and its leaf modules, All-to-All commands necessarily lead to contention between all required pairwise communications. The network schematics in Figure 3.1 gives a visual impression of how many cables would be needed to connect $N = 9, 18, 36$ nodes, respectively. An All-to-All communication command sends the j^{th} block of its input array from Process i to Process j and receives it into the i^{th} block of the output array on Process j. MPI has two All-to-All communication commands: `MPI_Alltoall` and `MPI_Alltoallv`. The former command sends the same amount of data between all processes, while the latter one can send variable (hence the letter "v" at the end of the command name) amounts of data between all processes [2]. To test the InfiniBand network, we will maximize the contention by communicating the largest block sizes possible. Thus, in our studies, also the variable version `MPI_Alltoallv` will send (by choosing an appropriate example data set) the same amount of data between all processes, since that maximizes contention between messages.

3.2 Experimental Design

In order to effectively stress inter-job communication, our team implemented a sorting function which transfers data among all nodes within the InfiniBand network utilizing the MPI commands `MPI_Alltoall` and `MPI_Alltoallv`. The idea of the algorithm follows [2, Chapter 10] that uses it to introduce these MPI commands. The data structure is given by n numbers, which are distributed onto the p parallel processes. Only local arrays of length $l_n := n/p$ are stored, never a global array of length n. Only the minimum number of arrays are used in the algorithm, namely one vector *unsorted* that holds the unsorted data originally and one vector *sorted* that holds the sorted data at the end of the algorithm. These two vectors have length l_n on each parallel MPI process. In [2], the algorithm has four steps: (i) The data in *unsorted* is sorted locally on each process (by any serial method of choice); while the numbers in *unsorted* are now sorted, they may contain components that need to be sent to the other process, thus creating the need for All-to-All communications. (ii) An `MPI_Alltoall` call communicates a single integer among all process pairs that informs the process pairs, how many pieces of data need to be sent and received among them in the next step. (iii) An `MPI_Alltoallv` call communicates the appropriate portions of the local *unsorted* vector on each process to the appropriate portions of the local *sorted* vector on each process. (iv) The numbers in the received *sorted* vector then still need local sorting (by any serial method) to obtain the final result of the algorithm, in which the *sorted* vectors — if concatenated from all processes — are globally sorted.

To focus entirely on the effect of the communications on the timings, we choose a sample dataset, in which neither of the local sort algorithms in steps (i) or (iv) above are needed. Moreover, since the goal is to stress the network by having as much simultaneous parallel communication as possible, we design the dataset in the initial *unsorted* vector to have an equal number of components that need to be sent to all other processes. That is concretely, out of the $l_n = n/p$ numbers in *unsorted* on one parallel process, the same block length of l_n/p components needs to be sent to each of the p processes.

The idea is best understood by the concrete example of $n = 48$ numbers, given as numbers $1, 2, \ldots, 48$, distributed to $p = 4$ processes, with ID numbers $0, 1, 2, 3$ in MPI counting, displayed in the matrix

$$unsorted = \begin{bmatrix} 1,\ 2,\ 3, & 13, 14, 15, & 25, 26, 27, & 37, 38, 39 \\ 4,\ 5,\ 6, & 16, 17, 18, & 28, 29, 30, & 40, 41, 42 \\ 7,\ 8,\ 9, & 19, 20, 21, & 31, 32, 33, & 43, 44, 45 \\ 10, 11, 12, & 22, 23, 24, & 34, 35, 36, & 46, 47, 48 \end{bmatrix}.$$

Each of the $p = 4$ rows in this matrix lists the $l_n = n/p = 48/4 = 12$ numbers that are initially on the Processes $0, 1, 2, 3$, respectively. We note that the numbers in each row above are already locally sorted, thus not requiring step (i) of the algorithm. To achieve a globally sorted vector, stored in local vector *sorted* on each process, requires for this sample dataset the communication of a block length $l_n/p = 12/4 = 3$ of numbers among all pairs of processes. For example for Process 0 (data in first row of the matrix), the group of numbers $13, 14, 15$ needs to be sent to Process 1, which — coming from Process 0 — will show up as the first numbers in vector *sorted* on Process 1. This communication gives the result that

can be summarized in the matrix

$$sorted = \begin{bmatrix} 1,\ 2,\ 3, & 4,\ 5,\ 6, & 7,\ 8,\ 9, & 10, 11, 12 \\ 13, 14, 15, & 16, 17, 18, & 19, 20, 21, & 22, 23, 24 \\ 25, 26, 27, & 28, 29, 30, & 31, 32, 33, & 34, 35, 36 \\ 37, 38, 39, & 40, 41, 42, & 43, 44, 45, & 46, 47, 48 \end{bmatrix},$$

which lists in each row the numbers in *sorted* on the Processes $0, 1, 2, 3$, respectively; notice the group $13, 14, 15$ at the start of the second row for Process 1. We observe that the numbers in each row of this matrix are sorted and no local sort of the vectors *sorted* on each process in step (iv) of the algorithm is needed.

3.3 Memory Predictions

To stress the network as much as possible, we need to make the amount of data communicated between each pair of parallel processes as large as possible. In the example dataset designed so far, this amount of data is simply a block length l_n/p of numbers, which is thus given indirectly by choosing n and p. We introduce now another independent variable m that allows to control the amount of this data independently from n and p. Namely, in place of each number in the example for the arrays *unsorted* and *sorted* we use a struct that contains an array of m double-precision numbers. We can now think of the numbers in *unsorted* and *sorted* as indices into an array of structs, and communicating each struct requires the sending and receiving of m doubles. In other words, in place of communicating l_n/p numbers between process pairs, we communicate l_n/p many vectors of m double-precision numbers, called a block size l_n/p of m-vectors for short.

An additional benefit of introducing m is that we can now explicitly control the memory requirement of the arrays by choosing m. The two local vectors, *unsorted* and *sorted*, are the overwhelming variables in memory. Since each node on the cluster tara has 24 GB of memory, total local memory must be less than 24 GB per node. To comfortably stay within this memory also on one node, the vectors are chosen as less than 10 GB each to insure that memory does not become a problem. In Table 3.1, we specialize our memory calculations to use the maximum possible number of 8 parallel processes on each compute node, which maximizes contention on each node for the All-to-All communications among its local processes and contention when all local processes access the InfiniBand cable at the same time. Table 3.1 provides the formulas for memory predictions for a global array of length n consisting of vectors of m doubles. The global vector is then divided into p local arrays of block length $l_n = n/p$ of m-vectors, such that the size of the local vectors is constant per number of processes p. The block size of the portions in the arrays *unsorted* and *sorted* that need to be communicated between process pairs is then the block size l_n/p of m doubles.

As explained in Section 2, we wish to use $N = 1, 3, 9, 18, 36$ nodes, which we choose by name so as to ensure their optimal connectivity in the leaf modules in the InfiniBand interconnect. Running then 8 processes on each node with two quad-core CPUs for most contention of network traffic, we have $p = 8\,N = 8, 24, 72, 144, 288$ parallel processes in a job. These numbers are listed in the first two rows of Table 3.1.

Table 3.1: Formulas for memory predictions.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
Dimension m	m	m	m	m	m
Length n of global array of m-vectors and their size in elements:					
Length n	n	n	n	n	n
Size	$m\,n$	$m\,n$	$m\,n$	$m\,n$	$m\,n$
Length $l_n = n/p$ of local arrays of m-vectors and their size in elements:					
Length l_n	$\frac{n}{p}$	$\frac{n}{p}$	$\frac{n}{p}$	$\frac{n}{p}$	$\frac{n}{p}$
Size	$m\,\frac{n}{p}$	$m\,\frac{n}{p}$	$m\,\frac{n}{p}$	$m\,\frac{n}{p}$	$m\,\frac{n}{p}$
Length l_n/p of block size of m-vectors in All-to-All and their size in elements:					
Length l_n/p	$\frac{n}{p^2}$	$\frac{n}{p^2}$	$\frac{n}{p^2}$	$\frac{n}{p^2}$	$\frac{n}{p^2}$
Size	$m\,\frac{n}{p^2}$	$m\,\frac{n}{p^2}$	$m\,\frac{n}{p^2}$	$m\,\frac{n}{p^2}$	$m\,\frac{n}{p^2}$

In all following experiments, we fix the length of the global array at $n = 2 \cdot (8 \cdot 18 \cdot 2 \cdot 3)^2 =$ 1,492,992. This number is designed to ensure that all desired values of the block length l_n/p divide n without remainder. That is, n needs to be divisible without remainder not just by p, but by p^2, since $l_n/p = n/p^2$. We had originally planned to consider also some other values of p, hence some additional factors are contained in the choice of n that are not strictly needed going forward.

4 Results

4.1 Experiment with Constant Global Memory

To effectively test the contention of the InfiniBand network, our team conducted a performance study with a constant global memory value, by fixing $m = 512$ as constant, which makes the global memory an estimated 6 GB for each of the two arrays *unsorted* and *sorted* in Table 4.1 for $n =$ 1,492,992. The local memory of $l_n = n/p$ decreases from 729 MB to 20 MB, as the numbers of processes p and nodes N increase. This effect of decreasing memory is amplified for the block size l_n/p, namely from process to process it decreases by another factor of p, so that 93,312 kB decrease dramatically to 72 kB eventually.

Table 4.2 and Figure 4.1 both display the results of observed wall clock time in seconds for the call to the `MPI_Alltoallv` command sending and receiving $m\,l_n/p$ doubles between processes for the choices of parameters in Table 4.1. The results show that the communication speed of the All-to-All command in fact decreases with additional nodes in the parallel job. The plot brings out how dramatic the decrease is.

This is remarkable and demonstrates that the high-performance InfiniBand interconnect can handle this stress successfully for constant global memory. In the context of a larger algorithm that uses All-to-All communications, this communication will not be a bottleneck.

Table 4.1: Constant global memory for $m = 512$: predicted memory usage for one array.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
$m = 512$	512	512	512	512	512
Length n of global array of m-vectors and their memory in GB:					
Length n	1,492,992	1,492,992	1,492,992	1,492,992	1,492,992
Memory	6 GB	6 GB	6 GB	6 GB	6 GB
Length $l_n = n/p$ of local arrays of m-vectors and their memory in MB:					
Length l_n	186,624	62,208	20,736	10,368	5,184
Memory	729 MB	243 MB	81 MB	41 MB	20 MB
Length l_n/p of block size of m-vectors in All-to-All and their memory in kB:					
Length l_n/p	23,328	2,592	288	72	18
Memory	93,312 kB	10,368 kB	1,152 kB	288 kB	72 kB

Table 4.2: Constant global memory for $m = 512$: wall clock time in seconds.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
$m = 512$	1.14	0.57	0.25	0.15	0.11

4.2 Experiment with Constant Local Memory

The results up to this point used a constant *global* memory with m constant for all p, which leads to a rapidly decreasing block size l_n/p between pairs of processes. In order to keep the block size in the All-to-All communications as large as possible, the vector length m will now be designed to increase with increasing $p = 8N$, as reported in Table 4.3. The goal is to keep the block size l_n/p as large as possible, while p increases. This is limited by the requirement that the arrays *unsorted* and *sorted* need to fit in memory on each node. This implies that we cannot keep the block size l_n/p constant, but only the local memory controlled by l_n; thus we pick the function $m = 512\,N$, so that the local memory of each array *unsorted* and *sorted* is 729 MB for all values of p; we call this the case of constant *local* memory. The block size l_n/p will then still decrease with increasing p, but less dramatically than before. This is seen in Table 4.3 in a decrease from 93,312 kB to 2,592 kB, which is a much larger final value than the 72 kB in Table 4.1. Notice the size of the global array increasing to a total of 205 GB on 36 nodes with increasing m, showing what significant problem size is eventually considered in this experiment.

The results displayed in Table 4.4 and Figure 4.2 present the observed wall clock times in seconds, as we increase the number of processes $p = 8\,N$, while holding local memory on N nodes constant using $m = 512\,N$. With the local memory held constant, the run times steadily increase as we increase N. The plot in Figure 4.2 brings the increase out very well, in particular compared to the decreasing line in Figure 4.1, which started from the same initial data point. Thus, in this case of maximum contention on the network, it is apparent

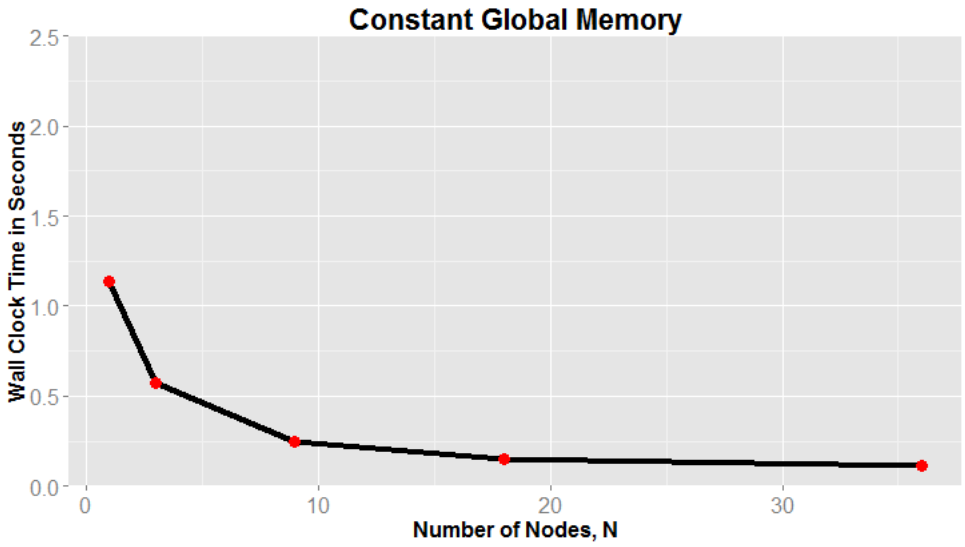


Figure 4.1: Constant global memory for $m = 512$: wall clock time in seconds vs. number of nodes.

Table 4.3: Constant local memory for $m = 512\,N$: predicted memory usage for one array.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
$m = 512\,N$	512	1,536	4,608	9,216	18,432
Length n of global array of m-vectors and their memory in GB:					
Length n	1,492,992	1,492,992	1,492,992	1,492,992	1,492,992
Memory	6 GB	17 GB	51 GB	103 GB	205 GB
Length $l_n = n/p$ of local arrays of m-vectors and their memory in MB:					
Length l_n	186,624	62,208	20,736	10,368	5,184
Memory	729 MB	729 MB	729 MB	729 MB	729 MB
Length l_n/p of block size of m-vectors in All-to-All and their memory in kB:					
Length l_n/p	23,328	2,592	288	72	18
Memory	93,312 kB	31,104 kB	10,368 kB	5,184 kB	2,592 kB

that the run times increase with the numbers of processes, and the InfiniBand interconnect is eventually overcome by the All-to-All contention. For the use of All-to-All communication commands as building blocks in larger algorithms, this means that parallel scalability studies cannot succeed, since communication time worsens as the number of processes p increases.

4.3 Remarks

The previous two subsections focused sharply on the contrast between the case of constant global memory with $m = 512$ for all N and of constant local memory with $m = 512\,N$. This

Table 4.4: Constant local memory for $m = 512\,N$: wall clock time in seconds.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
$m = 512\,N$	1.14	1.64	2.09	2.28	2.30

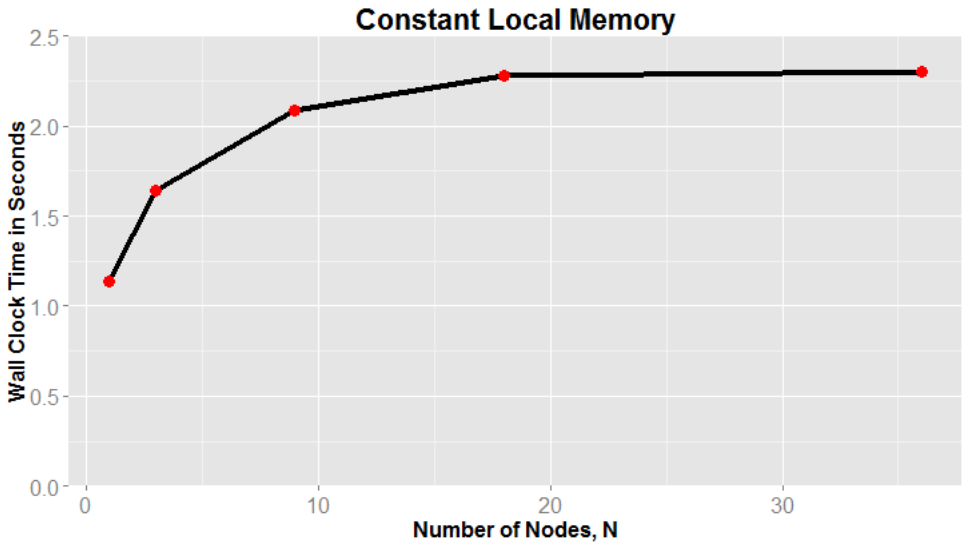


Figure 4.2: Constant local memory for $m = 512\,N$: wall clock time in seconds vs. number of nodes.

subsection contains two remarks that are separated out so as to avoid distracting from the comparison above.

Remark 1: The value 512 in $m = 512\,N$ in Section 4.2 was chosen so as to keep the memory usage safely under the available 24 GB on one node. This gave the results in Table 4.4. We actually conducted studies also for larger values than 512 in the formula for $m = 512\,N$. Table 4.5 extends Table 4.4 by results for 800, 810, and 1024, chosen by trial-and-error progressively closer to the absolute limit of 24 GB. That is, if one array with $m = 512\,N$ uses 6 GB of memory, as predicted in Table 4.3, then one array with $m = 1024\,N$ should use 12 GB, and thus two such arrays should still fit into 24 GB, even if barely.

This is brought out by the results in Table 4.5 that demonstrate the code to run for this value of m. However, the dramatically increased time, as one reads down the columns for $N = 1$ and $N = 3$, makes it clear that some swapping to hard disk is going on; this makes this case too large to draw reliable conclusions from. In fact, for larger $N > 3$, memory-related errors begin to appear, as indicated by the notation ERR in the table. These errors in fact begin to crop up also for smaller m values already, even if at larger N than for $m = 1024\,N$.

This explains our choice of $m = 512\,N$ to avoid any errors and safely stay within the available memory.

Table 4.5: Wall clock time in seconds. The notation ERR indicates a memory error.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
$m = 512\,N$	1.14	1.64	2.09	2.28	2.30
$m = 800\,N$	1.79	3.05	3.73	5.01	6.73
$m = 810\,N$	1.80	2.83	3.30	5.54	ERR
$m = 1024\,N$	85.00	170.62	ERR	ERR	ERR

Table 4.6: Constant global memory for $m = 512$: wall clock time in seconds for relative comparison of All-to-All commands.

Nodes N	1	3	9	18	36
Processes p	8	24	72	144	288
A. `MPI_Alltoall(int)`	<0.01	<0.01	<0.01	<0.01	<0.01
B. `MPI_Alltoallv(int)`	<0.01	0.01	0.10	0.32	0.59
C. `MPI_Alltoallv(double)`	1.14	0.57	0.25	0.15	0.11

Remark 2: The sketch of the algorithm in Section 3 mentions two All-to-All communications. All of our main results refer to the `MPI_Alltoallv` command that communicates the l_n/p blocks of vectors of m doubles, since that is the significant communication command, compared to the `MPI_Alltoall` command that communicates one single integer. These two cases are labeled C. `MPI_Alltoallv(double)` and A. `MPI_Alltoall(int)`, respectively, in Table 4.6. These two lines of data confirm that our intuition is correct, since all times for the case of A. `MPI_Alltoall(int)` are less than 0.01 seconds and much smaller than the timings for C. `MPI_Alltoallv(double)`. However, we also have — for testing purposes — a call to `MPI_Alltoallv` in our code that has the same structure as the `MPI_Alltoallv` of the m doubles but communicates l_n/p many integers (instead of l_n/p many m-vectors of doubles). For reasons that are unclear, the communication cost of this command labeled B. `MPI_Alltoallv(int)` in Table 4.6 increases dramatically with N and eventually overtakes both other commands. We have no explanation for this behavior. This demonstrates how much care has to be taken to write efficient and reliable parallel code.

5 Conclusions

As the results in Section 4.2 show, with local memory constant and contention on the network maximized, the run times for `MPI_Alltoallv` grow with the number of processes. This test case demonstrates that stress on the InfiniBand network can be created and will limit the scalability of parallel algorithms that use All-to-All communications as building blocks. This is as contrasted by the results in Section 4.1 that prove efficient behavior of the All-to-All communications, as long as the global memory stays constant, which implies a dramatic decrease of the block size of the pairwise communications in the `MPI_Alltoallv` command.

This is a realistic situation in many performance studies and shows that the high quality of the InfiniBand interconnect is able to handle many situations successfully, even if not the most extreme ones. Furthermore, two remarks in Section 4.3 show that for cases with larger memory requirement, we encounter excessive run times and eventually memory errors, and that care needs to be taken to implement efficient and reliable parallel code.

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