An Evaluation of Implementation Options for MPI One-Sided Communication

William Gropp and Rajeev Thakur

Mathematics and Computer Science Division
Argonne National Laboratory
Argonne, IL 60439, USA
{gropp, thakur}@mcs.anl.gov

Abstract. MPI defines one-sided communication operations—put, get, and accumulate—together with three different synchronization mechanisms that define the semantics associated with the initiation and completion of these operations. In this paper, we analyze the requirements imposed by the MPI Standard on any implementation of one-sided communication. We discuss options for implementing the synchronization mechanisms and analyze the cost associated with each. An MPI implementer can use this information to select the implementation method that is best suited (has the lowest cost) for a particular machine environment. We also report on experiments we ran on a Linux cluster and a Sun SMP to determine the gap between the performance that could be achievable and what is actually achieved with MPI.

1 Introduction

Over the past decade, one-sided communication has emerged as a promising paradigm for high-performance communication on low-latency networks. The advantage of one-sided communication lies in its asynchronous nature: Unlike in point-to-point (or two-sided) communication where the sender and receiver explicitly call send and receive functions, in one-sided communication only the origin process calls the data-transfer function (put or get), and data transfer takes place without the target process explicitly calling any function to transfer the data. This model allows parallel programs to be less synchronizing and allows communication hardware to move data from one process to another with maximal efficiency. Nonetheless, some synchronization mechanism is needed in the programming model for the target process to indicate when its memory is ready for being read or written by a remote process and to specify when the data transfer is completed.

Because of the growing popularity of one-sided communication, the MPI Forum defined a specification for one-sided communication in MPI-2 [8]. MPI defines three data-transfer functions for one-sided communication: put (remote write), get (remote read), and accumulate (remote update). These data-transfer functions must be used together with one of three synchronization mechanisms—fence, post-start-complete-wait, and lock-unlock—as shown in Figure 1. Many

```
Process 0              Process 1
MPI_Win_fence(win)     MPI_Win_fence(win)
MPI_Put(1)             MPI_Put(0)
MPI_Get(1)             MPI_Get(0)
MPI_Win_fence(win)     MPI_Win_fence(win)
```

a. Fence synchronization

```
Process 0              Process 1              Process 2
                       MPI_Win_post(0,2)
MPI_Win_start(1)                              MPI_Win_start(1)
MPI_Put(1)                                    MPI_Put(1)
MPI_Get(1)                                    MPI_Get(1)
MPI_Win_complete(1)                           MPI_Win_complete(1)
                       MPI_Win_wait(0,2)
```

b. Post-start-complete-wait synchronization

```
Process 0                 Process 1              Process 2
MPI_Win_create(&win)      MPI_Win_create(&win)   MPI_Win_create(&win)
MPI_Win_lock(shared,1)                           MPI_Win_lock(shared,1)
MPI_Put(1)                                       MPI_Put(1)
MPI_Get(1)                                       MPI_Get(1)
MPI_Win_unlock(1)                                MPI_Win_unlock(1)
MPI_Win_free(&win)        MPI_Win_free(&win)     MPI_Win_free(&win)
```

c. Lock-unlock synchronization

Fig. 1. The three synchronization mechanisms for one-sided communication in MPI. The numerical arguments indicate the target rank.

MPI implementations, including all vendor MPIs, support one-sided communication, with varying levels of optimization [1, 2, 4, 6, 7, 9, 10, 12, 14, 15]. Nonetheless, Gabriel et al. [3] found that, because of the synchronization overhead in one-sided communication, regular point-to-point communication performs better than one-sided communication in five MPI implementations: NEC, Hitachi, IBM, Sun, and LAM. The only exceptions were NEC and Sun MPI when window memory allocated with the special function `MPI_Alloc_mem` is used. Clearly, it is necessary to study the costs associated with the synchronization mechanisms and optimize the implementations. In this paper, we analyze the semantics of the synchronization mechanisms, discuss options for implementing them, and analyze the overhead. This information is useful to MPI implementers in deciding which implementation method to use for a particular machine environment.

2 Fence Synchronization

Figure 1a illustrates the fence method of synchronization. In MPI, the memory region that a process exposes to one-sided communication is called a *window*, and a collection of processes create a *window object* that is used in subsequent one-sided communication functions. `MPI_Win_fence` is collective over the communicator associated with the window object. A process may issue one-sided operations after the first call to `MPI_Win_fence` returns. The next call to fence completes the one-sided operations issued by this process as well as the operations targeted at this process by other processes. An implementation of fence synchronization must support the following semantics: A one-sided operation cannot access a process's window until that process has called fence, and the second fence on a process cannot return until all processes needing to access that process's window have completed doing so.

2.1 Implementing Fence

In general, an implementation has two options for implementing fence: *immediate* and *deferred*.

Immediate Method. This method implements the synchronization and communication operations as they are issued. A simple implementation of this option is to perform a barrier in the first fence; perform the puts, gets, and accumulates as they are called; and perform another barrier at the end of the second fence after all the one-sided operations have completed. The first barrier ensures that all processes know that all other processes have reached the first fence and that it is now safe to access their windows. The second barrier ensures that a process does not return from the second fence until all other processes have finished accessing its window.

On a distributed-memory environment without hardware support for barriers, a barrier can be implemented by using the dissemination algorithm [5] with 0-byte messages. If p is the number of processes and α is the latency (or startup time) per message, this algorithm costs $(\lg p)\alpha$. The immediate method requires two barriers, which cost $2(\lg p)\alpha$. This method is expensive in environments where the latency is high, such as on clusters and networks running TCP. It is appropriate for environments where barriers can be fast, such as shared-memory systems or machines with hardware support for barriers, such as the Cray T3E and IBM BG/L.

Deferred Method. This method [12] takes advantage of the MPI feature that puts, gets, and accumulates are nonblocking and are guaranteed to be completed only when the following synchronization function returns. In the deferred method, the first fence does nothing and simply returns. The ensuing puts, gets, and accumulates are simply queued up locally. All the work is done in the second fence, where each process first goes through its list of queued one-sided operations and determines, for every other process i, whether any of the one-sided operations have i as the target. This information is stored in an array, such that a 1 in the ith location of the array means that one or more one-sided operations are targeted to process i, and a 0 means otherwise. All processes then do a reduce-scatter sum operation on this array (as in `MPI_Reduce_scatter`). As a result, each process knows how many processes will be performing one-sided operations on its window, and this number is stored in a counter in the window object. Each process then performs the data transfer for its one-sided operations and ensures that the counter at the target is decremented when all the one-sided operations from this process to that target have been completed. As a result, a process can return from the second fence when the one-sided operations issued by that process have completed locally and when the counter in its window object reaches 0, indicating that all other processes have finished accessing its window.

This method thus eliminates the need for a barrier in the first fence and replaces the barrier at the *end* of the second fence by a reduce-scatter at the *beginning* of the second fence before any data transfer. After that, all processes can do their communication independently and return when they are done (asynchronously). This method also enables optimizations such as message reordering, scheduling, and aggregation, which the immediate method does not.

On a distributed-memory system, a reduce-scatter operation on an array of p short integers (2 bytes) costs $(\lg p)\alpha + 2(p-1)\beta$ [13], where β is the transfer time per byte between two processes. Because of the lower latency term, this method is preferred over the immediate method on systems where the latency is relatively high, such as on clusters.

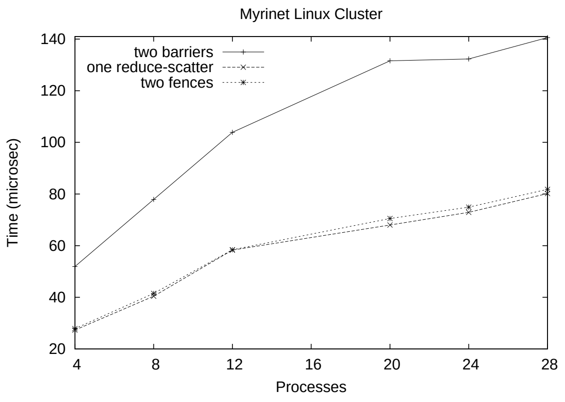
2.2 Performance

To determine how MPI implementations perform for fence synchronization, we measured the cost of two `MPI_Barrier`s, one `MPI_Reduce_scatter`, and two `MPI_Win_fence`s on a Myrinet-connected Linux cluster at Argonne and a Sun SMP at the University of Aachen in Germany. On the Linux cluster, we used a beta version of MPICH2 1.0.2 with the GASNET channel on top of GM. On the Sun SMP, we used Sun MPI. We performed the operations several times in a loop, calculated the average time for one iteration, and then the maximum time taken by all processes. We used `MPI_Alloc_mem` to allocate window memory and passed assert `MPI_MODE_NOPRECEDE` to the first fence and `(MPI_MODE_NOSTORE | MPI_MODE_NOPUT | MPI_MODE_NOSUCCEED)` to the second fence.

Figure 2 shows the results. On the Linux cluster, the cost of two barriers is far more than the cost of a single reduce-scatter. Therefore, the deferred method is the preferred option, which is what MPICH2 uses in this case. We see that the cost of two fences is almost the same as that of a reduce-scatter. On the Sun SMP, Sun MPI has a very fast implementation of barrier, and therefore the immediate method is the preferred implementation strategy for fence. From the graph, it appears that Sun MPI does use the immediate method, because the time for two fences is only slightly higher than the time for two barriers.

3 Post-Start-Complete-Wait Synchronization

Fence synchronization, being collective over the entire communicator associated with the window object, results in unnecessary overhead when only small subsets of processes actually communicate with each other. To avoid this drawback, MPI defines a second synchronization mechanism in which only subsets of processes need to synchronize, as shown in Figure 1b. A process that wishes to expose its



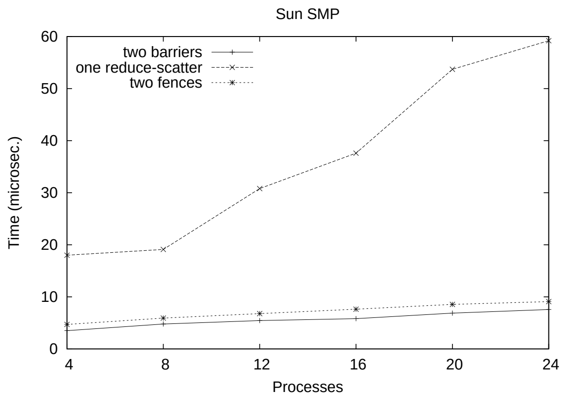


Fig. 2. Time taken for two barriers, one reduce-scatter, and two fences on a Myrinet-connected Linux cluster using MPICH2 (left) and on a Sun SMP using Sun MPI (right).

local window to remote accesses calls `MPI_Win_post`, which takes as argument an `MPI_Group` object that specifies the set of processes that will access the window. A process that wishes to perform one-sided communication calls `MPI_Win_start`, which also takes as argument an `MPI_Group` object that specifies the set of processes that will be the target of one-sided operations from this process. After issuing all the one-sided operations, the origin process calls `MPI_Win_complete` to complete the operations at the origin. The target calls `MPI_Win_wait` to complete the operations at the target.

An implementation of post-start-complete-wait synchronization must take into account the following semantics: A one-sided operation cannot access a process's window until that process has called `MPI_Win_post`, and a process cannot return from `MPI_Win_wait` until all processes that need to access that process's window have completed doing so and called `MPI_Win_complete`.

3.1 Implementing Post-Start-Complete-Wait

We again consider the immediate and deferred methods for implementing post-start-complete-wait. A few intermediate options also exist [4, 8] but, for simplicity, we do not consider them here.

Immediate Method. In this method, `MPI_Win_start` blocks until it receives a message from all processes in the target group indicating that they have called `MPI_Win_post`. Puts, gets, and accumulates are performed as they are called. `MPI_Win_complete` waits until all one-sided operations initiated by that process have completed locally and then sends a done message to each target process. On the target, `MPI_Win_wait` blocks until it receives the done message from each origin process. Assuming that the size of the origin and target groups is g, the overhead of this method is $2g\alpha$. This method is appropriate in environments with low latency and native support for one-sided communication, such as shared memory, so that the data transfer can be initiated as soon as it is called.

Deferred Method. This method defers data transfer until the second synchronization call [12]. In `MPI_Win_post`, if the assert `MPI_MODE_NOCHECK` is not specified, the process sends a zero-byte message to each process in the origin group to indicate that `MPI_Win_post` has been called. It also sets the counter in its window object to the size of this group. On the origin side, `MPI_Win_start` does nothing and simply returns. All one-sided operations are simply queued up locally. In `MPI_Win_complete`, the origin process first waits to receive the zero-byte messages from the processes in the target group. It then performs all the one-sided operations and ensures that the window counter at the target gets decremented when all the one-sided operations from this process to that target have been completed. `MPI_Win_complete` returns when all its operations have locally completed. On the target, `MPI_Win_wait` simply blocks and invokes the progress engine until its window counter reaches zero, indicating that all origin processes have finished accessing its window.

Thus the only synchronization in this method is the wait at the beginning of `MPI_Win_complete` for a zero-byte message from the processes in the target group, and this too can be eliminated if the user specifies the assert `MPI_MODE_NOCHECK` to `MPI_Win_post` and `MPI_Win_start` (similar to `MPI_Rsend`). If the size of the origin and target groups is g, the overhead of this method is $g\alpha$. Therefore, the deferred method is faster in environments where latency is high.

4 Lock-Unlock Synchronization

In the lock-unlock synchronization method, the origin process calls `MPI_Win_lock` to obtain either shared or exclusive access to the window on the target, as shown in Figure 1c. After issuing the one-sided operations, it calls `MPI_Win_unlock`. The target does not make any synchronization call. When `MPI_Win_unlock` returns, the one-sided operations are guaranteed to be completed at the origin *and* the target. `MPI_Win_lock` is not required to block until the lock is acquired, except when the origin and target are one and the same process. Implementing lock-unlock synchronization when the window memory is not directly accessible by all origin processes requires the use of an asynchronous agent at the target to cause progress to occur because one cannot assume that the user program at the target will call any MPI functions that will cause progress periodically [8].

4.1 Implementing Lock-Unlock

We consider the immediate and deferred methods of implementing lock-unlock.

Immediate Method. In this method, `MPI_Win_lock` sends a lock-request packet to the target and waits for a lock-granted reply. Puts, gets, and accumulates are performed as they are called. `MPI_Win_unlock` waits until all one-sided operations initiated by that process have completed locally and then sends an unlock request to the target. It also waits to receive an acknowledgment from the target that all the one-sided operations issued from this process have completed at the target, as required by the semantics of `MPI_Win_unlock`. The cost for acquiring the lock is 2α, and the cost for releasing the lock is also 2α. Therefore, the total cost of this method is 4α, assuming no lock contention.

Deferred Method. In this method [12], `MPI_Win_lock` does nothing and simply returns. All one-sided operations are simply queued up locally. In `MPI_Win_unlock`, the origin sends a lock-request packet to the target and waits for a lock-granted reply. It then performs the one-sided operations. When these operations have completed locally, it sends an unlock request to the target and, in the general case, waits for a reply from the target indicating that the operations have completed at the target.

The deferred method also costs 4α in the general case, but it permits several optimizations that the immediate method does not. One optimization is that if any of the one-sided operations is a get, it can be reordered and performed last. Since the origin must wait to receive data in the get, when the get completes, it implies that the one-sided operations have also completed at the target (assuming ordered completion). In this case, an additional acknowledgment is not needed from the target, thereby reducing the cost to 3α. Another optimization in the case of a single put, get, or accumulate is that the origin can perform it as an atomic lock-(put/get/accumulate)-unlock request without having to wait for a lock-granted reply. If the operation is a get, even the additional completion acknowledgment from the target is not needed. These optimizations reduce the cost of lock-unlock to α and 0, respectively, because the lock request becomes part of the data transfer.

5 Analysis for Shared-Memory Environments

Shared-memory environments offer unique opportunities for optimizing MPI one-sided communication because of their support for atomic operations for fast synchronization and the ability to directly copy data to/from the user's buffer on the target if the window memory was allocated with `MPI_Alloc_mem`. We analyze in further detail the implementation of one-sided communication on shared-memory environments with lock-unlock synchronization. Consider this simple example that puts `n` `long`s into the memory window on the process specified by `rank`:

```
MPI_Win_lock(MPI_MODE_EXCLUSIVE, rank, 0, win);
MPI_Put(buf, n, MPI_LONG, rank, 0, n, MPI_LONG, win);
MPI_Win_unlock(rank, win);
```

We assume that the window memory was allocated with `MPI_Alloc_mem` and is directly accessible by a remote process. If we ignore error checking of function parameters, an MPI implementation need perform only the following steps for each of the above functions.

`MPI_Win_lock`

1. Make a routine call with four arguments
2. Convert `win` into an address (if not already an address)
3. Look up the address of the lock at the target (indexed access into `win`)
4. Check shared or exclusive access
5. Remote update for the lock

`MPI_Win_put`

1. Make a routine call with eight arguments
2. Convert `win` into an address (if not already an address)
3. Check that the remote memory is directly accessible
4. Get the base address of the remote memory (indexed access into `win`)
5. Get the displacement unit (indexed access into `win`)
6. Determine whether origin data is contiguous and get length (access datatype and multiply count by datatype size)
7. Determine whether target data is contiguous
8. Perform the copy of local to remote memory

`MPI_Win_unlock`

1. Make a routine call with two arguments
2. Convert `win` into an address (if not already an address)
3. Look up the address of the lock at the target (indexed access into `win`)
4. Remote update for the unlock

While the number of steps may seem large, they in fact involve relatively few instructions. However, the access to remote memory, either for the lock accesses or for the memory copy at the end of the `MPI_Put` step, may require hundreds of processor cycles. To determine the cost of performing the above steps, we wrote a shared-memory program using OpenMP [11] in which one thread performs the equivalent of lock, put, and unlock on another thread. We wrote four versions of this program:

1. A single routine OpenMP program where the lock, put, and unlock are all performed in the main routine by simply setting and clearing a flag for the lock and unlock steps and using `memcpy` to move the data.
2. The lock, put, and unlock operations are performed in separate routines, thus adding function-call overhead.
3. An `MPI_Win`-like structure is added so that the addresses of the lock and the memory at the target have to be obtained by indexing into the structure.
4. The routines use the same arguments as the corresponding MPI functions. This version adds more arguments to the routines and requires an extra lookup in the `win` structure for the displacement unit at the target.

We ran these programs on a Sun SMP (Sun Fire E6900, 1.2 GHz Ultra Sparc IV) at the University of Aachen with the Sun OpenMP compiler. We also ran the MPI version of the program with Sun MPI and a beta version of MPICH2 1.0.2 with the sshm (scalable shared memory) channel. For windows allocated

Table 1. Time in seconds to perform a lock-put-unlock operation on a Sun SMP. n is the number of `long`s (4 bytes) moved. OpenMP 1 is a simple OpenMP implementation of this operation. The other three OpenMP programs add more features. OpenMP 4 mimics the steps an MPI implementation must implement. The last two columns show the times for two MPI implementations: Sun MPI and MPICH2.

n	OpenMP 1 (simple)	OpenMP 2 (routines)	OpenMP 3 (win struct)	OpenMP 4 (all MPI args)	Sun MPI	MPICH2
8	4.5e-7	4.8e-7	4.9e-7	5.4e-7	1.1e-6	1.3e-6
256	1.1e-6	1.1e-6	1.1e-6	1.2e-6	1.7e-6	1.9e-6
1024	4.7e-6	4.9e-6	5.0e-6	5.1e-6	5.2e-6	6.6e-6
64K	2.5e-4	2.6e-4	2.6e-4	2.7e-4	4.3e-4	5.4e-4

with `MPI_Alloc_mem`, this version of MPICH2 uses the immediate method to implement all three synchronization methods in the sshm channel.

Table 1 shows the time taken to move 8, 256, 1024, and 64K `long`s (4 bytes) by these programs. The results show that the fastest MPI version is slower by a factor of 1.4 to 2 than the OpenMP version with all MPI features. We plan to investigate the cause of this difference in further detail, but preliminary studies indicate that the cost of `MPI_Win_lock` followed by `MPI_Win_unlock` is itself roughly twice as large as the equivalent steps in the OpenMP version. This may be due to the difference in the handling of thread and process locks in the operating system, and we plan to investigate this issue further.

6 Conclusions and Future Work

MPI one-sided communication has the potential to deliver high performance to applications. However, MPI implementations need to implement it efficiently, with particular emphasis on minimizing the overhead added by the synchronization functions. In this paper, we have analyzed the minimum requirements an implementation must meet to honor the semantics specified by the MPI Standard. We have discussed and analyzed several implementation options and recommended which option to use in which environments. Our analysis of the performance of lock-put-unlock on the Sun SMP demonstrates that MPI implementations are not too far off from delivering what can be delivered by using direct shared memory, although there is room for improvement. We plan to investigate in further detail where the additional gap lies and how much of it can be reduced with clever implementation strategies.

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