SKaMPI-OpenSHMEM: Measuring OpenSHMEM Communication Routines

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Abstract. Benchmarking is an important challenge in HPC, in particular, to be able to tune the basic blocks of the software environment used by applications. The communication library and distributed runtime environment are among the most critical ones. In particular, many of the routines provided by communication libraries can be adjusted using parameters such as buffer sizes and communication algorithm. As a consequence, being able to measure accurately the time taken by these routines is crucial in order to optimize them and achieve the best performance. For instance, the SKaMPI library was designed to measure the time taken by MPI routines, relying on MPI’s two-sided communication model to measure one-sided and two-sided peer-to-peer communication and collective routines. In this paper, we discuss the benchmarking challenges specific to OpenSHMEM’s communication model, mainly to avoid inter-call pipelining and overlapping when measuring the time taken by its routines. We extend SKaMPI for OpenSHMEM for this purpose and demonstrate measurement algorithms that address OpenSHMEM’s communication model in practice. Scaling experiments are run on the Summit platform to compare different benchmarking approaches on the SKaMPI benchmark operations. These show the advantages of our techniques for more accurate performance characterization.

Keywords: First keyword · Second keyword · Another keyword.

1 Introduction

The ability to effectively utilize high-performance computing (HPC) systems to their best potential depends heavily on tuned library implementations specific to a machine’s processor, memory, and communications components. For distributed memory applications, the communication routines and distributed runtime system should be implemented and optimized in close association with the capabilities of the hardware interconnection network. This poses special challenges for standard communication interfaces designed to be portable across HPC platforms. The performance of low-level communication operations is important, but it is the communication model semantics that ultimately defines
the context for correct execution. Both aspects come into play when porting a communications library from one HPC architecture to another.

Benchmarking is a powerful technique for understanding HPC performance. When applied to the development and tuning of scalable distributed systems, especially portable parallel communication libraries, benchmarking can provide valuable insight for identifying high-value settings of parameters and algorithm variants for different use scenarios. The design of a benchmarking methodology and framework that can elaborate communication model behaviors and correctly generate test cases is highly relevant for achieving productive outcomes. It serves to maintain a coherent plan for measurement and analysis during the performance characterization and library tuning process.

The original goal of the research reported in this paper was to develop a benchmarking system for OpenSHMEM that could be used to tune OpenSHMEM implementations across multiple HPC machines. Most important to our work was designing a benchmarking methodology that was consistent with the OpenSHMEM standard and systematic in its processing. Unfortunately, only OpenSHMEM mini-benchmarks existed at the time the research began. While we anticipated that we would have to develop the tests for most of the OpenSHMEM operations, we wondered if we could reuse the high-level structure and methods of the SKaMPI benchmarking system [18]. The paper reports our experience and success in following this strategy.

There are four research contributions deriving from our work. First, we produced a "first of its kind" fully functional benchmarking system for OpenSHMEM, based on the SKaMPI methodology and framework. Second, we show how the SKaMPI methodology and framework could be reused for OpenSHMEM purposes. This outcome could be beneficial to extending SKaMPI with other communication libraries in the future. Third, we describe how the tests of communication routines specific to the OpenSHMEM standard are constructed. Finally, we demonstrate our benchmarking system on the Summit platform and report detailed analysis results.

The rest of the paper is structured as follows. In Section 2 we discuss related research work in the performance measurement, analysis, and benchmarking of communication libraries. Here we introduce the former SKaMPI work for MPI. Section 3 looks at the specific problem of measuring OpenSHMEM routines and the challenges of creating a portable benchmarking solution based on SKaMPI for characterization and tuning. Our experimental evaluation is presented in in Section 4. We show the use of our solution on the DOE Summit system at Oak Ridge National Laboratory (ORNL). Finally, we conclude and describe future directions.

2 Related works

Measuring the time taken by communications can be performed in two contexts. It can be made on parallel applications, in order to determine how much time the application spends communicating. Various robust profiling and tracing sys-
tems can be used, such as TAU [20], VTune [16], Scalasca [4], Score-P [11], and EZTrace [24]. The objective is to characterize communication performance for the routines actually used by the application.

The other context has to do with analyzing communications performance for the purpose of tuning the communication routines (point-to-point [2] or collective routines [13,10]), and to make sure that they fulfill performance requirements [23] on the system of interest. This benchmarking approach is fundamentally different from above, but can lead to important outcomes that contribute to better application communication performance. The Special Karlsruhe MPI benchmark (SKaMPI) was created to benchmark MPI communications for supercomputer users and system administrators who want to tune their MPI libraries [12], evaluate and choose algorithms for collective communications [25,26], and ensure performance portability of the MPI library across platforms [17].

Measuring the time spent in communications should consider parameters that might potentially be exploited by applications. Regardless of the communication library used, the effective bandwidth can be measured directly [15]. However, each library will have communication routines that will need specific measurement techniques to understand their operation. For instance, peer-to-peer communications are interesting because certain libraries might allow overlap with computation. The measurement methodology to capture phenomena in such cases can be non-trivial. Moreover, designing benchmarking methods that can be applied across communication libraries is a challenge.

SKaMPI overcomes most limitations of previous benchmarks such as PARKBENCH [6] and mpbench [14], as described in [18]. For instance, mpbench reduces the number of calls to the timer by calling the measured function several times in a loop and measuring the total time taken by the loop. However, some pipelining might occur between consecutive calls; for instance, when measuring tree-based collective operations, or point-to-point communications that do not ensure remote completion when the sender call returns.

In order to eliminate obvious pipelining between some collective operation calls, mpbench uses a different root for the operation (for broadcasts and reductions) at every iteration. However, depending on the communication topology used, this might not be enough and in some cases a pipeline can still establish between consecutive calls. Other algorithms have been designed to eliminate inter-call pipelining and perform an accurate measurement of these calls, relying on the synchronizing model of MPI peer-to-peer communications to enforce separation of consecutive collective routines [22], and on the synchronization model of MPI2 one-sided communications [1].

Theoretical models are a close relative to benchmarking and can complement its objectives, in that they utilize empirical values measured on target machines. The representative LogP model [3] expresses point-to-point communications using four parameters: the send and receive overheads, which are the time to prepare the data to send it over the network and the time to get it from the network and provide it to the application (denoted \( o_s \) and \( o_r \)), the wire latency, which is the time for the data to actually travel through the network.
(denoted $L$), and the gap, which is the the minimum interval between consecutive communications (denoted $g$). Since $o$ and $g$ can overlap, the LogP model encourages overlapping with computation with communication.

3 Measuring OpenSHMEM communication routines

SKaMPI’s measuring infrastructure and synchronization algorithms are described and evaluated in [5]. Our objective is to utilize the SKaMPI framework for benchmarking OpenSHMEM communication. However, considering studies of potential clock drift [9], we know that both barrier and window-based process synchronization suffer from drift and the processes might lose their synchronization as the measurement progresses. SKaMPI’s window-based clock synchronization can measure operations very accurately, but the logical global clocks drift quickly, so only a small number of MPI operations can be measured precisely. The hierarchical algorithm presented in [9] has a smaller clock drift, but the processes still skew during the measurement. As a consequence, we cannot rely on this synchronization only to perform our measurements, and whenever possible, we need to design measurement strategies that rely on more precise measurements than just a synchronization followed by a call to the measured routine.

Scalable clock synchronization algorithms are presented in [7] and can achieve synchronization in $O(\log(P))$ rounds, whereas SKaMPI’s algorithm takes $O(p)$ rounds. Adopting a better algorithm is related to the infrastructure that supports the measurements and is out of the scope of this paper. However, it is important that we use lightweight timing mechanisms that are non-perturbing relative to the granularity of the artifact being measured. In some fine-grained measurement cases, we had to update SKaMPI timing methods.

3.1 Point-to-point communication routines

Blocking operations. OpenSHMEM includes two categories of blocking point-to-point communication routines: remote memory access routines and atomic operations. In these two categories, we have two types of routines: those that return as soon as possible and not when the data has actually been delivered, and those that return when the data has been delivered in the destination buffer.

Routines from the latter category can be called fetching or get-based. Their completion time corresponds to the time elapsed between the call and the return of the communication routine (see Figure 1a), making them trivial to measure. Routines from the former category can be called non-fetching or put-based. They are supposed to return as soon as the source buffer can be reused and not when the data has actually been delivered to the destination buffer. Since OpenSHMEM is a one-sided communication model, the target process does not participate in the communication: a global synchronization routine like a barrier cannot ensure completion of the operation, since the target process can enter the barrier and exit before the one-sided operation completes (and, since the order of operations is not guaranteed, before it has even reached the target process).
Completion of the operation can be ensured with `shmem_quiet`. Therefore, we want to measure the time elapsed between the call to the communication routine and the return of `shmem_quiet` (see Figure 1b). However, calling `shmem_quiet` can have a cost. Therefore, we need to measure the cost of an almost empty call to `shmem_quiet` and with substract it from the measured time.

The `shmem_quiet` routine ensures completion of the outgoing put-based operations. It works on all active communications with remote processes for the calling process. To measure the routine, therefore, we must issue a `shmem_put` for one byte before the `shmem_quiet`. We cannot exclude this `shmem_put` from the measurement, because some communication engines might make it progress and complete before they schedule the communication with all the remote processes involved by `shmem_quiet`. However, it sends a small message and its latency should be combined with the latency of the first part of the `shmem_quiet`, so this `shmem_put` should have a negligible impact on the measurement of `shmem_quiet` (see Figure 1c).

Some implementations and some networks implement `shmem_put` as a non-blocking communication that only ensures that the sending buffer on the source process is reusable after the call exits (as in OpenMPI [19]). Others implement it like a blocking communication (oshmpi [1] implements it as two `MPI_Isend` followed by a `MPI_Waitall` [5,21]). Hence, measuring the time spent in the call to `shmem_put` is relevant. We provide a function for this.

```
measure(a) Measure a get.
measure(b) Measure a put.
measure(c) Measure a quiet.
```

![Figure 1](image.png)

**Fig. 1:** Different measurement cases for blocking operations.

**Non-blocking operations.** With some implementations and some networks, the call to the communication routine can just post the communication and the communication is performed in `shmem_quiet`. Therefore, we can measure the time taken by this call to `shmem_quiet` for a given communication size. In the preamble of the measurement routine, we measure the time to perform a complete non-blocking communication (including the call to `shmem_quiet`) for the same buffer size. Then we post the operation and wait twice the measured time. Then we measure the time spent in `shmem_quiet`. If the library has good overlap capabilities, the communication will be performed during the wait, and the call to `shmem_quiet` will not do anything. Otherwise, the communication will be performed in `shmem_quiet`. 

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3 SHA 62362849cae65b2445723e426affc2bb7918a6c8
4 SHA 776449f6ea0368b61450b0c37e834633576f1bf
Hence, we are providing four functions to measure non-blocking \textit{put} operations and four functions to measure non-blocking \textit{get} operations:

- \texttt{Shmem\_\{Put,Get\}_Nonblocking\_Full} measures the full completion of a non-blocking operation, with a \texttt{shmem\_put\_nbi} or a \texttt{shmem\_get\_nbi} immediately followed by a \texttt{shmem\_quiet}.
- \texttt{Shmem\_\{Put,Get\}_Nonblocking\_Quiet} measures the time spent in \texttt{shmem\_quiet}, called immediately after \texttt{shmem\_put\_nbi} or \texttt{shmem\_get\_nbi}. If there is no overlap, most of the communication time is expected to be spent here. Otherwise, this call should be fast.
- \texttt{Shmem\_\{Put,Get\}_Nonblocking\_Post} measures the time spent in the call to \texttt{shmem\_put\_nbi} or \texttt{shmem\_get\_nbi}. This call should be fast and the communication should not be performed here, otherwise the communication cannot be overlapped with computation.
- \texttt{Shmem\_\{Put,Get\}_Nonblocking\_Overlap} measures the time spent in \texttt{shmem\_put\_nbi} or \texttt{shmem\_get\_nbi} and the time spent in \texttt{shmem\_quiet}, separated by a computation operation that should take about twice the time to completed the full (non-blocking) communication.

These routines can be used to evaluate the overlapping capabilities of the library, by showing how much time is spent posting the non-blocking communications, waiting for them to complete, and comparing the time spent in these routines when they are and are not separated by a computation.

\subsection{Collective operations}

\subsubsection{Broadcast}

When measuring a broadcast, a major challenge concerns how to avoid a pipeline that might occur between consecutive communications. Therefore, we want to separate consecutive broadcasts, while avoiding external communication costs to be included. An initial possibility consists in separating consecutive broadcast with a barrier, and subtracting the time to perform a barrier (measured separately), as show by algorithm 1.

However, since with some broadcast algorithms, processes might exit early, the barrier performed after the broadcast could become unbalanced and take a time different than a barrier performed by a set of already more or less synchronized processes. For instance, Figure 2 depicts a case when a process ends after the other ones, so the barrier can be finalized as soon as it enters it and all the other processes are already synchronized ($m3 < m1$). Moreover, a barrier does
SKaMPI provides a time-based synchronization, provided by `start_synchronization` and `stop_synchronization` routines. We can measure the broadcast operation as in algorithm 2.

Another possibility to try to avoid overlap and get the full extent of a broadcast by doing broadcasts in rounds. Each process is made the root of a broadcast and multiple broadcasts are performed. However, depending on the broadcast topology, there might still be some overlap between consecutive broadcasts. Algorithm 3 was introduced by [22]. In turns, processes acknowledge completion of their part of the broadcast to the root. The time to perform an acknowledgment is measured prior to the measurement, and subtracted from the total time.

However, this algorithm was designed in a two-sided communication model, with synchronous communications. Conveniently, OpenSHMEM provides a routine that waits until a variable located in the shared heap validates a comparison: `shmem_wait_until`. The first step is used to measure the acknowledgment time (`rt1`) between the root process and each process `task`. The algorithm is using a "large" number of repetitions not truly synchronize the processes. For instance, they can be implemented as a reduction followed by a broadcast using the same root, and depending on which process is the root of these operations, the end of the second barrier in Figure 2 can create a skew between processes.

Fig. 2: Barrier-synchronized broadcast.

**Alg. 2:**
Active synchronization-based.

```
1 root ← 0;
2 for i ← 0 to iterations by 1 do
3     t1 ← start_sync();
4     broadcast(buffer, root);
5     t2 ← stop_sync();
6     t_bcast ← t_bcast + (t2 − t1);
7     t_bcast ← t_bcast/iterations;
```

**Alg. 3:** In rounds.

```
1 t1 ← start_sync();
2 for root ← 0 to size by 1 do
3     broadcast(buffer, root);
4     e_time ← stop_sync();
5     t_bcast ← (e_time − s_time)/size;
```

**Alg. 4:** (Part 1) One-sided communications broadcast measurement.

```
1 Function initialize(task)
2     /* Measure ack */
3     t1 ← wtime();
4     if root == rank then
5         ack(task);
6     wait_for_ack();
7     else if task == rank then
8         wait_for_ack();
9         ack(root);
10     rt1 ← wtime() − t1;
11     return rt1;
```
In the algorithm described in [22], this first step is made using an exchange of two-sided send and receive communications. This step is used to measure the time taken by an acknowledgment, later used in the algorithm. Then a first broadcast is performed and process \( task \) acknowledges it to the root of the broadcast (lines 3 to 8). Then comes the measurement step itself, performed \( M \) times for each task (line 24 to 29). The broadcast time is obtained by subtracting the acknowledgment measured in the first exchange step (line 34).

We are performing the acknowledgment by incrementing a remote counter using an atomic \texttt{fetch\_and\_inc} operation and waiting for the value of this counter. We are using a \texttt{fetch\_and\_add} operation instead of an add operation because, as specified by the OpenSHMEM standard, non-fetching calls may return before the operation executes on the remote process. We can wait for remote completion with a \texttt{shmem\_quiet}, but we decided to use the simplest operation available; besides, although this operation goes back-and-forth between the source and the target, we are measuring this exchange in the initialization of the measurement routine.

**Lemma 1.** even if a remote write operation interleaves between the operations \texttt{shmem\_int\_wait\_until( ack, SHMEM\_CMP\_EQ, 1 ) and *ack = 0}, there cannot be two consecutive remote increment of the \*ack variable. In other words, \*ack cannot take any other value than 0 and 1 and acknowledgments sent as atomic increments are consumed by \texttt{shmem\_int\_wait\_until} before another acknowledgment arrives.

**Proof.** If we denote:

\(- \prec \) the \textit{happens before} relation between two events, with \( a \prec b \) meaning that \( a \) happens before \( b \);

\begin{verbatim}
Alg. 4: (Part 2) One-sided communications broadcast measurement.
11 Proc warmup(task)
  /* Warm-up */
12   broadcast( buffer, root);
13   if root == rank then
14     ack(task);
15     wait_for_ack();
16   else if task == rank then
17     wait_for_ack();
18     ack(root);
19   return;
20 for task ← 0 to size by 1 do
  /* Initialize */
21   rt1 ← initialize( task );
22   warmup( task );
  /* Measure broadcast */
23   t1 ← wtime();
24   for i ← 0 to M by 1 do
25     broadcast( buffer, root);
26     if root == rank then
27       wait_for_ack();
28     else if task == rank then
29       _ack(root);
30   t2 ← wtime();
31   if rank == task then
32     rt2 ← t2 - t1;
33     myt ← rt2 - rt1;
34     btime ← max( btime, myt );
35 return btime;
\end{verbatim}
– \textit{broadcast}_y: the local operation on process \( y \) for the \( a \)th broadcast (beginning of the operation);
– \textit{fetch\_inc}_y: the local operation on process \( y \) for the \( a \)th \texttt{shmem\_int\_atomic\_fetch\_inc}
  (on the source process \( y \), beginning of the operation);
– \textit{inc}_y: the increment of \texttt{*ack} on process \( y \) for the \( a \)th \texttt{shmem\_int\_atomic\_fetch\_inc}
  (on the target process \( y \));
– \textit{wait}_y: the \( a \)th time process \( y \) waits for the value of \texttt{*ack} to be modified
  with \texttt{shmem\_int\_wait\_until( ack, SHMEM\_CMP\_EQ, 1 )};
– \textit{assignment}_y: the \( a \)th time process \( y \) assigns \texttt{*ack} to the value 0, hence
  consuming previously received acknowledgments.

These operations are represented Figure 3. Even if \texttt{*ack} is incremented remotely
which the broadcast operation is still in progress on the root process, it will not
be read before the end of the root’s participation to the broadcast. Hence, the
root cannot begin the next broadcast before it is done with the current one. We
need to note the fact that other processes might still be in the broadcast.

![Fig. 3: Broadcast measurement](image)

The next broadcast starts after \texttt{*ack} has been set back to 0. We have:

– on the root process:
  \( \texttt{broadcast}_1\texttt{root} \prec \texttt{inc}_1\texttt{root} \prec \texttt{wait}_1\texttt{root} \prec \texttt{assignment}_1\texttt{root} \prec \texttt{broadcast}_2\texttt{root} \prec \texttt{inc}_2\texttt{root} \prec \texttt{wait}_2\texttt{root} \prec \texttt{assignment}_2\texttt{root} \)
– on any \( P_x \)
  \( \texttt{broadcast}_{1x} \prec \texttt{fetch\_inc}_{1x} \prec \texttt{broadcast}_{2x} \prec \texttt{fetch\_inc}_{2x} \)

We also know that:

– \( \texttt{fetch\_inc}_{1x} \prec \texttt{inc}_1\texttt{root} \)
– \( \texttt{inc}_1\texttt{root} \prec \texttt{assignment}_1\texttt{root} \)

The OpenSHMEM standard states that: "When calling multiple subsequent
collective operations on a team, the collective operations—along with any relevant
team based resources—are matched across the PEs in the team based on ordering
of collective routine calls". Hence, for any two processes \( x \) and \( y \), \( \texttt{broadcast}_{1x} \prec \texttt{broadcast}_{2y} \), so \( \texttt{fetch\_inc}_{1x} \prec \texttt{fetch\_inc}_{2y} \).

Therefore, by transitivity of the \( \prec \) relation:

\( \texttt{fetch\_inc}_{1x} \prec \texttt{assignment}_1\texttt{root} \prec \texttt{inc}_2\texttt{root} \prec \texttt{assignment}_2\texttt{root} \)
we can conclude that there cannot be two consecutive `shmem_int_atomic_fetch_inc` on the root process with no re-assignment to 0 between them, and on any process, the acknowledgment cannot be sent while the previous or the next broadcast is in progress on other processes. □

The corollary of the lemma is that acknowledgment exchanges cannot be interleaved with broadcasts (only local operations can be), and therefore 1) there is no deadlock and 2) consecutive broadcasts cannot interleave.

### 3.3 Fine-grain measurements

There are important concerns we needed to pay attention to when updating SKaMPI for making fine-grain measurements.

**Alg. 5: Timing outside.**

1. `t1 ← wtime();`
2. `for i ← 0 to iterations by 1 do`
3. `    shmem_putmem(...);`
4. `    shmem_quiet();`
5. `    ttime ← wtime() − t1;`
6. `return ttime/iterations;`

**Alg. 6: Timing inside.**

1. `tttime ← 0;`
2. `for i ← 0 to iterations by 1 do`
3. `    t1 ← wtime();`
4. `    shmem_putmem(...);`
5. `    shmem_quiet();`
6. `    ttime ← ttime + wtime() − t1;`
7. `return ttime/iterations;`

**Measurement disturbance.** The timing function in SKaMPI (a call to PAPI’s timing routine) takes a time of the same order of magnitude or, in some cases, higher that the time taken by some of the functions we are measuring. Hence, we want to minimize the number of calls to the timing function during a measurement. We observed very significant differences between the times obtained using Algorithm 5 and Algorithm 6. A lot of calls to the timing function, which, if using an external function such as PAPI, we might not be able to inline, is causing very significant disturbance to the measurement.

**Alg. 7: Timing `shmem_quiet`.**

1. `tttime ← 0;`
2. `for i ← 0 to iterations by 1 do`
3. `    shmem_putmem(...);`
4. `    t1 ← wtime();`
5. `    shmem_quiet();`
6. `    ttime ← ttime + wtime() − t1;`
7. `return ttime/iterations;`

**Alg. 8: Subtraction method.**

1. `tpost = get_post_time();`
2. `t1 ← wtime();`
3. `for i ← 0 to iterations by 1 do`
4. `    shmem_putmem(...);`
5. `    shmem_quiet();`
6. `    ttime ← wtime() − t1;`
7. `return ttime/iterations − tpost;`

**Separating calls.** Some functions we are measuring can be called only in the context of another function. For instance, if we want to measure the time spent waiting for a non-blocking communication to complete, we need to post a non-blocking communication before. We cannot post a set of non-blocking communications and call `shmem_quiet` in a loop, because it waits for completion of all
the outstanding non-blocking communications at the same time. Therefore, each `shmem_quiet` must correspond to a previously posted non-blocking communication. However, we cannot isolate it on our measurement such as described by Algorithm 7 for the reasons presented in the previous paragraph. Therefore, we are initializing the measurement by measuring the time taken by the routine that posts the non-blocking communication, measuring the whole loop, and subtracting the post time from the result (Algorithm 8).

**Stability.** The aforementioned methods rely on subtracting values measured during the initialization of the measurement. Therefore, the experimental conditions must remain stable through the measurement. For instance, we noticed instabilities on machines that were being used by multiple users at the same time, while the measurements were quite stable on nodes used in exclusive mode. Moreover, SKaMPI calls each measuring function multiple times and keeps calling them until the standard deviation between measurements is small enough. However, we found significant improvement in the stability between experiments when each measurement function was, itself, performing a significant number of measurements and returning their mean.

**Busy wait.** In order to avoid voluntary context switches, we are not using a `sleep` to wait while the communication is progressing in the background. Instead, we are performing a computation operation that takes the same time, but does not involve the operating system. Our approach is to increment a variable in a loop and we avoid compiler optimization by inserting an call to an empty assembly instruction (`asm(``) in the loop.

## 4 Experimental evaluation

We used our extended SKaMPI on the Summit supercomputer, which features 4608 two-socket IBM POWER9 nodes, 6 Nvidia V100 GPUs per node and 512GB of DDR4 plus 96GB of HBM2 per node. The network is a Mellanox EDR 100G InfiniBand non-blocking fat tree. We used the provided IBM Spectrum MPI and OpenSHMEM library version 10.3.1.02rtm0 and the IBM XL compiler V16.1.1. The input files used to run these experiments are available along with the SKaMPI source file. The remainder of this section discusses selected outcomes from the full set of SKaMPI-OpenSHMEM results.

### 4.1 Loop measurement granularity

In section 3.3 we mentioned the importance of how loops are measured. We compared the time returned by the functions that measure a non-blocking put (`shmem_put` immediately followed by `shmem_quiet`, `shmem_put` and `shmem_quiet` measured separately). We can see that iteration-level measurement introduce a very significant latency, which is not visible for longer measurements that are not latency-bound (higher buffer sizes).
Similarity, we compared these time measurement strategies on the measurement of the overlap capabilities of non-blocking communications. Iteration-level measurement uses four calls to the timing routines in each iteration of the measurement loop: before and after posting the non-blocking communication, and before and after calling \texttt{shmem\_quiet} to wait for its completion. The global loop measurement times the whole loop and subtracts the time assumed to be taken by the computation used to (try to) overlap the computation. As discussed in section 3.3, it relies on the hypothesis that this time will be stable throughout the measurement. However, as we can see Figure 5, the latency introduced by the iteration-level measurement strategy is such that the numbers returned by this method are too far from reality for small messages.

Consequently, the results presented in this section were measured using our global timer approach (as described in section 3.3). The results are shown in the figures. It can be seen that the global timer measurements produced smaller and more reliable values versus iteration timers.
4.2 Point-to-point communications: blocking vs non-blocking

We measured the performance difference between a blocking communication and a non-blocking communication, and the time it takes to wait for completion of the communication. For instance, Figure 6 shows the communication performance on a single node and between two nodes. We can see that blocking communications have a smaller latency than a non-blocking communication followed by a \texttt{shmem\_quiet} that waits for its completion. We can also see the breakdown between how much time is spent posting the non-blocking communication and how much is spent waiting for its completion.

4.3 Point-to-point communications: overlap capabilities

We can also use SKaMPI to measure the overlapping capabilities of the OpenSHMEM library, as described in section 3.1. Figure 7 shows how much time is spent in a complete non-blocking operation (\texttt{shmem\_put} or \texttt{shmem\_get} immediately followed by \texttt{shmem\_quiet}) and how much is spent in these operations separated by some computation. We can see on Figures 7b and 7a that, since the interconnection network used on the Summit machine can make the communication progress in the background, it achieves good overlap between communication and computation. The time spent in communication routines is constant (called ”non-overlapped”) on the figure, corresponding to the time spent in the communication routines. On the other hand, intra-node communications cannot progress in the background. This can be seen in Figure 7d and 7c where the time spent in communication routines is the same as when these routines are called back-to-back with no computation (i.e., these communications are not overlapped). We can see on Figure 6 that the time is actually spent in \texttt{shmem\_quiet}, which is completing (actually performing) the communication.
4.4 Collective communications: broadcast

It is interesting to observe the differences in experimental results for the various measurement algorithms. In particular, we expect the in round approach to give a smaller value, since consecutive broadcasts can establish a pipeline depending on the communication topology used by the broadcast. We also see on Figure 8 that the broadcast separated by barriers can give smaller measurement values. As explained in section 4.4, we expect this observation can be explained by the final barrier being faster on the last processes to finish (see Figure 2).

The other algorithms give very similar results. As discussed in section 3.2, the synchronized broadcast can be less reliable because of time drifts and less significant statistically speaking, since we are measuring broadcasts one by one. Moreover, the SK algorithm with consecutive broadcasts separated by a sleep is likely to be more relevant, although here it gives similar results.

Fig. 7: Overlap capabilities of point-to-point communications.

Fig. 8: Comparing times returned by the broadcast measurement algorithms.
4.5 Locks

OpenSHMEM provide global locking functions. Our measurement of the time taken by these functions takes into account whether the lock is already taken, who is requesting it, and so on. Some of these measurements and their scalability are shown Figure 9.

(a) Acquisition and release.  (b) Test.

Fig. 9: Global lock functions.

5 Conclusion and perspectives

Our research work delivers a portable benchmarking framework for OpenSHMEM, in the spirit of the successful SKaMPI benchmarking system for MPI. While the communication libraries are distinct from one another, the benchmarking methodology practiced in SKaMPI is more general and very relevant to our OpenSHMEM benchmarking objectives. Indeed, we made the important decision to work within the SKaMPI benchmarking infrastructure and implement OpenSHMEM-specific functionality, thereby delivering a more robust outcome in the end. Clearly, the most important contribution of our research are the algorithms we created for the unique requirements of measuring OpenSHMEM routines.

The original SKaMPI benchmarking offered portability across platforms and the ability to help tune communication library implementation. Our OpenSHMEM benchmarking development carries forward these key attributes. To illustrate its use, we conducted experimental evaluation on the Summit machine. Our results demonstrate the richness of performance insight we can gain on point-to-point and collective operations. We show how this can be used to optimize certain implementation parameters.

The increasing complexity of HPC environments will further complicate abilities to measure their performance. A well-defined benchmarking methodology can serve as the core for evaluating multiple communication libraries. That perspective is well-supported based on our experience. It is reasonable to expect that the approach we followed of specializing SKaMPI’s infrastructure for OpenSHMEM would work well with other communication models and libraries.

SKaMPI-OpenSHMEM can be downloaded from GitHub at the following address: https://github.com/coti/SKaMPI
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