Mercury: Enabling Remote Procedure Call for High-Performance Computing

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***Abstract*—Remote procedure call (RPC) is a technique that has been largely adopted by distributed services. This technique, now more and more used in the context of high-performance computing (HPC), allows the execution of routines to be delegated to remote nodes, which can be set aside and dedicated to specific tasks. However, existing RPC frameworks assume a socket-based network interface (usually on top of TCP/IP), which is not appropriate for HPC systems, because this API does not typically map well to the native network transport used on those systems, resulting in lower network performance. In addition, existing RPC frameworks often do not support handling large data arguments, such as those found in read or write calls.**

We present in this paper an asynchronous RPC interface, called Mercury, specifically designed for use in HPC systems. The interface allows asynchronous transfer of parameters and execution requests and provides direct support of large data arguments. Mercury is generic in order to allow any function call to be shipped. Additionally, the network implementation is abstracted, allowing easy porting to future systems and efficient use of existing native transport mechanisms.

I. Introduction

When working in an heterogeneous environment, an engineer or a scientist may often find it useful to distribute the various steps of an application workflow—particularly in high-performance computing where it is common to see systems or nodes embedding different types of resources and libraries that can be dedicated to specific tasks such as computation, storage, or analysis and visualization. Remote procedure call (RPC) [1] is a technique that follows a client/server model and allows local calls to be transparently executed on remote resources. It consists of serializing the local function parameters into a memory buffer and sending that buffer to a remote target that in turn deserializes the parameters and executes the corresponding function call. Libraries implementing this technique can be found in various domains such as web services with Google Protocol Buffers [2] or Facebook Thrift [3] or in domains such as grid computing with GridRPC [4]. RPC can also be realized by using a more object-oriented approach with frameworks such as CORBA [5] or Java RMI [6], where abstract objects and methods can be distributed across remote resources.

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However, using these standard and generic RPC frameworks on a high-performance computing (HPC) system presents two main limitations: the inability to take advantage of the native transport mechanism in order to transfer data efficiently, since these frameworks are mainly designed on top of TCP/IP protocols, and the inability to transfer very large amounts of data, since the limit imposed by the RPC interface is generally on the order of a megabyte. In addition, even if no limit is enforced, transferring large amounts of data through the RPC library is usually discouraged, mostly because of overhead from serialization and encoding, causing the data to be copied many times before reaching the remote node.

We present in this paper Mercury, an asynchronous RPC interface designed for HPC systems that addresses these limitations. Mercury's main purpose is to serve as a basis for higher-level frameworks such as I/O forwarders, remote storage systems, or analysis frameworks that need to remotely exchange or operate on large data in a distributed environment. Mercury primarily exposes the semantics required for making nonblocking RPC as well as for supporting large data arguments. Higher-level features such as multithreaded execution, request aggregation, and pipelining operations, are not provided by Mercury directly but can easily be built on top of it.

This paper is organized as follows. In Section II we first discuss related work. Then in Section III we discuss the network abstraction layer on top of which the interface is built, as well as the architecture defined to transfer small and large data efficiently. Section IV outlines the API and shows its advantages in enabling the use of pipelining techniques. We also describe the development of network transport plugins for our interface, as well as performance evaluation results. Section V presents conclusions and future research directions.

II. Related Work

RPC has been largely adopted by distributed services and the Network File System (NFS) [7] is a good example of the use of RPC with large data transfers, therefore close to the use of RPC on an HPC system. It makes use of XDR [8] to serialize arbitrary data structures and create a

system-independent description; the resulting stream of bytes is then sent to a remote resource, which can deserialize and get the data back from it. Recent versions of NFS can also make use of separate transport mechanisms to transfer data over RDMA protocols, in which case the data is processed outside the XDR stream. The interface that we present in this paper follows similar principles but in addition handles bulk data directly. It is also not limited to the use of XDR for data encoding, which can negatively impact performance, especially when sender and receiver share a common system architecture. By providing a *network abstraction layer*, the RPC interface that we define enables the user to send small data and large data efficiently, using either small messages or remote memory access (RMA) types of transfer that fully support one-sided semantics present on recent HPC systems. Furthermore, the interface is nonblocking and therefore allows an asynchronous mode of operation, freeing the caller from having to wait for one operation to execute before another one can be issued.

The *I/O Forwarding Scalability Layer* (IOFSL) [9] is another project on which part of the work presented in this paper is based. IOFSL makes use of RPC to specifically forward I/O calls. It defines an API called ZOIDFS that locally serializes function parameters and sends them to a remote server, where they can in turn get mapped onto file-system-specific I/O operations. One of the main motivations for extending IOFSL is the ability to send not only a specific set of calls, such as those defined through ZOIDFS, but also a varied set of calls that can be dynamically and generically defined. We note that IOFSL is built on top of the BMI [10] network transport layer used in the Parallel Virtual File System (PVFS) [11]. It allows support for dynamic connection as well as fault tolerance, but also defines two types of messaging, unexpected and expected (described in Section III-B), that can enable an asynchronous mode of operation. Nevertheless, BMI is limited in its design by not directly exposing the RMA semantics that are required to explicitly achieve RDMA operations from the client memory to the server memory; this limitation can be an issue and can negatively impact performance (the main advantages of using an RMA approach are described in Section III-B). In addition, while BMI does not offer one-sided operations, it does provide a relatively high-level set of network operations. This makes porting BMI to new network transports (such as the Cray Gemini interconnect [12]) nontrivial and time consuming since only a subset of the functionality provided by BMI is required for implementing RPC in our context.

Another project, Sandia National Laboratories' *NEtwork Scalable Service Interface* (Nessie) [13], provides a simple RPC mechanism originally developed for the Lightweight File Systems [14] project. It provides an asynchronous RPC solution, designed to overlap computation and I/O. The RPC interface of Nessie directly relies on XDR, which is designed mainly to communicate between heterogeneous architectures, even though practically all HPC systems are homogeneous. Nessie provides a separate mechanism to handle bulk data transfers, which can use RDMA to transfer data efficiently from one memory to the other, and supports several network transports. The Nessie client uses the RPC interface to push control messages to the servers. Additionally, Nessie exposes a different, one-sided API (similar to Portals [15]), which the user can use to push or pull data between client and server. Mercury is different, in that its interface, which also supports RDMA natively, can transparently handle bulk data for the user by automatically generating abstract memory handles representing the remote large data arguments, which are easier to manipulate and do not require any extra effort by the user. Mercury also provides fine-grained control of the data transfer if required (for example, to implement pipelining). In addition, Mercury provides a higher-level interface than does Nessie, greatly reducing the amount of user code needed to implement RPC functionality.

Another similar approach can be seen with the *Decoupled and Asynchronous Remote Transfers* (DART) [16] project. While DART is not defined as an explicit RPC framework, it allows transfer of large amounts of data using a client/server model from applications running on the compute nodes of an HPC system to local storage or remote locations, in order to enable remote application monitoring, data analysis, code coupling, and data archiving. The key requirements that DART is trying to satisfy include minimizing data transfer overheads on the application, achieving high-throughput, low-latency data transfers, and preventing data losses. To this end, DART is designed so that dedicated nodes (i.e., separate from the application compute nodes) asynchronously extract data from the memory of the compute nodes using RDMA. In this way, expensive data I/O and streaming operations from the application compute nodes to dedicated nodes are offloaded, and allow the application to progress while data is transferred. While using DART is not transparent and therefore requires explicit requests to be sent by the user, there is no inherent limitation for integrating it within our network abstraction layer, hence allowing users to transfer data using DART on the platforms it supports.

III. Architecture

Mercury's interface relies on three main components: a network abstraction layer; an RPC interface that is able to handle calls in a generic fashion; and a bulk data interface, which complements the RPC layer and is intended to easily transfer large amounts of data by abstracting memory segments. We present in this section the overall architecture and each of its components.

A. Overview

The RPC interface follows a client/server architecture. As described in Figure 1, issuing a remote call results in different steps depending on the size of the data associated with the call. We distinguish two types of transfers: transfers containing typical function parameters, which are generally small, and are referred to as *metadata*, and transfers of function parameters, which describe large amounts of data, and are referred to as *bulk data*.

Every RPC call sent through the interface results in the serialization of function parameters into a memory buffer (its

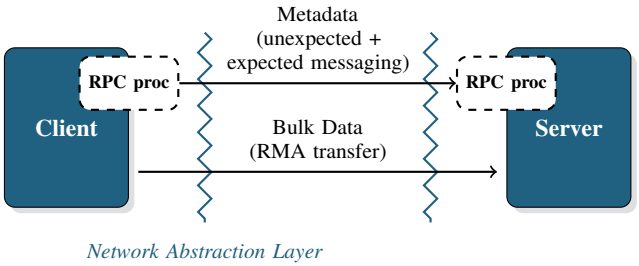


Fig. 1: Architecture overview: each side uses an RPC *processor* to serialize and deserialize parameters sent through the interface. Calling functions with relatively small arguments results in using the short messaging mechanism exposed by the network abstraction layer, whereas functions containing large data arguments additionally use the RMA mechanism.

size generally being limited to one kilobyte, depending on the interconnect), which is then sent to the server using the network abstraction layer interface. One of the key requirements is to limit memory copies at any stage of the transfer, especially when transferring large amounts data. Therefore, if the data sent is small, it is serialized and sent by using small messages; otherwise a description of the memory region that is to be transferred is sent within this same small message to the server, which can then start pulling the data (if the data is the input of the remote call) or pushing the data (if the data is the output of the remote call). Limiting the size of the initial RPC request to the server also helps in scalability, since it avoids unnecessary server resource consumption if large numbers of clients are concurrently accessing the same server. Depending on the degree of control desired, all these steps can be transparently handled by Mercury or directly exposed to the user.

B. Network Abstraction Layer

The main purpose of the *network abstraction layer* is to abstract the network protocols that are exposed to the user, allowing multiple transports to be integrated through a system of plugins. To this end a lightweight interface is provided, for which only a reasonable effort is required in order to implement a new plugin. The interface itself defines three main types of mechanisms for transferring data: unexpected messaging, expected messaging and remote memory access; but additional setup is required to establish a connection between the client and the server (a dynamic connection may not be always feasible depending on the underlying network implementation used).

Unexpected and expected messaging is limited to the transfer of short messages and makes use of a two-sided approach. The maximum message size is, for performance reasons, determined by the interconnect and can be as small as a few kilobytes. The concept of unexpected messaging is used in other communication protocols such as BMI [10]. Sending an unexpected message through the network abstraction layer does not require a matching receive to be posted before it can complete. By using this mechanism, clients are not blocked; and the server can, every time an unexpected receive is issued, pick up the new messages that have been posted. Another difference between expected and unexpected messages is that unexpected messages can arrive from any remote source, while expected messages require the remote source to be known.

The RMA interface allows remote memory chunks (contiguous and noncontiguous) to be accessed. In most one-sided interfaces and RDMA protocols, memory must be registered to the network interface controller (NIC) before it can be used. The purpose of the interface defined in the network abstraction layer is to create a first degree of abstraction and define an API that is compatible with most RMA protocols. Registering a memory segment to the NIC typically results in the creation of a handle to that segment containing virtual address information. The local handle created needs to be communicated to the remote node before that node can start a put or get operation. The network abstraction is responsible for ensuring that these memory handles can be serialized and transferred across the network. Once handles are exchanged, a nonblocking put or get can be initiated. On most interconnects, put and get will map to the put and get operation provided by the specific API provided by the interconnect. The network abstraction interface is designed to allow the emulation of one-sided transfers on top of two-sided sends and receives for network protocols such as TCP/IP that support a two-sided messaging approach only.

With this network abstraction layer in place, Mercury can easily be ported to support new interconnects. The relatively limited functionality provided by the network abstraction (for example, no unlimited-size two-sided messages) ensures close to native performance.

C. RPC Interface and Metadata

Sending a call that involves only small data makes use of the unexpected/expected messaging defined in Section III-B. At a higher level, however, sending a function call to the server means that the client must know how to encode the input parameters before it can start sending information and must know how to decode the output parameters once it receives a response from the server. On the server side, the server must also know what to execute when it receives an RPC request and how it can decode and encode the input and output parameters. The framework for describing the function calls and encoding/decoding parameters is key to the operation of our interface.

One of the important criteria is the ability to support a set of function calls that can be sent to the server in a generic fashion, avoiding the limitations of a hard-coded set of routines. The generic framework is described in Figure 2. During the initialization phase, the client and server register encoding and decoding functions by using a unique function name that is mapped to a unique ID for each operation, shared by the client and server. The server also registers the callback that needs to be executed when an operation ID is received with a function call. To send a function call that does not involve bulk data transfer, the client encodes the input parameters along with that operation's ID into a buffer and sends it to the server

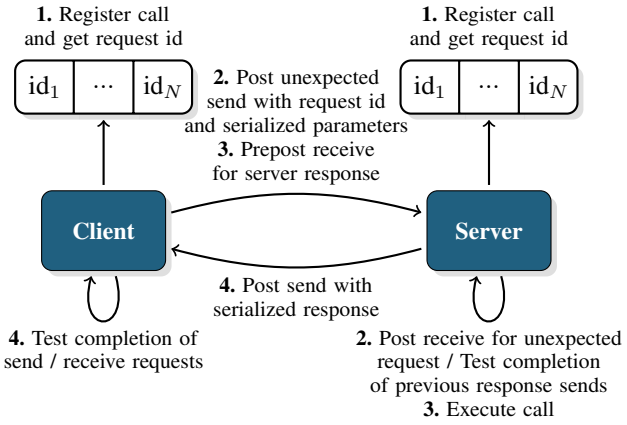


Fig. 2: Asynchronous execution flow of RPC call. The receive buffer is preposted, allowing the client to get other work done while the call is executed and the response is sent back.

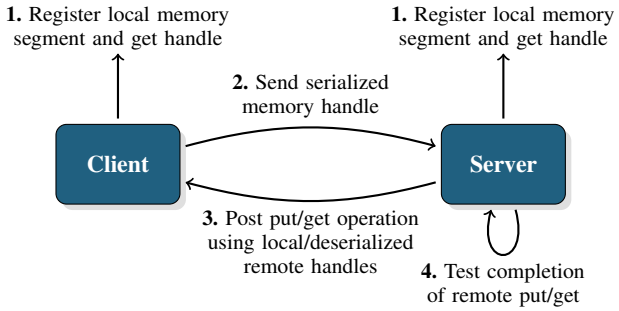


Fig. 3: Additional steps when doing an RPC that requires large data to be sent to the server. The client memory handle is serialized and sent to the server along with other parameters using the conventional RPC mechanism.

using an unexpected messaging protocol, which is nonblocking. To ensure full asynchrony, the memory buffer used to receive the response back from the server is also preposted by the client. For reasons of efficiency and resource consumption, these messages are limited in size, typically to a few kilobytes. If, however, the metadata exceeds the size of an unexpected message, the client will need to transfer the metadata in separate messages, making transparent use of the bulk data interface described in Section III-D, in order to expose the additional metadata to the server.

When the server receives a new request ID, it looks up the corresponding callback, decodes the input parameters, executes the function call, encodes the output parameters, and starts sending the response back to the client. Sending a response back to the client is also nonblocking; therefore, while receiving new function calls, the server can also test a list of response requests to check their completion, freeing the corresponding resources when an operation completes. Once the client knows that the response has been received (using a wait/test call) and therefore that the function call has been remotely completed, it can decode the output parameters and free the resources that were used for the transfer.

D. Bulk Data Interface

In addition to the previous interface, some function calls may require the transfer of larger amounts of data. For these function calls, the bulk data interface is used and is built on top of the RMA protocol defined in the network abstraction layer. Only the RPC server initiates one-sided transfers so that it can, as well as controlling the data flow, protect its memory from concurrent accesses.

As shown in Figure 3, the bulk data transfer interface uses a one-sided communication approach. The RPC client exposes a memory region to the RPC server by creating a bulk data descriptor (which contains virtual memory address information, size of the memory region that is being exposed, and other parameters that depend on the underlying network implementation). The bulk data descriptor can then be serialized and sent to the RPC server along with the RPC request parameters (using the RPC interface defined in Section III-C). When the server decodes the input parameters, it deserializes the bulk data descriptor and gets the size of the memory buffer that has to be transferred.

In the case of an RPC request that *consumes* large data parameters, the RPC server may allocate a buffer of the size of the data that needs to be received, expose its local memory region by creating a bulk data block descriptor, and initiate an asynchronous read/get operation on that memory region. The RPC server then waits/tests for the completion of the operation and executes the call once the data has been fully received (or partially if the execution call supports it). The response (i.e., the result of the call) is then sent back to the RPC client, and memory handles are freed.

In the case of an RPC request that *produces* large data parameters, the RPC server may allocate a buffer of the size of the data that is going to be produced, expose the memory region by creating a bulk data block descriptor, execute the call, and then initiate an asynchronous write/put operation to the client memory region that has been exposed. The RPC server may then wait/test for the completion of the operation and send the response (i.e., the result of the call) back to the RPC client. Memory handles can then be freed.

Transferring data through this process can be transparent for the user, especially since the RPC interface can also take care of serializing/deserializing the memory handles along with the other parameters. This feature is particularly important when noncontiguous memory segments have to be transferred. In either case memory segments are registered on the RPC client and are abstracted by the memory handle created. The memory handle is then serialized along with the parameters of the RPC function, and transferring large data using noncontiguous memory regions results in the same process as described above. This time, however, the memory handle may be of variable size as the underlying network implementation may

not support registration of noncontiguous memory segments directly. In the particular case where the handle is too large to be exchanged using the unexpected messaging interface, Mercury can internally create a bulk data descriptor and the handle is exchanged using the bulk data interface.

IV. Evaluation

Mercury's architecture enables generic RPC calls to be shipped along with handles that can describe contiguous and noncontiguous memory regions when a bulk data transfer is required. We present in this section how one can take advantage of this architecture to build a pipelining mechanism that can easily request blocks of data on demand.

A. Pipelining Bulk Data Transfers

Pipelining transfers is a typical use case when one wants to overlap communication and execution. In the architecture that we described, requesting a large amount of data to be processed results in an RPC request being sent from the RPC client to the RPC server as well as a bulk data transfer. In a common use case, the server may wait for the entire data to be received before executing the requested call. By pipelining the transfers, however, one can start processing the data while it is being transferred, and avoid paying the cost of the latency for an entire RMA transfer. Using this technique can also be particularly useful if the RPC server does not have enough memory to handle all the data that needs to be sent, in which case it will also need to transfer pieces of data as they are processed. A simplified version of the RPC client code is presented below.

```
#define BULK_NX 16
#define BULK_NY 128

int main(int argc, char *argv[])
{
  hg_id_t rpc_id;
  write_in_t in_struct;
  write_out_t out_struct;
  hg_request_t rpc_request;
  int buf[BULK_NX][BULK_NY];
  hg_bulk_segment_t segments[BULK_NX];
  hg_bulk_t bulk_handle = HG_BULK_NULL;

  /* Initialize the interface */
  [...]

  /* Register RPC call */
  rpc_id = HG_REGISTER("write",
    write_in_t, write_out_t);

  /* Provide data layout information */
  for (i = 0; i < BULK_NX ; i++) {
    segments[i].address = buf[i];
    segments[i].size = BULK_NY * sizeof(int);
  }

  /* Create bulk handle with segment info */
  HG_Bulk_handle_create_segments(segments,
    BULK_NX, HG_BULK_READ_ONLY, &bulk_handle);

  /* Attach bulk handle to input parameters */
  [...]
  in_struct.bulk_handle = bulk_handle;

  /* Send RPC request */
  HG_Forward(server_addr, rpc_id,
    &in_struct, &out_struct, &rpc_request);

  /* Wait for RPC completion and response */
  HG_Wait(rpc_request, HG_MAX_IDLE_TIME,
    HG_STATUS_IGNORE);

  /* Get output parameters */
  [...]
  ret = out_struct.ret;

  /* Free bulk handle */
  HG_Bulk_handle_free(bulk_handle);

  /* Finalize the interface */
  [...]
}
```

When the client initializes, it registers the RPC call it wants to send. Because this call involves noncontiguous bulk data transfers, memory segments that describe the memory regions are created and registered. The resulting `bulk_handle` is then passed to the `HG_Forward` call along with the other call parameters. One may then wait for the response and free the bulk handle when the request has completed (a notification may also be sent in the future to allow the bulk handle to be freed earlier, and hence the memory to be unpinned).

The pipelining mechanism operates on the server, which takes care of the bulk transfers. The pipeline itself has a fixed size and a pipeline buffer size. A simplified version of the RPC server code is presented below.

```
#define PIPELINE_BUFFER_SIZE 256
#define PIPELINE_SIZE 4

int rpc_write(hg_handle_t handle)
{
  write_in_t in_struct;
  write_out_t out_struct;
  hg_bulk_t bulk_handle;
  hg_bulk_block_t block_handle[PIPELINE_SIZE];
  hg_bulk_request_t bulk_request[PIPELINE_SIZE];
  void *buf[PIPELINE_SIZE];
  size_t nbytes, nbytes_read = 0;
  size_t start_offset = 0;

  /* Get input parameters and bulk handle */
  HG_Handler_get_input(handle, &in_struct);
  [...]
  bulk_handle = in_struct.bulk_handle;

  /* Get size of data and allocate buffer */
  nbytes = HG_Bulk_handle_get_size(bulk_handle);

  /* Initialize pipeline and start reads */
  for (p = 0; p < PIPELINE_SIZE; p++) {
    size_t offset = p * PIPELINE_BUFFER_SIZE;
    buf[p] = malloc(PIPELINE_BUFFER_SIZE);

    /* Create block handle to read data */
    HG_Bulk_block_handle_create(
      buf[p], PIPELINE_BUFFER_SIZE,
      HG_BULK_READWRITE, &block_handle[p]);

    /* Start read of data chunk */
    HG_Bulk_read(client_addr, bulk_handle,
      offset, block_handle[p], 0,
      PIPELINE_BUFFER_SIZE, &bulk_request[p]);
  }
```

```
    while (nbytes_read != nbytes) {
      for (p = 0; p < PIPELINE_SIZE; p++) {
        size_t offset = start_offset +
          p * PIPELINE_BUFFER_SIZE;

        /* Wait for data chunk */
        HG_Bulk_wait(bulk_request[p],
          HG_MAX_IDLE_TIME, HG_STATUS_IGNORE);
        nbytes_read += PIPELINE_BUFFER_SIZE;

        /* Do work (write data chunk) */
        write(fd, buf[p], PIPELINE_BUFFER_SIZE);

        /* Start another read */
        offset += PIPELINE_BUFFER_SIZE *
          PIPELINE_SIZE;
        if (offset < nbytes) {
          HG_Bulk_read(client_addr,
            bulk_handle, offset,
            block_handle, 0,
            PIPELINE_BUFFER_SIZE,
            &bulk_request[p]);
        } else {
          /* Start read with remaining piece */
        }
      }
      start_offset += PIPELINE_BUFFER_SIZE
        * PIPELINE_SIZE;
    }

    /* Finalize pipeline */
    for (p = 0; p < PIPELINE_SIZE; p++) {
      HG_Bulk_block_handle_free(block_handle[p]);
      free(buf[p]);
    }

    /* Start sending response back */
    [...]
    out_struct.ret = ret;
    HG_Handler_start_output(handle, &out_struct);
  }

  int main(int argc, char *argv[])
  {
    /* Initialize the interface */
    [...]

    /* Register RPC call */
    HG_HANDLER_REGISTER("write", rpc_write,
      write_in_t, write_out_t);

    while (!finalized) {
      /* Process RPC requests (nonblocking) */
      HG_Handler_process(0, HG_STATUS_IGNORE);
    }

    /* Finalize the interface */
    [...]
  }
```

Every RPC server, once it is initialized, must loop over a `HG_Handler_process` call, which waits for new RPC requests and executes the corresponding registered callback (in the same or new thread, depending on user needs). Once the request is deserialized, the `bulk_handle` parameter can be used to get the total size of the data that is to be transferred, allocate a buffer of the appropriate size, and start the bulk data transfers. In this example, the pipeline size is set to 4, and the pipeline buffer size is set to 256, which means that 4 RMA requests of 256 bytes are initiated. One can then wait for the first piece of 256 bytes to arrive and process it. While it is being processed, other pieces may arrive. Once one piece is processed, a new RMA transfer is started for the piece that is at stage 4 in the pipeline, and one can wait for the next piece and process it. Note that while the memory region registered on the client is noncontiguous, the `HG_Bulk_read` call on the server presents it as a contiguous region, simplifying server code. In addition, logical offsets (relative to the beginning of the data) can be given to move data pieces individually, with the bulk data interface taking care of mapping from the continuous logical offsets to the noncontiguous client memory regions.

We repeat this process until all the data has been read/processed and the response (i.e., the result of the function call) can be sent back. Again we only start sending the response by calling the `HG_Handler_start_output` call, and its completion will only be tested by calling `HG_Handler_process`, in which case the resources associated with the response will be freed. Note that all functions support asynchronous execution, allowing Mercury to be used in event-driven code if desired.

B. Network Plugins and Testing Environment

Two plugins have been developed to illustrate the functionality of the network abstraction layer. At this point, the plugins have not been optimized for performance. One plugin is built on top of BMI [10]. However, as we pointed out in Section II, BMI does not provide RMA semantics to efficiently take advantage of the network abstraction layer defined and the one-sided bulk data transfer architecture. The other plugin is built on top of MPI [17], which has been providing full RMA semantics [18] only recently with MPI 3 [19]. Many MPI implementations, specifically those delivered with already installed machines, do not yet provide all MPI 3 functionality. Since BMI has not yet been ported to recent HPC systems, to illustrate the functionality and measure early performance results, we consider only the MPI plugin in this paper. This plugin, to be able to run on existing HPC systems limited to MPI 2 functionality, such as Cray systems, implements bulk data transfers on top of two-sided messaging. In practice, this means that for each bulk data transfer, an additional bulk data control message needs to be sent to the client to request either sending or receiving data. Progress on the transfer can then be realized by using a progress thread or by entering progress functions. For testing we used two different HPC systems. One is an InfiniBand QDR 4X cluster with MVAPICH2 1.8.1 [20]; the other is a Cray XE6 with Cray MPT 5.6.4 [21].

C. Performance Evaluation

For the first experiment, we measured the time it takes to execute a small RPC call (without any bulk data transfer involved) for an empty function (i.e., a function that returns immediately). On the Cray XE6 machine, measuring the average time for 20 RPC invocations, each call took 23 µs. This time includes the XDR encoding and decoding of the parameters of the function. However, since most HPC systems are homogeneous they do not require the data portability provided by XDR. When disabling XDR encoding (performing

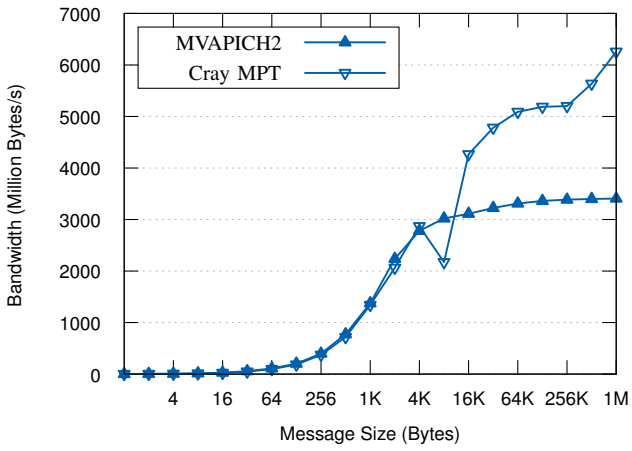


Fig. 4: OSU point-to-point micro-benchmark on InfiniBand cluster (MVAPICH2) and Cray XE6 (Cray MPT).

a simple memory copy instead), the time drops to 20 µs. This non-negligible improvement (15%) demonstrates the benefit of designing an RPC framework specifically for HPC environments.

TABLE I: Bandwidth of bulk transfers on QDR 4X InfiniBand cluster (MVAPICH2) with a total buffer size of 512 MB.

Pipeline Buffer Size (kB)	Time (s)	Bandwidth (MB/s)
—	0.370792	1380.83
4096	0.187509	2730.54
2048	0.191347	2675.77
1024	0.201990	2534.78
512	0.222204	2304.19
256	0.271534	1885.58
128	0.358534	1428.04
64	0.539834	948.44
32	0.900985	568.27
16	1.071185	477.98

The second experiment consists of testing the pipelining technique for bulk data transfers between one client and one server. As shown in Table I, on the InfiniBand cluster pipelining transfers can be particularly efficient when requests have already completed while other pipeline stages are being processed, allowing high bandwidth and avoiding paying the cost of the latency for an entire RMA transfer of 512 MB.

We also tested the pipelining technique and the scalability of the RPC server by evaluating the total data throughput while increasing the number of clients. Figures 5a and 5b show the results for a QDR InfiniBand system (using MVAPICH2) and the Cray XE6 system respectively. In both cases, in part because of the server-side bulk dataflow control mechanism, Mercury shows excellent scalability, with throughput either increasing or remaining stable as the number of concurrent clients increases. For comparison, Figure 4 shows the point-to-point message bandwidth on each system. Figure 5a also presents results without pipelining transfers. On the InfiniBand system, Mercury achieves about 98% of maximum network bandwidth. This is an excellent result, considering that the Mercury time represents an RPC call in addition to the data transfer, compared with the time to send a single message for the OSU benchmark. On the Cray system, performance is not as good (about 50% of peak). We suspect that this is due mainly to the relatively poor small message performance of the system, combined with the extra control messages caused by the one-sided emulation. Performance variation can also be caused by the anisotropic interconnect [22] of the Cray XE6, as different sets of nodes may be given between each run. A better node ordering for allocation and process placement would therefore be required in order to achieve full bandwidth; this will be the object of a future work. It is also worth noting that Nessie shows the same low bandwidth for a similar operation (read) [23], even though it is using true RDMA by bypassing MPI and using the interconnect's native uGNI API instead.

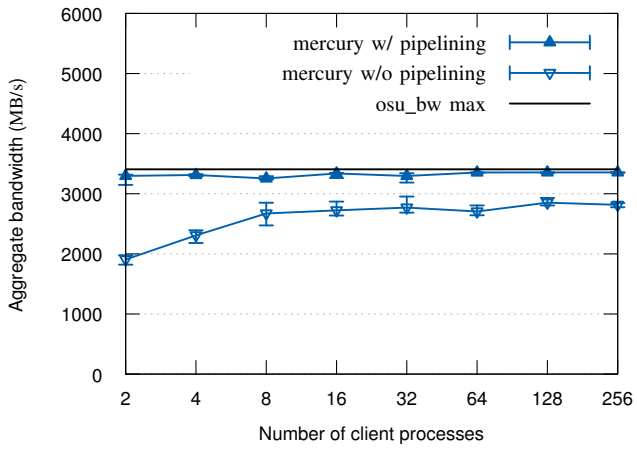
V. Conclusion and Future Work

In this paper we presented the Mercury framework. Mercury is specifically designed to offer RPC services in a high-performance computing environment. Mercury builds on a small, easily ported network abstraction layer providing operations closely matched to the capabilities of contemporary HPC network environments. Unlike most other RPC frameworks, Mercury offers direct support for handling remote calls containing large data arguments. Mercury's network protocol is designed to scale to thousands of clients. We demonstrated the power of the framework by implementing a remote *write* function including pipelining of large data arguments. We subsequently evaluated our implementation on two different HPC systems, showing both single client performance and multiclient scalability.

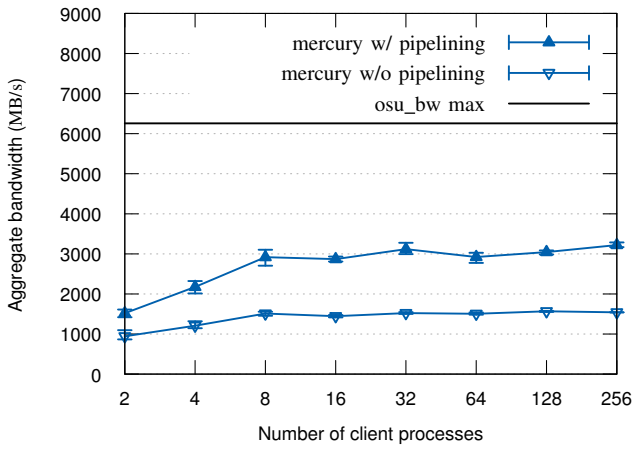
With the availability of the high-performing, portable, generic RPC functionality provided by Mercury, IOFSL can be simplifed and modernized by replacing the internal, hard-coded IOFSL code by Mercury calls. Since the network abstraction layer on top of which Mercury is built already supports using BMI for network connectivity, existing deployments of IOFSL continue to be supported, at the same time taking advantage of the improved scalability and performance of Mercury's network protocol. Currently, Mercury does not offer support for canceling ongoing RPC calls. Cancellation is important for resiliency in environments where nodes or network can fail and future work will include support for it.

While Mercury already supports all required functionality to efficiently execute RPC calls, the amount of user code required for each call can be further reduced. Future versions of Mercury will provide a set of preprocessor macros, reducing the user's effort by automatically generating as much boilerplate code as possible.

The network abstraction layer currently has plugins for BMI, MPI 2 and MPI 3. However, since MPI RMA functionality is difficult to use in a client/server context [24], we intend to add native support for InfiniBand, Cray Gemini/Aries and IBM Blue Gene/Q networks.



(a) Pipeline buffer size of 4 MB on InfiniBand cluster (MVAPICH2).



(b) Pipeline buffer size of 64 MB on Cray XE6 (Cray MPT).

Fig. 5: Aggregate bandwidth of RPC request with a 512 MB bulk data transfer.

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