Client-Server Computing on the SHRIMP Multicomputer

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Abstract

The client-server is the dominant programming model in distributed computing and has been used extensively as a structuring method for large software systems. Remote procedure call (RPC) and stream sockets form the basis of the communication system for a wide variety of distributed applications. Unfortunately advances in processor and network technology do not translate directly in performance improvements in the client-server model, mainly because of the tremendous software overhead.

However, the emergence of new network interface technology is enabling new approaches to the development of communications software.

This paper presents two implementations of RPC and one of stream sockets for the SHRIMP *multicomputer.* SHRIMP *supports protected, user-level data transfer, allows user-level code to perform its own buffer management, and separates data transfers from control transfers so that data transfers can be done without interrupting the receiving node's CPU.*

1 Introduction

The client-server paradigm has been very useful for large classes of applications. Most client-serverapplications rely on RPC or the Berkeley stream sockets model for interprocess communication. RPC provides a connection-oriented bidirectional abstraction, with well defined semantics that resemble the local procedure call semantics. Transfering data as well as control is done with a single procedure call that gets executed on a (potentially) remote system. The stream sockets interface provides a connection-oriented, bidirectional byte-stream abstraction, with well-defined mechanisms for creating and destroying connections and for detecting errors.

Technological advances in network and processor speeds do not seem to lead to equally large improvements in the performance of client-server systems. The main reason for this is that software overhead dominates communication. Thus, improvements in hardware performance do not project to user applications.

The *SHRIMP* project [?, ?, ?] at Princeton University supports user level comuunication between processes by mapping memory pages between virtual address spaces. This virtual memory-mapped network interface seems to have many advantages including flexible user-level communication, and very low overhead to initiate data transfers.

In this work we examine two implementations of RPC and sockets for the *SHRIMP* multicomputer that deliver to user applications almost raw hardware performance.

The first RPC library (*vRPC*) meets the *SunRPC* interface and achieves a round trip latency of 33 microseconds for a null call with no arguments, without compromising compatibility with the *SunRPC* standard.

Our experiments with *vRPC* show that even without changing the stub generator or the kernel, RPC can be made several times faster on the new network interface than on conventional networks. *vRPC* outperforms the best reported implementation (to our knowledge) for fast networks [?] by more than a factor of four. A null RPC round trip takes about 33 microseconds. Even greater gains could be achieved by applying well-known techniques that rely on changes to the stub generator.

The second RPC library, *ShrimpRPC*, is a full-functionality RPC system but is not compatible with any standard. *ShrimpRPC* achieves a round trip latency of 9.5 microseconds, or about one microsecond above the hardware minimum for round-trip communication.

The stream sockets library is compatible with the stream sockets interface; it properly detects broken connections and correctly implements the `select` call. The sockets library performs much better than all previous sockets implementations for small transfers, with an end-to-end latency of 11 microseconds for an 8-byte transfer. Small transfers are important because they are very common in many applications [?]. For large transfers, we obtained a bandwidth of 13.5 MBytes/sec, which is close to the hardware limit when the receiver must perform a copy.

2 *SHRIMP* Hardware

The *SHRIMP* multicomputer is a network of commodity systems. Each node is a Pentium PC running the Linux operating system. The network is a multicomputer routing network [?] connected to the PC nodes via custom-designed network interfaces. The

SHRIMP network interface closely cooperates with a thin layer of software to form a communication mechanism called virtual memory-mapped communication (VMMC) [?]. This mechanism supports various message-passing packages and applications effectively, and delivers excellent performance [?].

The network connecting the nodes is an Intel routing backplane consisting of a two-dimensional mesh of Intel Mesh Routing Chips (iMRCs) [?], and is the same network used in the Paragon multicomputer [?].

The custom network interface [?, ?] is the system's key component. It connects each PC node to the routing backplane and implements the hardware support for VMMC.

3 Virtual Memory-Mapped Communication

Virtual memory-mapped communication (VMMC) [?] was developed in response to the need for a basic multicomputer communication mechanism with extremely low latency and high bandwidth. These performance goals are achieved by allowing applications to transfer data directly between two virtual memory address spaces over the network. The basic mechanism is designed to efficiently support applications and common communication models such as message passing, shared memory, and client-server.

The VMMC mechanism consists of several calls to support user-level buffer management, various data transfer strategies, and transfer of control.

3.1 Import-Export Mappings

In the VMMC model, an *import-export mapping* must be established before communication begins. A receiving process can *export* a region of its address space as a receive buffer together with a set of permissions to define access rights for the buffer. In order to send data to an exported receive buffer, a user process must *import* the buffer with the right permissions.

After successful imports, a sender can transfer data from its virtual memory into imported receive buffers at user-level without further protection checking or protection domain crossings. Communication under this import-export mapping mechanism is protected in two ways. First, a trusted daemon process implements import and export operations. Second, the hardware virtual memory management unit (MMU) on an importing node makes sure that transferred data cannot overwrite memory outside a receive buffer.

3.2 Transfer Strategies

The VMMC model defines two user-level transfer strategies: *deliberate update* and *automatic update*. Deliberate update is an explicit transfer of data from a sender's memory to a receiver's memory.

In order to use automatic update, a sender *binds* a portion of its address space to an imported receive buffer, creating an *automatic update binding* between the local and remote memory. All writes performed to the local memory are automatically propagated to the remote memory as well, eliminating the need for an explicit send operation.

An important distinction between these two transfer strategies is that under automatic update, local memory is "bound" to a single receive buffer at the time a binding is created, while under deliberate update there is no fixed binding between a region of the sender's memory and a particular receive buffer. Automatic update is optimized for low latency, and deliberate update is designed for flexible import-export mappings and for reducing network traffic.

The VMMC model does not include any buffer management since data is transferred directly between user-level address spaces. This gives applications the freedom to utilize as little buffering and copying as needed. The model directly supports zero-copy protocols when both the send and receive buffers are known at the time of a transfer initiation.

The VMMC model assumes that receive buffer addresses are specified by the sender, and received data is transferred directly to memory. Hence, there is no explicit receive operation. CPU involvement in receiving data can be as little as checking a flag, although a hardware notification mechanism is also supported.

Figure 1 shows the latency and bandwidth delivered by the *SHRIMP* VMMC layer [?].

3.3 Notifications

The *notification* mechanism is used to transfer control to a receiving process, or to notify the receiving process about external events. It consists of a message transfer followed by an invocation of a user-specified, user-level handler function. The receiving process can associate a separate handler function with each exported buffer, and notifications only take effect when a handler has been specified.

4 The RPC Paradigm

RPC provides the user with a well understood programming model; remote procedure calls with well defined semantics that are close to the semantics of local procedure calls are the basic mechanism for communication. A software system is usually divided into servers and clients. The servers export well defined service interfaces to the clients, that can access the services with simple procedure calls. *SunRPC* is a RPC specification available in many systems. In this section we first present some background information about *SunRPC* and then describe the implementation and performance of our RPC libraries.

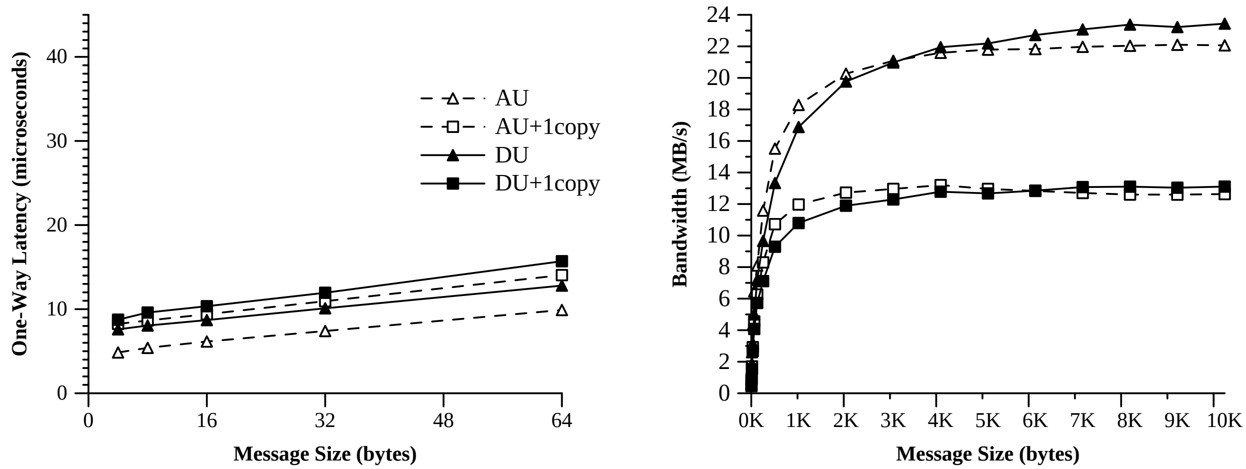


Figure 1: Latency and bandwidth delivered by the *SHRIMP* VMMC layer using automatic update (AU) and deliberate update (DU). `+1copy` indicates that the data is copied once on the receiving side.

4.1 SunRPC

SunRPC [?] is a widely used remote procedure call interface and specification. *SunRPC* consists of a set of library functions and a stub generator that follows the XDR [?] standard for data representation. *SunRPC* is a single thread implementation.

The general structure of *SunRPC* is shown in Figure 2. It is implemented as a series of layers, each providing services to the layers above.

- The *network* layer implements the `read` and `write` system calls that transfer data across the network.
- The *stream* layer does buffer management. It provides a set of functions to write data (byte strings, integers, etc.) to, or read data from, a stream. The stream layer hides the details of buffer management and network packet size from the higher layers. Its existence is very important to the performance of standard *SunRPC* implementations, since it reduces accesses to the expensive lower layers.
- The *XDR* [?] layer implements the XDR data representation specification, which insulates the higher layers from issues of machine-specific data representation. Data transferred between nodes in a network are translated to XDR format before sending, and translated back from XDR when received. The XDR layer provides a set of functions to send and receive data of a certain set of types: byte streams, longs, strings, unions etc.
- The RPC library implements most of the *SunRPC* protocol, including the management of client-server connections.
- The stub generator RPCGEN produces RPC stubs based on an interface definition supplied by the user.

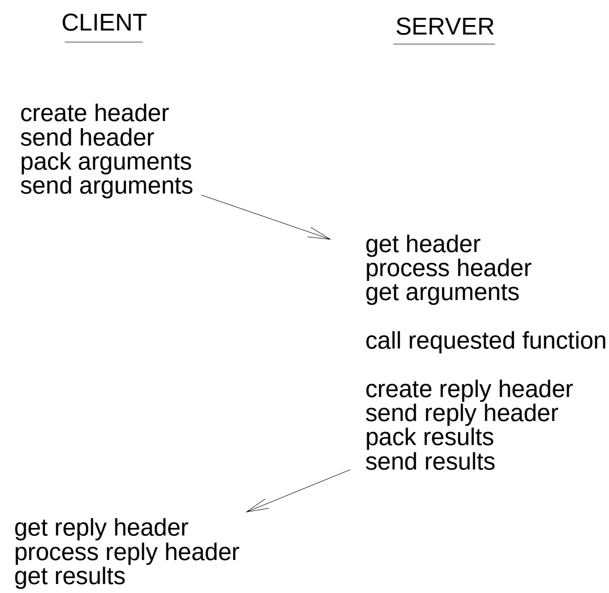


Figure 3: The common execution path in a RPC.

As Figure 2 shows, the interface below the XDR layer separates the machine-dependent code from the machine independent layers.

Figure 2 also shows where copying takes place. Data is copied from the user buffers into the stream buffers and then passed to the operating system functions. In *SunRPC* there are two copies per side per RPC call at user level, plus the copies necessary at protection boundary crossings (one or two), and potentially copies in the kernel between kernel-driver buffers. These amount to a total of at least six copies per RPC call.

Figure 3 shows the common execution path in an RPC. The client sends the header and then the data.

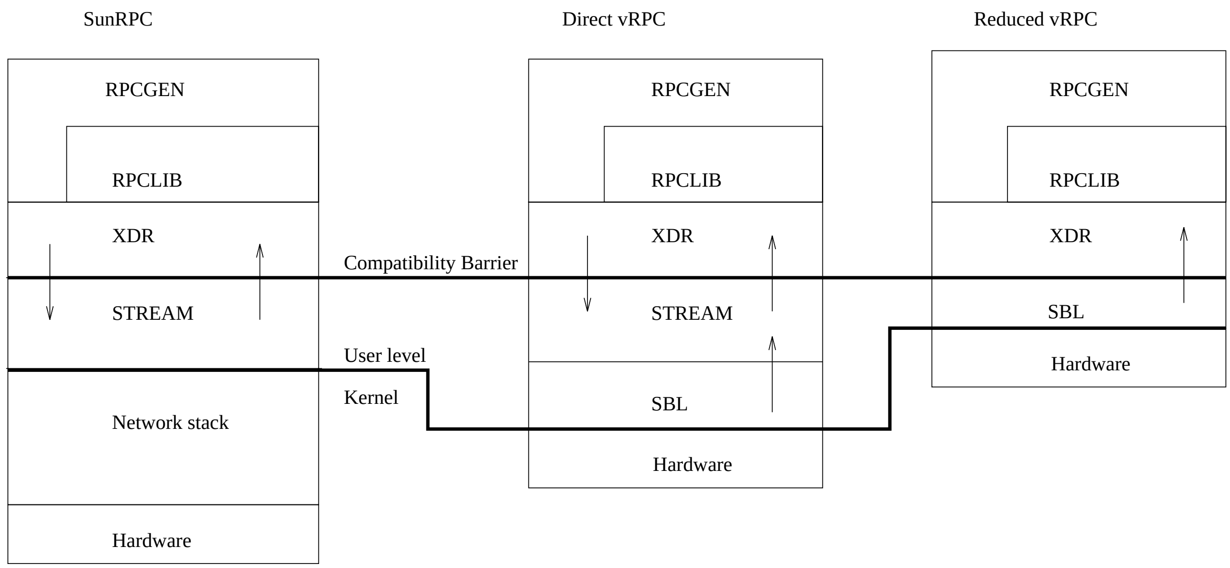


Figure 2: The structure of the different implementations. The arrows indicate the direction and number of copies at user level.

When the server replies the client receives first the header of the reply message and then the results. Because of the multiple layers, each call to XDR to send a datum results in a chain of several procedure calls.

4.2 *vRPC*

Our strategy in implementing *vRPC* on *SHRIMP* was to change as little as possible, and to remain fully compatible with existing *SunRPC* implementations. In order to meet these goals, we changed only the runtime library; we made minor changes to the stub generator[1] and we did not modify the kernel.

We used two main techniques to speed up the library. First, we re-implemented the network layer directly on top of the *SHRIMP* network interface. Because the *SHRIMP* interface is simple and allows direct user-to-user communication, our implementation of the network layer is much faster than the standard one. Our second optimization was to collapse the stream and SBL layers into a new single thin layer that provides the same functionality, thus reducing the number of layers by one.

Communication setup For *vRPC* a pair of mappings is established between every client and the server. Although creating mappings is expensive (relative to the very inexpensive communication) because exporting and importing buffers requires system calls, these operations are performed only once, during the initialization phase. In that sense RPC is a typical case of communications software where one can separate the expensive setup phase from the common case. The VMMC interface takes advantage of this.

The first version of *vRPC*, *Direct vRPC*, replaces the stream layer with a simple stream communication abstraction implemented directly on top of the VMMC interface. The are still six copies per RPC. Elimination of kernel involvement in the communication path is the only difference from *SunRPC*. Figure 2 shows the overall structure of *vRPC*.

Collapsing Layers As noted above, in standard implementations of *SunRPC*, the stream layer is needed to decouple the XDR layer from the network layer, because calls to the network layer are expensive system calls. Now that the communication is done at user level there is no need for the stream layer. In fact, as we described above, the VMMC stream layer of *Direct vRPC* implements a stream. Eliminating the stream layer of *SunRPC* leads to the second version of *vRPC*, *Reduced vRPC*, as shown in Figure 2.

Apart from considerably reducing the layering overhead, this change also eliminates two copies per node per RPC. The only copies left are the transfers of data between library and user buffers on the receiving side. This copy is essential to maintain *SunRPC* semantics.

These two improvements, eliminating the overhead of a whole layer and avoiding copying, are due to

1. the low cost of the user level communication mechanisms which makes the extra stream layer unnecessary, and

2. the direct placement of data in virtual memory.

Moreover, the fact that the client and the server run on nodes of the same multiprocessor leads to two additional improvements. There is no need for translation of the data to and from an agreed transmission

[1]We only added support for the new protocol, so that code for it is automatically generated.

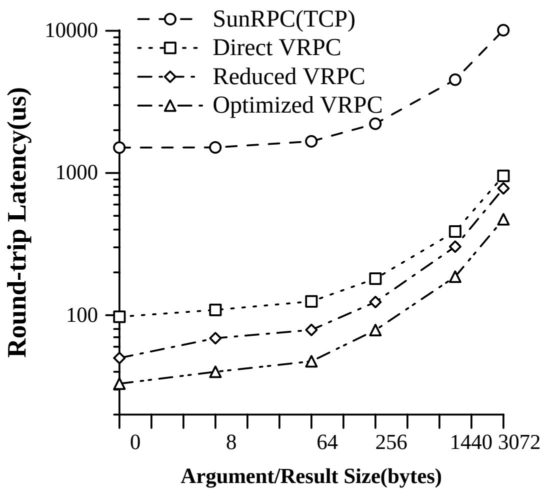


Figure 4: *SunRPC* and *vRPC* latency.

format. Also, authentication can be done once, when the *SHRIMP* connection is set up, rather than on every RPC.

Tuning *vRPC* *Reduced vRPC* is much faster than *SunRPC*, and in fact is faster than any previous RPC implementation that we are aware of. We achieved this performance by merely porting and adapting existing code to the *SHRIMP* network interface. We can improve the performance further by tuning the RPC library for the *SHRIMP* and taking advantage of the *SunRPC* semantics and implementation.

We tuned *Reduced vRPC* to take advantage of these opportunities. This resulted in the final version of *vRPC*, *Optimized vRPC*, which uses single-write automatic update to transfer control information. For transferring data both synchronous deliberate update and block-write automatic update can be used. We compare these configurations in section **??**.

4.2.1 Measurements

Our experiments compare *SunRPC* and the three versions of *vRPC*. We divide the code into sections and present timing measurements for each section of the code, for null calls with six argument/result sizes: zero bytes, 8 bytes, 64 bytes, 256 bytes, 1440 bytes and 3K bytes. We measured 1000 calls in each case, eliminated outlying points (due to experiments being interrupted by system daemon activity, etc.) and then averaged over the remaining runs. Full results appear in Appendix A of [?].

Figures 4 and 5 summarize these results. They present the time spent in the client and the server per section of a call, for the above argument/result sizes, as a percentage of the total cost of the call. The *send* and *exec* sections for the client and the server respectively, are almost negligible, as expected. *send* doesn't do much since the transfer is already initiated (automatic update) and the procedure executed in the server is a null procedure; it just sends back a reply of the same size as the arguments to the call.

4.3 *ShrimpRPC*: A Specialized Implementation

While our *vRPC* library has very good performance, its implementation was limited by the need to remain compatible with the existing *SunRPC* standard. To explore the further performance gains that are possible, we implemented a non-compatible version of remote procedure call.

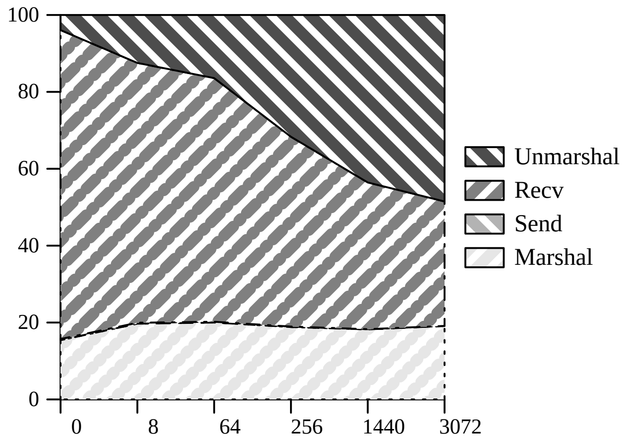
ShrimpRPC is not compatible with any existing RPC system, but it implements the full RPC functionality, with a stub generator that reads an interface definition file and generates code to marshal and unmarshal complex data types. The stub generator and runtime library were designed with *SHRIMP* in mind, so we believe they come close to the best possible RPC performance on the *SHRIMP* hardware.

Buffer Management The design of *ShrimpRPC* is similar to Bershad's URPC [?]; the main difference is that URPC runs on shared-memory machines while *ShrimpRPC* runs on the distributed-memory *SHRIMP* system. Each RPC binding consists of one receive buffer on each side (client and server) with bidirectional import-export mappings between them. When a call occurs, the client-side stub marshals the arguments into its buffer, and then transmits them into the server's buffer. At the end of the arguments is a flag which tells the server that the arguments are in place. The buffers are laid out so that the flag is in the same place for all calls that use the same binding, and so that the flag is immediately after the data. This allows both data and flag to be sent in a single data transfer.

When the server sees the flag, it calls the procedure that the client requested. At this point the arguments are still in the server's buffer. When the call is done, the server sends return values and a flag back to the sender.

Exploiting Automatic Update The structure of our *ShrimpRPC* works particularly well with automatic update. In this case, the client's buffer and the server's buffer are connected by a bidirectional automatic update binding; whenever one process writes its buffer, the written data is propagated automatically to the other process's buffer. The data layout and the structure of the client stub cause the client to fill memory locations consecutively while marshaling the arguments, so that all of the arguments and the flag can be combined into a single packet by the client-side hardware.

On the server side, return values (`OUT` and `INOUT` parameters) need no explicit marshaling. These variables are passed to the server-side procedure by reference: that is, by passing a pointer into the server's communication buffer. The result is that when the procedure writes any of its `OUT` or `INOUT`



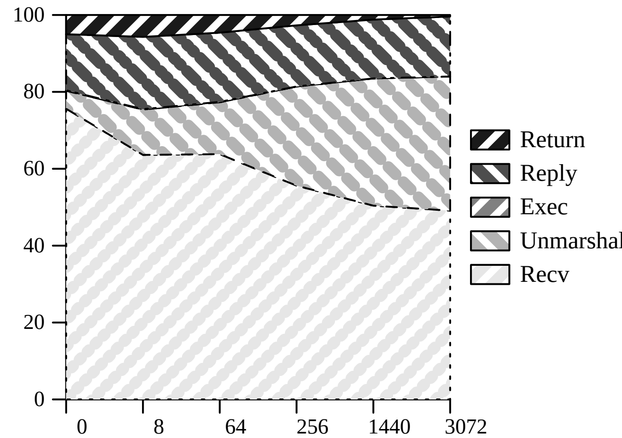


Figure 5: Distribution of the cost in the client (left) and the server (right) for *Optimized vRPC*.

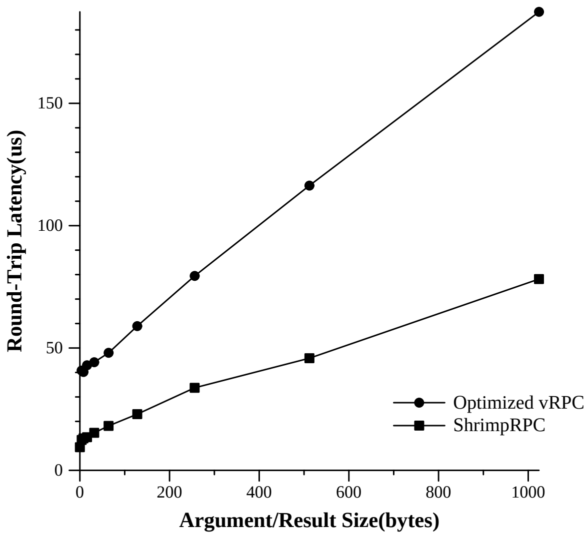


Figure 6: *Round-trip time for null RPC, with a single INOUT argument of varying size.*

parameters, the written values are silently propagated back to the client by the automatic update mechanism. This communication is overlapped with the server's computation, so in many cases it appears to have no cost at all. When the server finishes, it simply writes a flag to tell the client that it is done.

Performance Figure 6 compares the performance of two versions of RPC: the *SunRPC*-compatible VRPC, and the non-compatible *ShrimpRPC*. We show the fastest version of each library, which uses automatic update in both cases.

The difference in round-trip time is more than a factor of three for small argument sizes: 9.5 μs for the non-compatible system, and 33 μs for the *SunRPC*-compatible system. The difference arises because the *SunRPC* standard requires a nontrivial header to be sent for every RPC, while the non-compatible *ShrimpRPC* system sends just the data plus a one-word flag, all of which can be combined by the hardware into a single packet. For large transfers, the difference is roughly a factor of two. This occurs because *ShrimpRPC* does not need to explicitly send the INOUT and OUT arguments from the server back to the client; these arguments are implicitly sent, in the background, via automatic update as the server writes them.

Since the round-trip latency of a *ShrimpRPC* call is within one microsecond of the hardware minimum, we do not provide a detailed breakdown of how *ShrimpRPC* spends its time.

5 Shrimp Sockets

The *SHRIMP* socket API is implemented as a user library, using the VMMC interface. It is compatible, and seamlessly integrated with the Unix stream sockets facility [?]. A new address family, `AF_SHRIMP`, was added to support the new type of socket. The stream protocol was implemented for this new family.

We implemented three variations of the socket library, two using deliberate update and one using automatic update. The first protocol performs two copies, one on the receiver to move the data into the user memory and the other on the sender to eliminate the need to deal with data alignment. We can improve the performance by eliminating the send-side copy, leading to a one-copy protocol, although we must still use the two-copy protocol when dictated by alignment. The automatic-update protocol always does two copies, since the sender-side copy acts as the send operation.

It is not possible to build a zero-copy deliberate-update protocol or a one-copy automatic-update protocol without violating the protection requirements of the sockets model. Such a protocol would require a page of the receiver's user memory to be exported; the sender could then clobber this page at will. This is

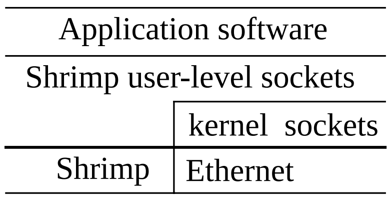


Figure 7: *Implementation Layers*

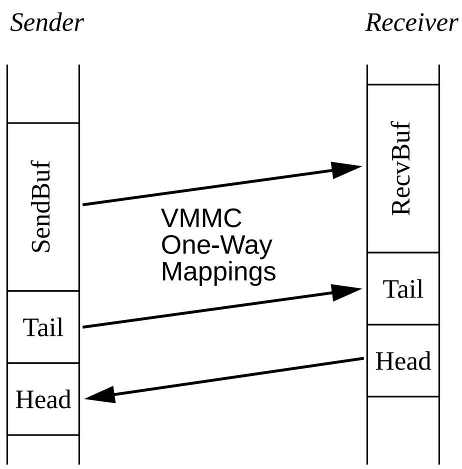


Figure 8: *Unidirectional Byte Stream*

not acceptable in the sockets model, since the receiver does not necessarily trust the sender.

Design The user-level library's socket descriptor table contains one entry for each open socket, regardless of the socket type. When non-*SHRIMP* sockets are used, our library passes calls through to the regular `libc` calls, while still keeping a descriptor table entry. Also, our library uses calls to the regular `libc` functions in order to bootstrap the *SHRIMP* connection. Figure 7 illustrates the software layers in our implementation.

Implementation This section describes the data structures used to implement *SHRIMP* sockets. We use a straightforward implementation of circular buffers in order to manage each socket's incoming and outgoing data. First, we will describe how to implement a simple unidirectional byte stream on *SHRIMP*. Then we will show how this simple structure was used as the building block for our library.

The byte stream is managed by a circular buffer that consists of a data buffer and the head and tail indices. In order to implement a simple unidirectional byte stream the sender and receiver each allocate a copy of the circular queue and cross map the three components. The buffer and tail indices are mapped from the sender to the receiver and the head index is mapped from the receiver to the sender (see Figure 8).

Figure 9 illustrates how this simple queue structure can be used to transfer bytes. The sender writes the buffer and the tail index and only reads the head index, while the receiver only reads the buffer and tail index and writes the head index. Since writes are always exclusive, race conditions are eliminated.

```
simple_send(msg)
{
   wait until buffer space is available
   copy msg into sendbuf
   transfer sendbuf data to receiver
   update tail pointer
   transfer tail pointer to receiver
}

simple_recv(buf)
{
   wait until data is available
   copy data from recvbuf to buf
   update head pointer
   transfer head pointer to sender
}
```

Figure 9: *Pseudo code for simple send and recv*

In order to construct a bidirectional byte stream we use two unidirectional byte streams described above: one for sending bytes and one for receiving bytes. There is additional complexity introduced when implementing some of the other socket functions, as well as dealing with connection establishment and byte alignment. The basic underlying implementation is simple, straightforward, and works very well with *SHRIMP*'s VMMC communication mechanism.

For each socket descriptor that specifies a *SHRIMP* socket, two data structures are maintained with data grouped based on who writes the data: incoming (from the remote process) and outgoing (to the remote process). These two structures are then used to construct the two unidirectional bytes streams described above. The size of each circular buffer is determined at compile time. All of the results in this paper use 32 kbyte buffers.

Connection Setup and Shutdown During connection establishment, the implementation uses a regular Internet socket, via Ethernet, to exchange the data required to establish two VMMC mappings (one in each direction). The Internet socket is held open, and is used to detect if the connection breaks.

When a connection is terminated (using `close`) the specified socket's descriptor table entry is freed and the associated VMMC mapping is removed.

`recv` must copy data that is in the incoming buffer to the user-specified buffer. Once it consumes the data, it updates the `head` pointer on the remote node. Each call costs one copy (or two, depending on the state of the circular buffer) and a one-word message to update the pointer. The pseudo code for `recv` is as follows:

- **check** that socket is valid/alive
- **verify** that data is available to receive, if not, wait for data to arrive
- **copy** data from socket library's circular buffer into user buffer
- **update** remote node's circular buffer start pointer (using a notification)

`send` must copy the user data into the circular buffer and initiate the transfer to the remote node. For deliberate update this requires an explicit *SHRIMP* call to initiate data transfer. Two calls are required if the data wraps around the circular buffer. When automatic update is used, copying the data into the circular buffer automatically triggers the send. Once the data is sent, another send is required to notify the remote node that new data has arrived (by updating the tail pointer). The pseudo code for `send` is as follows:

- **check** that socket is valid/alive
- **verify** that space is available for the remote node to receive data, if not spin
- **send** data from user space to remote node using *SHRIMP*. Either automatic or deliberate update can be used.
- **update** remote node's circular buffer tail pointer (using a notification)

`select` deals with both regular and *SHRIMP* sockets and thus is the most complex function in the library. It uses notifications in order to trap the arrival of new *SHRIMP* data. A null user-level notification handler is used because notifications are only needed to implement `select`.

When a buffer is exported, notifications are optionally activated, and a user-level handler is specified. Each exported buffer's notifications can be in one of three states:

- *ignore*: notifications are dropped
- *queue*: notifications blocked are queued for later delivery
- *deliver*: all queued, and any incoming, notifications are delivered

Since notifications are implemented using interrupts we do not want the common case to pay the notification processing cost. To achieve this initially all of the socket library's buffers *ignore* notifications. `select` must first *queue* notifications for the sockets in question.

The algorithm for our `select` was developed around the functionality of the standard `select`. `select` returns when I/O occurs or any signal is trapped. Since signals are used to implement notifications, they are also trapped by the standard `select`. When `select` completes it returns no indication of which, if any, notifications have occurred. This leads to the following implementation of `select`:

loop until data arrives, or timeout:

- *queue notifications*: we do not want to miss any that might occur
- *deliver notifications*: turn on notifications for the Shrimp socket data structures
- *check for new data*: check the Shrimp socket data structures to see if any data has arrived
- `select`: wait for a notification, other I/O, with a timeout. Since a notification can arrive after checking for data and before calling `select` we cannot block forever. Instead, we must a mini-timeout in tandem with the loop.
- *ignore notifications*: return notifications to the fast common case
- *check for new data*: do another check in case any data has arrived in the interim

Integration with `libc` Integrating the functions in the user level library with those already present in `libc` was straightforward. For each function implemented in our library, we renamed the corresponding function in `libc` by changing the name to all uppercase. In order to keep things simple, we did this directly in the binary object modules of `libc`. Where necessary, our library is able to call the original socket functions.

5.1 Measurements

This section describes the performance measurements we obtained using our implementation of sockets. All tests were performed on a prototype four-node *SHRIMP* system. Each node is a 60 MHz Pentium PC running Linux 1.2.8. We used `gcc` 2.6.3 with all optimizations enabled (`-O3`).

All measurements were taken for three different implementations of the socket library. The three implementations differed only in the data transfer mechanism that was used:

- **DU+1copy**: deliberate update with only one copy. The receiver moves the incoming data from the library's internal buffer to the user's buffer.
- **DU+2copy**: deliberate update with two copies. The sender copies the data from the source to the library's internal buffer and the receiver moves the incoming data from the library's internal buffer to the user's buffer.
- **AU+1copy**: automatic update with one copy. The receiver moves the incoming data from the library's internal buffer to the user's buffer. Note that the sender also does a copy from the source to the library's internal buffer but this copy is not counted because it acts as the actual data transfer.

Finally, we use the following three metrics from [?] to characterize performance:

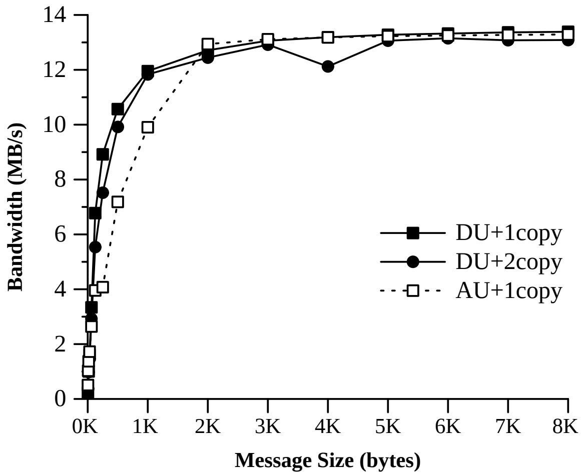


Figure 10: *Micro-benchmark socket bandwidth*

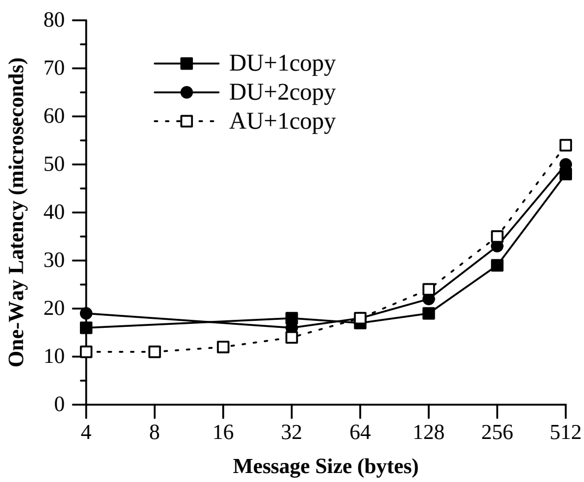


Figure 11: *Micro-benchmark socket latency*

r_∞ = peak bandwidth for infinitely large packets
$n_{\frac{1}{2}}$ = packet size to achieve $\frac{r_\infty}{2}$ bandwidth
l = one way packet latency

Micro-Benchmarks To determine the bandwidth performance of our sockets library, we measured the time required for a large number of consecutive transfers in the same direction. Figure 10 shows the results. All three implementations have similar performance. For large messages, performance is very close to the raw hardware one-copy limit of about r_∞=13.5 MBytes/sec. Further, all three of the performance curves have a steep rise indicating that peak performance is obtained quickly: $n_{\frac{1}{2}}$=256 bytes.

Figure 11 shows the latency for small transfers, measured using a ping-pong test. For small messages, we incur a one-way latency of $l = 11$ μsec, or about 7 μsec above the hardware limit. This extra time is spent equally between the sender and receiver performing procedure calls, checking for errors, and accessing the socket data structure.

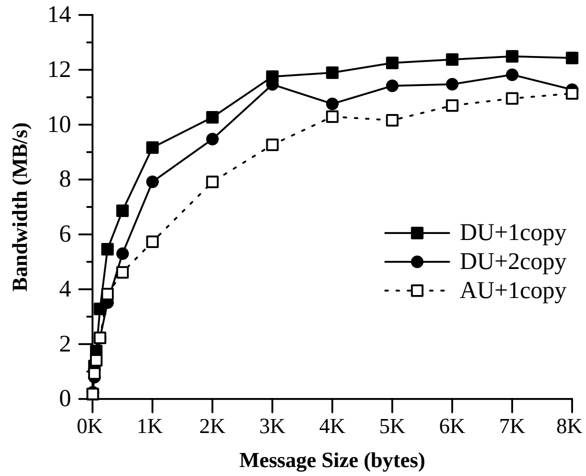


Figure 12: `Ttcp` *socket bandwidth*

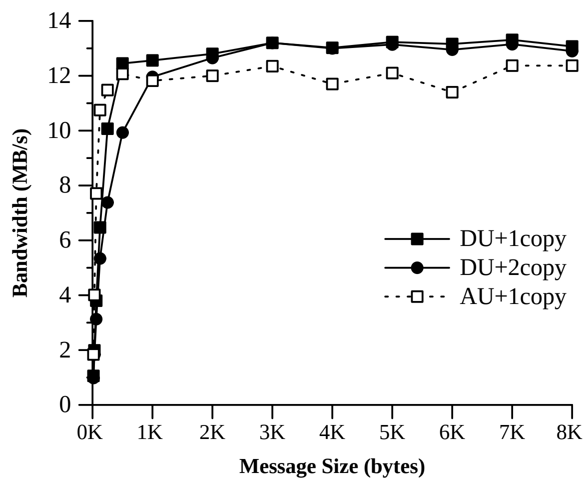


Figure 13: `Netperf` *socket bandwidth*

`Ttcp` is a public-domain benchmark originally written at the Army Ballistics Research Lab. `Ttcp` measures network performance using a one-way communication test in which the sender continuously pumps data to the receiver. The performance of our library as reported by `ttcp` is shown in Figure 12. `Ttcp` obtained a peak bandwidth of r_∞=12.4 MBytes/sec using 7 KByte messages. Once again, the bandwidth rises quickly as the message size increases: $n_{\frac{1}{2}}$=512 bytes.

`Netperf` (Revision 1.7) is another public domain benchmark developed at Hewlett-Packard. Figure 13 shows the performance of our library as reported by the TCP stream test. The peak bandwidth is about r_∞=13 MBytes/sec and $n_{\frac{1}{2}}$=256 bytes.

For more detailed performance results see [?].

6 Future Work

The sockets implementation we described does not allow open sockets to be preserved across `fork` and `exec` calls. With `fork`, the problem is arbitrating socket access between the two resulting processes. `exec` is difficult because *SHRIMP* communicates through memory and `exec` allocates a new memory space for the process. Maeda and Bershad discuss how to implement `fork` and `exec` correctly in the presence of user-level networking software [?]. We intend to follow their solution.

Moreover our sockets implementation ignores all `fcntl` calls, passing them through to the underlying kernel socket. While this behavior is correct in some cases, in others it is not. We intend to implement a better `fcntl` that handles all of the `fcntl` directives correctly.

Finally, our current sockets implementation does not support asynchronous I/O to sockets. Doing so would require a straightforward use of *SHRIMP* notifications, but we have not implemented it yet.

As mentioned above, VMMC delivers very high performance to communications libraries. However, certain aspects of the client-server model are not supported. Protection is one of these. Although each mapping is a one way communication channel between two processes, other processes could maliciously destroy data by guessing correctly certain pieces of information. This is not a problem for *vRPC* since *SunRPC* includes provision for authentication between the client and the server. In the case of stream sockets the application would have to built its own protection mechanisms. Currently we are investigating extensions to VMMC to better support the client-server model.

7 Related Work

RPC Our approach is similar in some ways to URPC [?], since both exploit user-level communication. URPC is built on top of a shared memory architecture while we use the distributed-memory *SHRIMP* architecture.

Bershad's LRPC [?] tries to optimize the kernel path for same-machine RPC calls. Since we have eliminated the kernel entirely, LRPC does not apply to our situation.

Thekkath and Levy [?] investigated the impact of recent improvements in network technology on communication software. They point out that both high throughput and low latency are required by modern distributed systems and that newer networks strive only for high throughput. They develop techniques to achieve low latency in communication software, using RPC as a case study. Their goal along with demonstrating the new techniques is to provide design guidelines for network controllers that will facilitate writing low latency communication software in traditional architectures.

Active messages [?] are a restricted form of RPC, in which the server-side procedure may not perform any actions that might block. Active messages achieve performance similar to *ShrimpRPC* on high-performance hardware, but without allowing general handlers to be invoked. The Optimistic Active Messages [?] approach allows an arbitrary handler to be invoked, using a fast-path implementation but switching to a slower path if the handler blocks. Neither of these systems provides full RPC services, such as automatic stub generation or binding between untrusting parties.

Several papers (e.g. [?, ?]) describe optimizations that dramatically improve the performance of RPC in traditional systems. This is generally done by avoiding copying, and reducing context switching overhead and network and RPC protocol overhead.

Stream Sockets Several groups have studied how to support the socket interface on experimental high-performance network interfaces.

Boden et al. [?] describe an implementation of TCP/IP on using the Myrinet API. This implementation had a minimum user-to-user latency of over 40 μsec, which is considerably larger than ours. Two factors contribute to this: first, they implemented full TCP/IP while we support the stream socket interface directly; second, their underlying hardware has a higher communication latency than ours.

To illustrate this, consider the following measurements of two custom APIs that are not compatible with sockets. Myricom's custom API using their interconnect results in a latency of 40 μsec and a peak bandwidth of 27 Mbytes/sec. Illinois Fast Messages (FM) [?] also implement a custom API using the Myrinet hardware. FM sacrifices some features available in the Myricom API and some peak bandwidth in order to reduce the small-message latency by a factor of almost two. Their one-way latency is 24 μsec while they obtain a peak bandwidth of 19.6 Mbytes/sec.

U-Net [?] describes an architecture for user-level communications which is independent of the network interface hardware. Using Sun SparcStations and Fore Systems ATM interfaces, they measured a TCP one-way latency of 78 μsec and a bandwidth of 14.4 Mbytes/sec for 4 Kbyte packets.

The x-kernel framework allows user-level implementation of a wide variety of network protocols. Experimental results for sockets on high-performance network interfaces are not yet available.

8 Conclusion

Network interfaces can have a great impact on communication performance and ease of programming. User level communication and virtual memory mapped network interfaces embody many of the optimizations done in other systems at extra work. Simply modifying an existing communication library can give results close to or better than the most highly optimized version in traditional interfaces. Copying can be limited to a minimum, and there are no interrupts on packet receipt and no kernel intervention.

The VMMC interface reduces the user to user latency. Using low latency mechanisms and providing support for user level communication leads to high performance communication software.

Our libraries are able to achieve very low latency by exploiting the features of *SHRIMP*. The freedom to use customized buffer management strategies allows us to design very efficient implementations of communication libraries. The separation of control transfer from data transfer allowed us to avoid receive-side interrupts, where this can be beneficial.

This effort shows that new architectures can open new horizons to distributed programming by providing high performance at low implementation cost.

Acknowledgments

We would like to thank Kai Li, Matt Blumrich, Liviu Iftode and the rest of the *SHRIMP* Group at Princeton for their many useful suggestions that contributed to this work.

This project is sponsored in part by ARPA under contract N00014-95-1-1144, by NSF under grant MIP-9420653, by Digital Equipment Corporation and by Intel Corporation. Felten is supported by an NSF National Young Investigator Award.