Evaluating the Performance Limitations of MPMD Communication*

Chi-Chao Chang†, Grzegorz Czajkowski†, Thorsten von Eicken†, and Carl Kesselman‡

† Department of Computer Science
Cornell University
Ithaca, NY 14853

‡ Information Sciences Institute
University of Southern California
Marina Del Rey, CA 90292

Abstract

The MPMD approach for parallel computing is attractive for programmers who seek fast development cycles, high code re-use, and modular programming, or whose applications exhibit irregular computation loads and communication patterns. Remote method invocation is widely adopted as the communication abstraction for crossing address space boundaries. However, the communication overheads of existing RMI-based systems are usually an order of magnitude higher than those found in highly tuned SPMD systems. This problem has thus far limited the appeal of high-level programming languages based on MPMD models in the parallel computing community.

This paper investigates the fundamental limitations of MPMD communication using a case study of two parallel programming languages, Compositional C++ (CC++) and Split-C, that provide support for a global name space. To establish a common comparison basis, a new implementation of CC++ was developed to use Active Messages and a native threads package. A series of micro-benchmarks compares the communication performance of this new CC++ implementation with Split-C on an IBM SP multi-computer. The impact of these costs on three applications is also evaluated and suggests that MPMD communication can be used effectively in many high-performance parallel applications.

1 Introduction

The Multiple-Program-Multiple-Data (MPMD) model is attractive yet rarely exploited in parallel applications running on distributed memory multi-computers. In contrast to the Single-Program-Multiple-Data (SPMD) model, in which a fixed number of identical programs operate on their local data and communicate with one another at well defined points in time, the MPMD model is more general. It allows multiple programs to dynamically create concurrently executing tasks that communicate with one another at any point in time. This approach is well suited for applications that exhibit irregular or unknown communication patterns, or that can benefit from a "client-server" type of setting. Software engineering is made easier due to the modularity of the code, which promotes code re-use and the ability to compose programs [4].

In its most general form, communication between different programs takes the form of one-sided remote procedure calls (RPC). In this paper, we refer to this one-sided RPC as a remote method invocation (RMI) to distinguish it from the more traditional two-sided RPC [1]. An RMI specifies the data that is to be transferred and the remote operation that is to be performed with the data. Through a simple procedure call abstraction, the data is then transferred from one address space to another and the remote operation executes on a new thread of control to assimilate the data. Traditional point-to-point communication mechanisms can be easily constructed from this basic operation. From a software-engineering point of view, RMI is a widely accepted communication abstraction for an MPMD environment [9].

In multi-computers, lower-level messaging systems such as MPI [23] and PVM [21] can be used for MPMD programming and typically achieve good performance. However, they lack the elegant abstractions provided by

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higher-level systems and require that the receiver know when to expect incoming communication, limiting the range of MPMD applications that can be expressed conveniently.

High-level MPMD languages (e.g. Mentat [12], CC++ [4], and Fortran-M [8]) and runtime systems (e.g. Nexus [10]) support some combination of dynamic task creation, load balancing, global name space, concurrency, and heterogeneity. Due to the need for crossing program domains, for asynchronously detecting incoming communication, and for potentially spawning new threads, the communication overheads in these systems are often prohibitively high for a multi-computer. As a result, systems based on an SPMD model (e.g. Split-C [7] and CRL [13]) have a significant performance advantage over MPMD-based ones and are preferred for parallel application development.

This paper investigates the feasibility of high-performance parallel computing using an MPMD model by analyzing the fundamental performance limitations in communication. This analysis is based on the implementations of two representative languages, CC++ and Split-C, running on the IBM RS/6000 SP (a.k.a. SP2). CC++ offers an MPMD programming model with RMI as the primary communication abstraction and has been used in meta-computing applications [15]. Split-C is built on Active Messages (AM) [22] and has been widely used in high-performance parallel computing research [5,16]. This work focuses on a homogeneous environment in order to isolate the inherent costs of MPMD over SPMD communication. Other factors that affect the performance of MPMD applications such as load balancing, data distribution, and heterogeneity are beyond the scope of this paper.

The original implementation of CC++ is layered on top of Nexus, a modular, highly portable runtime system that supports heterogeneous machines and networks. Because of the difficulty in distinguishing the fundamental MPMD communication overheads from those introduced by software engineering constraints, a new implementation of CC++ runtime was developed to use AM [5] and a native threads package directly. This new implementation does not modify the CC++ front-end translator or the back-end compiler and achieves a base communication performance comparable to Split-C. The impact of these costs is also evaluated on three applications written in both languages. Our observations suggest that the MPMD model is reasonable for many applications running on multi-computers especially when the software-engineering benefits outweigh the small performance gap.

This paper makes the following contributions:

- It discusses the major limitations of MPMD communication in a homogeneous, high-performance environment.
- It quantifies these limitations using a direct comparison between an MPMD language (CC++) and an SPMD one (Split-C) through a series of micro-benchmarks and three representative applications.
- It describes an efficient, lean implementation of CC++ over AM that achieves performance comparable to highly tuned SPMD languages such as Split-C on a multi-computer.

The rest of this paper is organized as follows. Section 2 gives a brief introduction to Split-C and CC++. Section 3 discusses the issues in RMI-based communication. Section 4 describes a high-performance implementation of CC++ runtime over AM, and shows how some of the issues are resolved. Section 5 describes the experimental setup used to evaluate communication in CC++. Section 6 presents the results of our experiments. Section 7 discusses related work and Section 8 concludes.

2 Split-C and CC++: SPMD versus MPMD

Split-C is a parallel extension of C that supports efficient access to global address space using global pointers. It provides a small set of global access primitives and simple parallel storage layout declarations. The compiler performs simple source-to-source transformations, converting the language extensions into runtime library calls. The global name space assumes an SPMD model: all processors execute the same program. Split-C has been ported to several distributed memory multiprocessors and is generally very efficient.

CC++ is a parallel extension of C++ designed for the development of task-parallel object-oriented programs. CC++ uses processor objects to abstract the different address spaces in an MPMD application. It provides a global name space across processor objects through global pointers, and parallel control structures that allow blocks of code to be executed concurrently. A regular C++ class can be elevated to a processor object through language extensions, making all its public methods and data accessible by other processor objects using global pointers. Processor object types can be inherited.

The key differences between these languages are:

Control and Synchronization: In Split-C, the program executing on one node is single-threaded and synchronizes with the other nodes through `barrier` calls. In CC++, new threads of control can be created using `spawn`, and control blocks can execute concurrently if annotated with the `par` and `parfor` keywords. Synchronization is achieved using write-once `sync` variables.

Global Name Space: The structure of Split-C's global name space is made visible to the programmer in that a global pointer consists of a processing node number and a local address on that node. In particular, arithmetic on the node part of the global pointer is used to access static variables on arbitrary nodes and to spread arrays across all nodes. The Split-C type system distinguishes global pointers from ordinary local ones and communication takes place automatically when a remote pointer is dereferenced. Unlike Split-C, global pointers in CC++ are opaque. The compiler front-end translates all global pointer dereferences into RMIs. Member methods of remote objects referenced by a global pointer can be invoked directly. Method invocation stubs with argument marshalling and unmarshalling code and communication calls into the runtime system are generated automatically.

Communication: Split-C uses a number of variants of the C assignment statement to access remote locations synchronously, to issue split-phase gets, puts, and one-way stores. A number of bulk-transfer primitives support the efficient transfer of contiguous memory blocks. In CC++, all communication takes place in the form of an RMI. Although there is no restriction on the number and types of arguments and of the result value that a remote method can have, CC++ programmers have to provide their own data marshalling operations for complex data structures. Bulk data transfer is attained by passing all the data as arguments to an RMI.

3 Remote Method Invocation

RMI introduces a number of issues into the communication layer that are absent from Split-C: method names must be resolved to entry point addresses, arguments must be marshaled, and multiple threads of control must be supported. In addition, the modularity and higher levels of abstraction offered by CC++ require a more local view of the interactions of communication and computation than in Split-C, which affects how the arrival of messages is detected and how atomic actions are implemented.

Method Name Resolution: A CC++ application can be composed of multiple, separately compiled program images. So the compiler and runtime system cannot determine the existence or location of a remote method statically. The mapping from the method name to its entry point address must be made at runtime, which requires either extra round-trip inquiry messages or the transmission of the name instead of its address in messages. In contrast, the Split-C runtime system handles only a single program image and assumes that remote code and data are located at the same addresses as on the local node.

Argument Marshalling: In CC++ the arguments of a remote method invocation can be arbitrary objects and each object defines its own serialization methods. Thus, in general, the compiler must invoke a method to serialize each argument into the outgoing message buffer and, on message reception, the stub must similarly invoke a method to extract each argument or the return value. This flexibility makes CC++'s RMI strictly more powerful than the global memory access primitives in Split-C, which only supports a "shallow copy" of user-defined data types. On the other hand, this flexibility incurs at least one extra copying of the data as well as the overhead of calling the serialization methods. The CC++ compiler can only inline these calls in simple cases, but in other cases (especially if inheritance is possible) a full dynamic method invocation is required. Some systems [1,18] attempt to reduce the cost of RMI by restricting the types that can be marshaled or by only supporting shallow copies of data.

Multithreading: An RMI requires that control be transferred to a new thread at the receiving end because no restrictions are placed on the operations performed in remotely invoked methods. In particular, a method may block on a lock held by the interrupted computation, requiring the latter to proceed before the former can complete. This requires that each program have multiple threads and that the reception of a message, at least logically, create a new thread. Clearly, having multiple threads has other benefits, such as providing the ability to hide the communication latency. But the effectiveness of such techniques depends on the relative costs of the thread operations (creation, context switching, and synchronization) with respect to the latency. In addition, the use of multithreading requires judicious introduction of locks into the runtime and communication layer to maintain thread-safety.

Most threaded SPMD systems [3,6] minimize the threading costs by making threads run to completion to eliminate context switches, by performing custom stack management (e.g. using stacklets [11] or spaghetti stacks), or by reducing synchronization costs through custom code generation [11]. Split-C takes an even more radical approach — offering only a single computation thread — and relies on split-phase remote accesses to tolerate latencies.

Message Reception: A critical component of the communication latency is the queuing delay incurred by messages at the receiving end before they are serviced. In an SPMD system, where communication phases can be planned globally, it is feasible to require the programmer (or the compiler) to introduce explicit `poll` operations to check for message arrival. Polling is generally very cheap and can yield low latencies if executed often enough. This approach is used in Split-C.

The more modular programming style promoted by CC++ generally favor an interrupt-driven message reception. The software interrupt generated on message arrival is propagated to the application's runtime system, which creates a new thread to handle the message. However, the overheads of the interrupt and of the kernel layers propagating it to the application are often significant, increasing the overall communication latency.

Summary: The issues discussed in the section arise due to the semantics of RMI, which allows communication to take place between different address spaces through a local procedure call abstraction. Method names need to be mapped from one address space to the other, arguments need to be passed by value, and access to local shared data as well as message dispatch need synchronization among threads. As a result, communication in MPMD systems is inherently more expensive than in SPMD ones. The following section presents a lean implementation of CC++ runtime system that allows us to quantify these inherent costs.

4 CC++ Implementation

The CC++ system consists of a front-end translator, a back-end compiler and a runtime layer. The front-end translates the CC++ extensions into pure C++ code. The back-end compiler is an off-the-shelf C++ compiler. The latest release of CC++ (version 0.4) is built on top of Nexus v3.0. Nexus is highly portable, supporting a number of architectures, communication protocols, and thread packages.

We developed a new implementation of CC++ to enable a direct comparison of the communication costs in CC++ and Split-C. The new CC++ runtime system is layered directly on top of AM and a lightweight, native, non-preemptive POSIX-compliant threads package. All modifications were performed in the runtime system and no changes were made to the front-end translator. We also wrote a small library, ThAM, which links against the CC++ runtime system and contains modules that deal with processor object startup, method name mapping, and buffer management.

	CC++ v4.0 w/Nexus		CC++ v4.0 w/ThAM	
	Nexus v3.0	CC++	ThAM	CC++
# of .C lines	39226	1936	1155	2682
# of .H lines	6552	1366	726	1346

Table 1. Source code size comparison between the old and the new CC++ runtime implementations.

Apart from the reduced code size and complexity (Table 1), we achieved performance gains by introducing the following optimizations:

Method Stub Caching: The entry point addresses for remote method stubs are resolved using a look-up into a local hash table. Each processing node maintains a table of stub addresses which is indexed by processor number and method name hash value. During runtime initialization, local method stubs are registered into the table, and remote entries are marked as invalid.

The initiator of an RMI uses the processor number (taken from the global pointer) and the method hash value to index into the table. If the entry is valid, the stub entry point address is fetched and passed to the remote node in the message. If the entry is invalid, the entire method name is passed in the message and the resolution occurs at the remote end with a message being sent back to update the local entry.

In the case of a non-threaded RMI, if the address resolution can occur at the sending node, the remote stub can be invoked directly as the active message handler. For a threaded RMI, the invocation message is always sent to a generic active message handler who creates a new thread and then calls the desired method. In the latter case, the main benefit of resolving the name on the sending side is to reduce the size of the messages.

Method stub caching effectively solves the name-mapping problem between different address spaces. This technique can be easily extended to a scenario where multiple programs execute on the same processing node by introducing the program ID as another index to the hash table.

Persistent Buffers: To reduce the marshalling overheads, send (S-) and receive buffers (R-buffers) are pre-allocated, and R-buffers for recently invoked methods are kept allocated so they can be managed by the sender. Initially, for a "cold" method invocation, arguments are marshaled into the S-buffer and transferred to a per-node static buffer area at the receiver's end. The message handler allocates a new R-buffer, copies the data from the static buffer area into the R-buffer, and marks it as attached to the method being called. The address of the R-buffer is returned with the stub table update message. Subsequent cached invocations will copy data directly into the persistent R-buffer associated with the remote method.

Polling Thread: Due to the high cost of software interrupts on message arrival on the IBM SP, message reception is based on polling that occurs on a node every time a message is sent [5]. In order to avoid deadlocks when there is no runnable thread, a polling thread is forked at initialization.

5 Experiments

The experimental setup consists of a series of CC++ and Split-C communication micro-benchmarks and three applications: EM3D, Water, and Blocked LU Decomposition[1]. The AM layer and the threads package have been heavily instrumented to account for the number, types, and sizes of message transfers as well as the number of threads, context switches, and synchronization operations. All experiments run on an IBM SP with an AIX 3.2.5 operating system. Although the languages use different back-end compilers (CC++ uses IBM C++ and Split-C uses gcc), the performance of the FP kernel in all three applications is about the same.

Micro-benchmarks: Figure 2 and Figure 3 show the micro-benchmarks used:

- Several variations on Ping-Pong to measure the round-trip time of the null RMI (calling a null method of a remote object referenced by a global pointer and waiting for its completion): *0-Word Simple* (no thread switches at the sender nor receiver), *0-Word*, *1-Word*, *2-Word* (each with a thread switch at the sender only), *0-Word Threaded* (thread switches at both sender and receiver), and *0-Word Atomic* (*0-Word Threaded* with the method executed atomically).
- Remote access to a 64-bit `double` through a global pointer (*GP Read/Write*), which consists of a RMI plus a reply message with the return value (`double`).
- Bulk transfer of an array of 20 `double`s using a CC++ RMI and Split-C bulk reads and writes (*Bulk-Read/Write*).
- Prefetching of 20 remote `double`s accessed through global pointers using `parfor` blocks in CC++ and split-phase gets in Split-C (*Prefetch*).

EM3D: is a parallel application that simulates electromagnetic wave propagation [7,17]. The main data structure is a distributed graph. Half of its nodes represent values of an electric field (E) at selected points in space, and the other corresponds to values of the magnetic field (H). The graph is bipartite: no two nodes of the same type (e.g. E or H) are adjacent. Each of the processors has the same number of nodes, and each node has the same number of neighbors. Computation consists of a sequence of identical steps: each processor updates values of its local H- and E-nodes as a weighed sum of their neighbors.

Three versions of EM3D in CC++ and Split-C are compared here by varying the percentage of adjacent nodes that are located on remote processors. Each version uses a different method to transfer data. The first version (*em3d-base*) dereferences a global pointer to a remote node each time the value is needed. Since some co-located graph nodes may share remote neighbors, introducing local ghost nodes, which represent remote graph elements can

[1] The CC++ version of these applications is heavily based on the original Split-C implementations [16] to allow for a fair comparison.

```
// Split-C definitions
double lx;
double *global gpY;
double lA[20];
void *global gpA;


// 0-Word N/A

// 1-Word N/A

// 2-Word N/A

// 0-Word Atomic RPC
atomic(foo, 0);
// GP 2-Word Read
lx = *gpY;
// GP 2-Word Write
*gpY = lx;
// Bulk Read
bulk_read(&lA,gpA,20*sizeof(double));
// Bulk Write
bulk_write(gpA,&lA,20*sizeof(double));
// Prefetch
for (i = 0; i < 20; i++)
  lx := *gpY; // split-phase
sync();
```

Figure 2. Split-C Micro-benchmarks Pseudo-Code

```
// CC++ definitions
double lx;
double *global gpY;
ARRAYOFDOUBLE lA(20);
ARRAYOFDOUBLE *global gpA;
OBJ *global gpObj;
int ly, lz;

// 0-Word RMI
gpObj->foo();
// 1-Word RMI
gpObj->foo(ly);
// 2-Word RMI
gpObj->foo(ly, lz);
// 0-Word Atomic RMI
gpObj->atomic_foo();
// GP 2-Word Read
lx = *gpY;
// GP 2-Word Write
*gpY = lx;
// Bulk Read
lA = gpObj->get(gpA);
// Bulk Write
gpObj->put(lA, gpA);
// Prefetch
parfor (i = 0; i < 20; i++)
  lx = *gpY;
```

Figure 3. CC++ Micro-benchmarks Pseudo-Code

eliminate redundant global accesses. This simple form of caching is used in *em3d-ghost*, where first the values of all ghost nodes are fetched and the main computation loop is purely local. This version can be further optimized by aggregating all ghost nodes being transferred from one processor to another. *Em3d-bulk* uses this optimization to issue bulk transfers instead of many individual fetches.

The benchmark runs shown in this paper uses a synthetic graph of 800 nodes distributed across 4 processors where each node has degree 20 for a total of 4000 edges. The fraction of edges that cross processor boundaries is varied from 10% to 100% in order to change the computation to communication ratio.

Water: is an N-body molecular dynamics application taken from the SPLASH benchmark suite [20] that computes the forces and energies of a system of water molecules. The computation iterates over a number of steps, and each of which involves computing the intra- and inter-molecular forces for molecules contained in a "cubical" box, which runs in $O(N^2)$ time. A predictor-corrector method is used to integrate motion of water molecules over time. The total potential energy is calculated as the sum of intra- and inter-molecular potentials. The main data structure is an array of molecules distributed statically across all processors. The intra-molecule interactions are computed locally, whereas the inter-molecule ones require reads and writes of remote data.

Two versions of Water written in CC++ and Split-C are compared. The base version (*water-atomic*) issues atomic reads and writes to access and update the remote molecules. The optimized version (*water-prefetch*) replaces the atomic read requests with selective prefetching, where selected data of remote molecules are bundled and fetched from their respective processors prior to local computing. Both versions are run with inputs of 64 and 512 molecules distributed over 4 processors.

Blocked LU Decomposition: implements LU factorization of a dense matrix as described in the SPLASH benchmark suite [20]. The matrix is divided into blocks distributed among processors. Every step comprises three sub-steps: first, the pivot block (I,I) is factored by its owner; second, all processors which have blocks in the I-th row or I-th column obtain the updated pivot block; third, all internal blocks are updated. All remote blocks requested in a given sub-step need to be fetched since they were modified in preceding sub-steps.

The base Split-C version (*sc-lu*) uses one-way stores for explicitly transferring pivot blocks and prefetches all blocks before beginning the third sub-step. In the CC++ version (*cc-lu*), the one-way stores and prefetches are replaced by RMIs. The input is a 512x512 matrix of `doubles` with a block size of 16x16.

6 Results

Micro-benchmarks: As seen in Table 4, the round-trip time of a *0-Word Simple* is only 12 µs slower than the base round-trip time of the AM layer, and 21 µs faster than IBM MPL. Other variations of the null RMI scale according to the number of thread operations involved. Due to method stub caching, the method lookup cost is about 3 µs and is accounted for in *CC++ Runtime* overhead.

Although the marshalling of basic types introduces a negligible cost in the *CC++ Runtime*, the data is sent using AM bulk transfer primitives, which incurs an additional 15 µsecs overhead (as seen in *1-Word*, *2-Word*). This overhead is avoided in *GP Read/Write* since accesses to simple data types through global pointers are optimized using small request/reply active messages.

The cost of marshalling becomes significant for the array of 20 doubles. Bulk reads cost more than bulk writes in CC++ because the return data has to be copied twice: once from the static buffer to the receive buffer, and again from the receive buffer to the CC++ object. This cost would be eliminated if the initiator of a bulk read passed an R-buffer address where the return value would be stored. The prefetching benchmark shows that the overhead of thread management reduces the effectiveness of latency hiding substantially.

EM3D: Figure 5 shows the per-edge EM3D performance broken down into a *CPU* component, a *net* component, a *thread mgmt* component for thread creations and context switches, a *thread sync* component for locks and signals, and a *CC++ runtime* component for argument marshalling, method name lookup, and other runtime overheads.

The EM3D performance of CC++ is competitive with Split-C for each of the versions. In *em3d-base*, the big difference between CC++ and Split-C for low remote edge percentages is due to the overhead of accesses to local data through global pointers. As the percentage of remote edges increases, the relative performance of CC++ converges to about a factor of 2 of Split-C. In *em3d-ghost*, the number of global accesses is much smaller than in *em3d-base* and the relative performance converges quickly to 2.5 as the number of remote edge increases. Even though bulk transfers require an additional copy in CC++, no significant performance difference is observed in *em3d-bulk*. This is because the total number of bytes transferred per edge is very small (about 5 bytes). To really

Benchmarks	*CC++*							*Split-C*		
			Threads							
	Total (us)	*AM (us)*	*Time (us)*	*Yield*	*Create*	*Sync*	*Runtime (us)*	*Time (us)*	*AM (us)*	*Runtime (us)*
0-Word Simple	67	55	4	0	0	10	8	-	-	-
0-Word	77	55	12	1	0	15	10	-	-	-
1-Word	94	70	12	1	0	15	12	-	-	-
2-Word	95	70	12	1	0	15	13	-	-	-
0-Word Threaded	87	55	21	2	1	10	11	-	-	-
0-Word Atomic	88	55	21	2	1	14	12	56	53	3
GP 2-Word R/W	92	55	21	2	1	10	16	57	53	4
BulkWrite 40-Word	154	70	21	2	1	10	63	74	70	4
BulkRead 40-Word	177	70	21	2	1	10	86	75	70	5
Prefetch 20-Word	35.4	5.3	21	2	1	10	9.1	12.1	6.2	5.9

Table 4. Micro-benchmark results. The *Total* time reported for each test was obtained by averaging over 10000 iterations. In CC++, *Total* is the sum of the messaging layer (*AM*), the *Threads Time*, and the *Runtime*. In Split-C, it is just *AM* plus *Runtime*. *Threads Time* is estimated by multiplying the number of thread calls per iteration with their respective costs (4.6 µsecs for thread creation, 5.8 µsecs for a context switch, and 0.4 µsecs for a lock, unlock, or condition variable signal call). The round-trip latency of IBM's native MPL under AIX 3.2.5 is 88 µs.

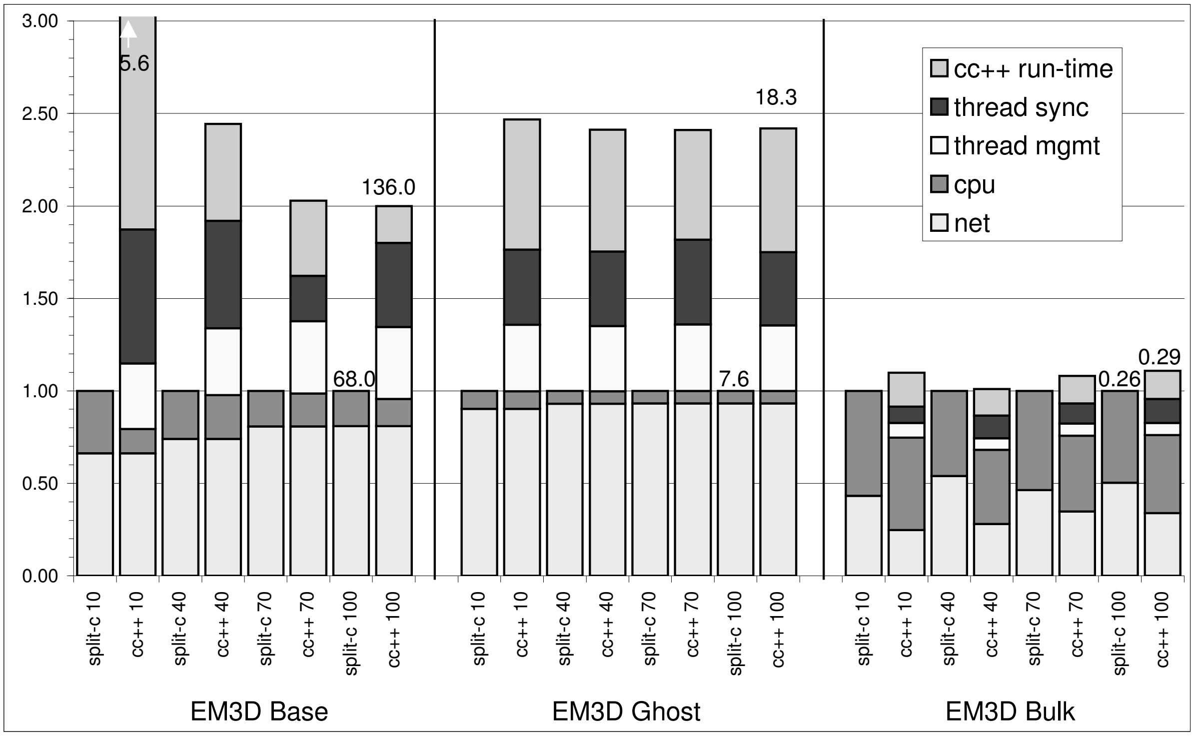

Figure 5. Breakdown of EM3D per-edge execution times for 10%, 40%, 70%, and 100% of remote edges, normalized against Split-C. The absolute execution time (in seconds) for 100% of remote edges is indicated above the respective bars.

observe a significant hit, the problem size has to be increased by a factor of about 200.

It is important to notice that the optimizations used in all three versions of EM3D benefit Split-C and CC++ equally. For 100% remote edges, *em3d-ghost* reduces the execution time of *em3d-base* by 87-89%, and *em3d-bulk* reduces that of *em3d-ghost* by more than 95% for both languages.

Water: Figure 6 shows the performance of the main computation loop in Water. *Water-atomic* uses small messages to read from and write to the remote molecules. The performance gap between CC++ and Split-C is 2.6 for 64 molecules and 5.6 for 512 molecules. The number of remote accesses in CC++ increases quadratically with the input size, increasing its runtime overhead and degrading its relative performance. *Water-atomic* can be further optimized by replacing the atomic read requests with selective prefetching (*water-prefetch*). This technique causes a 10-fold reduction in remote accesses and thus yields in both Split-C and CC++ a 60% improvement for 64 molecules. However, for 512 molecules, CC++ improves by 51% compared to Split-C's 22%, closing the performance gap to 3.5. The impact of this optimization is larger in CC++ because of higher communication latencies. CC++ *runtime* accounts for about 50-60% of the gap, a great deal of which is due to data marshalling.

LU: The performance gap of 3.6 between CC++ and Split-C is mainly due to the extra data copying during matrix block transfers (about 20% of the gap) and to the intense synchronization (about 32%). The *net* time in *cc-lu* is about 2 times higher than in *sc-lu*, because of higher remote access latencies. As a result, polling occurs more frequently, increasing the amount of *thread sync*.

Comparison with CC++/Nexus: Additional measurements with the same set of applications compiled with CC++/Nexus[2] show that the CC++/ThAM yields improvements of 5 to 35-fold over CC++/Nexus. In compute-bound applications (*water-atomic/prefetch* with 512 molecules and *cc-lu*), the performance gap between CC++/ThAM and CC++/Nexus is about 5x to 6x. In applications with higher communication to computation ratios,

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[2] The CC++ compiler v0.4 with Nexus v3.0 is configured with the TCP/IP communication protocol running over the SP2 high-performance switch. Due to technical problems, we have been unable to configure the compiler to use IBM MPL.

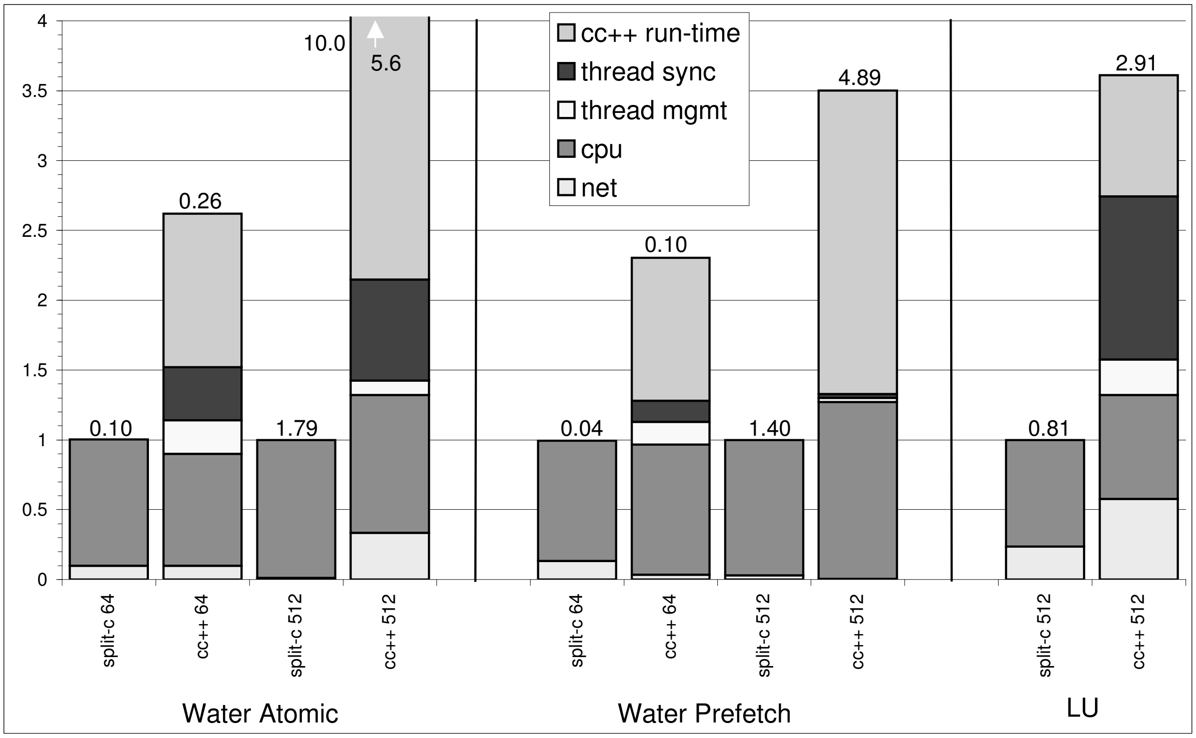

Figure 6. Breakdown of Water and LU absolute execution times (printed on top of each bar, in seconds), normalized against Split-C.

the gap is about 16x to 22x in *water-atomic/prefetch* (with 64 molecules), 10x in *em3d-bulk*, 29x in *em3d-ghost*, and 35x in *em3d-base* (all with 100% remote edges).

Discussion: The micro-benchmark results demonstrate that the basic MPMD communication in CC++ is competitive with Split-C as well as other messaging layers. The remaining overheads appear to be fundamental to the MPMD model. CC++ applications perform within a factor of 2 to 6 of Split-C.

CC++ pays a substantial price for supporting multiple threads. Synchronization incurs a significant amount of overhead: from 14% (of the performance gap) in *water-atomic* and 19% in *em3d-ghost* to as high as 32% in *cc-lu*. 98-99% of this overhead is to ensure consistency of shared data and thread-safety in the runtime and communication layers. This is exacerbated by the observation that about 95% of lock acquisitions are contention-less. The cost of thread management is acceptable (between 10-15% in CC++ applications), but can be prohibitively high if a more heavyweight or preemptive threads package is used. 75-85% of this cost is due to context switches, a large fraction of which can be attributed to the polling thread. This overhead may be alleviated in the future by reducing the cost of software interrupts, which eliminates the need for the polling thread.

The overhead of method name translation is negligible in the CC++ *runtime* due to the stub caching. Data copying overheads are only substantial when large amounts of data are transferred, as in LU, and when the communication to computation ratio is high, as in Water. Finally, the same optimization techniques used in Split-C benefit CC++ equally well, as demonstrated in EM3D and Water.

7 Related Work

As far as we know, this is the first study that compares and evaluates the performance of MPMD communication with respect to SPMD on a multi-computer. Previous research on MPMD systems [10,12] usually emphasizes other aspects such as portability, flexibility, and heterogeneity, making it difficult to identify the fundamental overheads. Moreover, such systems are usually evaluated in isolation.

A key performance aspect in the MPMD model is the efficient integration of communication and threads. The simplest form of single-threaded remote method invocation was introduced by Active Messages [22]. Optimistic Active Messages (OAM) [24] augments AM with threads, removing some of the restrictions in AM handlers. To implement a fast RPC, OAM optimistically executes the handler code on the stack — the handler is aborted and re-started on a separate thread if it blocks. But OAM assumes an SPMD model and does not specifically address the communication bottlenecks when that assumption is no longer valid. Nexus also provides a framework for integrating threads with communication [10], but does not investigate the performance impact in applications.

Other research [11,19] has contributed sophisticated runtime techniques that reduce the overall cost of RMI on multi-computers. Most of this research was done in the context of specialized languages (ABCL/f [25] and CA [14]) with intensive back-end compiler modifications. We base our findings in languages that are extensions of C and C++ and that are implemented on commodity runtime packages like AM and threads without making any modifications to the compiler.

8 Conclusion

This paper investigates the feasibility of high-performance MPMD parallel computing by analyzing the performance limitations of the MPMD communication paradigm. The analysis is based on a direct comparison of between an MPMD language (CC++) and an SPMD one (Split-C) running on an IBM SP multi-computer. The runtime systems of both languages are built on AM in order to isolate the fundamental communication costs of the models from those generated by software-engineering constraints.

Results show that basic remote data access operations in CC++ can be optimized to within a factor of 2 from Split-C and native messaging layers. As a result, our CC++ applications perform within a factor of 2 to 6 from Split-C, and with an order of magnitude improvement over previous CC++ implementations. In general, a large fraction of the remaining gap is due to thread synchronization (15-30%), which is necessary for maintaining thread-safe communication in CC++, and to data marshalling (20-40%), especially when the communication to computation ratio is high. Thread management operations such as creation and context switching account for less than 15% of the gap. Finally, optimization techniques such as selective prefetching and caching used in Split-C can be easily introduced in CC++ and benefit CC++ applications equally.

This work suggests that the MPMD model is reasonable for high-performance applications running on multi-computers. In many cases, the software-engineering benefits such as modularity and program composition outweigh the performance gap.

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