An MPI Prototype for Compiled Communication on Ethernet Switched Clusters*

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Abstract

Compiled communication has recently been proposed to improve communication performance for clusters of workstations. The idea of compiled communication is to apply more aggressive optimizations to communications whose information is known at compile time. Existing MPI libraries do not support compiled communication. In this paper, we present an MPI prototype, *CC–MPI*, that supports compiled communication on Ethernet switched clusters. The unique feature of *CC–MPI* is that it allows the user to manage network resources such as multicast groups directly and to optimize communications based on the availability of the communication information. *CC–MPI* optimizes one–to–all, one–to–many, all–to–all, and many–to–many collective communication routines using the compiled communication technique. We describe the techniques used in *CC–MPI* and report its performance. The results show that communication performance of Ethernet switched clusters can be significantly improved through compiled communication.

Keywords: Communication Optimization, MPI, Clusters of Workstations, Compiled Communication, Collective Communication

1 Introduction

As microprocessors become more and more powerful, cluster of workstations has become one of the most common high performance computing environments. Many institutions have Ethernet–switched clusters of workstations that can be used to perform high performance computing. One of the key building blocks for such systems is a message passing library. Standard message passing libraries, including MPI [8] and PVM [19], have been developed. Current implementations, such as MPICH [9] and LAM/MPI [22], focus on moving data across processors and addressing portability issues. Studies have shown that current implementations of message passing libraries are not tailored to achieve high communication performance over clusters of workstations [4].

Compiled communication has recently been proposed to improve communication performance for clusters of workstations [25, 27]. In compiled communication, the compiler determines the communication requirement of a

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program. The compiler then uses its knowledge of the application communications, together with its knowledge of the network architecture, to directly manage network resources, schedule the communications, and exploit optimization opportunities. Compiled communication is more aggressive than traditional communication optimization methods, which are performed either in the library or in the compiler. Depending on the resources that the compiler has accesses, compiled communication can potentially perform optimizations across communication patterns at the software level, the protocol level, and even the hardware level.

To facilitate compiled communication, mechanisms must be incorporated in the communication library to expose network resources to the users. Existing messaging libraries, including MPICH [9] and LAM/MPI [22], hide network details from the user and do not support compiled communication. In this paper, we introduce an MPI prototype, *CC–MPI*, that serves as a run-time system for compiled communication on Ethernet switched clusters. Since the targeted users of *CC–MPI* are compilers and advanced programmers who know system details, we will use the terms user, compiler, and advanced programmer interchangeably throughout this paper.

CC–MPI optimizes one–to–all, one–to–many, all–to–all, and many–to–many collective communication routines through compiled communication by separating network control from data transmission. For each communication routine, zero, one or more network control routines and one or more data transmission routines are supported in the library. Depending on the information available to the user, different combinations of network control and data transmission routines can be used for a communication to achieve optimal performance. *CC–MPI* allows the user to directly manage network resources, amortize the network control overhead over a number of communications, and use more efficient methods for static communications when more information about the communication is known.

A number of factors enable *CC–MPI* to achieve high communication performance. First, *CC–MPI* uses different methods for each type of communication. Each method does not have to be effective for *all* situations. It only needs to be effective in some cases since *CC–MPI* relies on its user to select the best method for a communication. This gives *CC–MPI* more flexibility in using customized communication methods. Second, some communication routines in *CC–MPI* make more assumptions about the communications to be performed than the general-case routines. With these assumptions, more effective communication routines are developed. Although such routines are not general, they provide high performance when applicable. Notice that *CC–MPI* only provides mechanisms for compiled communication, the compiler needs to exploit these mechanisms to achieve efficient communications.

We describe the techniques used in *CC–MPI* and report our performance study of *CC–MPI*. The results of our study indicates that the communication performance of Ethernet switched clusters can be improved substantially through compiled communication. For example, on 16 nodes, *CC–MPI* speeds up the IS benchmark (class A), a

program from the NAS suite [20], by 54% over LAM/MPI and 286% over MPICH.

The rest of the paper is organized as follows. The related work is presented in Section 2. In Section 3, we discuss features in switched Ethernet that affect the method for efficient communication. In Section 4, we present the techniques used in *CC–MPI*. In Section 5, we report the results of the performance study. Finally, Section 6 concludes the paper.

2 Related Work

Extensive research has been conducted to improve communication performance in high performance computing systems. Many projects have focused on reducing the communication overheads in the software messaging layer [5, 24]. Many parallel compiler projects also try to improve communication performance by generating efficient communication code [1]. Optimizations with compiled communication are more aggressive by integrating the compiler and library approaches.

The development of *CC–MPI* is motivated by compiled communication [2, 3, 14, 25, 26, 27] and the need to support architecture-dependent communication optimization [11] at the library level. While it has been found that information about most communications in scientific programs and in particular MPI programs can be determined at compile time [7, 15], existing standard libraries, such as MPI [8] and PVM [19], do not support any mechanisms to exploit such information. *CC–MPI* is an attempt to extend the standard MPI library to support the compiled communication model and to allow the user to perform architecture-dependent communication optimization across communication patterns.

The success of the MPI standard can be attributed to the wide availability of two MPI implementations: MPICH[9] and LAM/MPI [22]. Many researchers have been trying to optimize the MPI library [13, 17, 21, 23]. In [13], optimizations are proposed for collective communications over Wide-Area Networks. In [21], a compiler based optimization approach is developed to reduce the software overheads in the library, which focuses on point–to–point communications. In [17], MPI point–to–point communication routines are optimized using a more efficient primitive (Fast Message). Optimizations for a thread-based MPI implementation are proposed in [23]. Our research is different from the existing work in that we develop an MPI library that allows static communication information to be exploited.

3 Switched Ethernet

CC–MPI is designed for Ethernet switched homogeneous clusters. We assume that TCP/IP protocols are running on the end hosts and IP multicast can be used through the UDP interface. To achieve optimal performance,

CC–MPI exploits the following features in switched Ethernet. First, switched Ethernet supports broadcast at the hardware level, which indicates that using multicast primitives to realize broadcast types of routines, including *MPI_Bcast*, *MPI_Scatter*, and *MPI_Scatterv*, will likely result in good communication performance. Second, Ethernet switches support unicast traffic effectively when there is no network contention in the system. Third, multicast traffic in switched Ethernet negatively affects unicast traffic. Multicast should be used with great caution in Ethernet switched clusters. Fourth, the machines are close to each other in an Ethernet switched network and the communication propagation delay is small. Also, the transmission error rate is very low in an Ethernet switched network.

One major limitation when compiled communication is applied to Ethernet switched clusters is that the heavy weight TCP/IP protocol is used as the underlying transport layer protocol. This means that send and receive operations are expensive due to the overheads of system calls. As a result, most of our techniques are developed for communications with large messages when data transmission time is significant in comparison to the overall communication time (data transmission time plus communication overheads in end nodes).

4 CC-MPI

CC–MPI optimizes one–to–all, one–to–many, all–to–all, and many–to–many communications through compiled communication. To present the techniques used in *CC–MPI*, we will use *MPI_Bcast* to illustrate how we implement one–to–all communication, *MPI_Scatter* for one–to–all personalized communication, *MPI_Scatterv* for one–to–many personalized communication, *MPI_Alltoall* for all–to–all communication, and *MPI_Alltoallv* for many–to–many communication. In this section, we will first describe techniques used in one–to–all and one–to–many communications, including issues related to multicast. We will then discuss all–to–all and many–to–many communications, including our use of *phased* communication [12] to avoid network contention.

4.1 One–to–all and One–to–many Communications

MPI_Bcast, *MPI_Scatter*, and *MPI_Scatterv* realize one–to–all and one–to–many communications. These routines are traditionally implemented using unicast primitives with a logical tree structure [9, 22]. In addition to unicast based implementations, *CC–MPI* also provides implementations using multicast. Multicast based implementations can potentially achieve higher communication performance than a unicast based implementation because multicast reduces both the message traffic over the network and the CPU processing at the end hosts and because Ethernet supports broadcast at the hardware level.

There are two issues to be addressed when using multicast: reliability and group management. The TCP/IP protocol suite only supports unreliable IP multicast through the UDP interface. MPI, however, requires 100%

reliability. Thus, reliable multicast primitives must be implemented over the standard IP multicast to facilitate the use of multicast. *CC–MPI* uses an ACK-based reliable multicast protocol [16] to reliably deliver multicast messages. We adopt this protocol for its simplicity. Group management is another issue to be addressed in a multicast-based implementation. Basically, a multicast group must be created before any multicast message can be sent to that group. A group management scheme determines when to create/destroy a multicast group. Given a set of N processes, the number of potential groups is 2^N. Thus, it is impractical to establish all potential groups for a program, and group management must be performed as the program executes. In fact, most network interface cards limit the number of multicast groups; as an example, Ethernet cards allow only 20 such groups simultaneously. Because the group management operations require the coordination of all members in the group and are expensive, the ability to manage multicast groups effectively is crucial for a multicast-based implementation. *CC–MPI* supports three group management schemes: the *static* group management scheme, the *dynamic* group management scheme, and the *compiler–assisted* group management scheme.

Static group management scheme. In this scheme, a multicast group is associated with each communicator. The group is created/destroyed when the communicator is created/destroyed. Because a communicator is usually used by multiple communications in a program, the static group management scheme amortizes the group management overheads and makes the group management overhead negligible. This scheme is ideal for one–to–all communications, such as *MPI_Bcast*. Using the static group management scheme, *MPI_Bcast* can be implemented by having the root (sender) send a reliable broadcast message to the group.

A multicast based *MPI_Scatter* is a little more complicated. In the scatter operation, different messages are sent to different receivers. To utilize the multicast mechanism, the messages for different receivers must be aggregated to send to all receivers. For example, if messages $m1$, $m2$ and $m3$ are to be sent to processes $p1$, $p2$ and $p3$, the aggregate message containing $m1$, $m2$ and $m3$ will be sent to all three processes as one multicast message. Once a process receives the aggregated multicast message, it can identify its portion of the message (because the message sizes to all receivers are the same and are known at all nodes assuming a correct MPI program) and copy the portion to user space. In comparison to the unicast based *MPI_Scatter*, where the sender loops through the receivers sending a unicast message to each of the receivers, the multicast based implementation increases the CPU processing in each receiver because each receiver must now process a larger aggregated message, but decreases the CPU processing in the root (sender), as fewer system calls are needed. Because the bottleneck of the unicast implementation of *MPI_Scatter* is at the sender side, it is expected that the multicast based implementation offers better performance when the aggregated message size is not very large. When the size of the aggregated message is too large, the multicast based implementation may perform worse than the unicast based implementation because it slows down the receivers.

Realizing *MPI_Scatterv* is similar to realizing *MPI_Scatter*, with some complications. In *MPI_Scatterv*, different receivers can receive different sized messages and each receiver only knows its own message size. While the sender can still aggregate all unicast messages into one large multicast message, the receivers do not have enough information to determine the layout and the size of the aggregated message. *CC–MPI* resolves this problem by using two broadcasts in this function. The first broadcast tells all processes in the communicator the amount of data that each process will receive. Based on this information, each process can compute the memory layout and the size of the aggregated message. The second broadcast sends the aggregate message. Notice that it is difficult (although possible) to perform broadcast with an unknown message size. As a result, *MPI_Scatterv* is implemented with two *MPI_Bcast* calls. *MPI_Scatterv* can realize one–to–many communication by having some receivers not receive any data. Using the static group management scheme, the one–to–many communication is converted into an one–to–all communication because all processes in the communicator must receive the aggregated message. This is undesirable because it keeps the processes that are not interested in the communication busy. In addition, this implementation sends a reliable multicast message to a group that is larger than needed, which can affect the performance of the reliable multicast communication. The dynamic group management scheme and the compiler–assisted group management scheme overcome this problem.

Dynamic group management scheme. In this scheme, a multicast group is created when needed. This group management scheme is built on top of the static group management scheme in an attempt to improve the performance for one–to–many communications. To effectively realize one–to–many communication, the dynamic group management scheme dynamically creates a multicast group, performs the communication with only the intended participants, and destroys the group. In *MPI_Scatterv*, only the sender (root) has the information about the group of receivers (each receiver only knows whether it is in the group, but not whether other nodes are in the group). To dynamically create the group, a broadcast is performed using the static group associated with the communicator. This informs all members in the communicator of the nodes that should be in the new group. After this broadcast, a new group can be formed and the uninterested processes that are not in the new group can move on. After the communication is performed within the new group, the group is destroyed. With the dynamic group management scheme, *MPI_Scatterv* performs three tasks: new group creation (all nodes must be involved), data transmission (only members in the new group are involved), and group destruction (only members in the new group are involved). Dynamic group management introduces group management overheads for each communication and may not be efficient for sending small messages.

Compiler–assisted group management scheme. In this scheme, we extend the MPI interface to allow users to directly manage the multicast groups. For *MPI_Scatterv*, *CC–MPI* provides three functions: *MPI_Scatterv_open_group*, *MPI_Scatterv_data_movement*, and *MPI_Scatterv_close_group*. *MPI_Scatterv_open_group* creates a new group for

the participating processes in a one–to–many communication and initializes related data structures. *MPI_Scatterv_close_group* destroys the group created. *MPI_Scatterv_data_movement* performs the data movement assuming that the group has been created and that the related information about the communication is known to all participated parties. Notice that *MPI_Scatterv_data_movement* requires less work than *MPI_Scatterv* with the static group management scheme. This is because the message size for each process is known to all processes when *MPI_Scatterv_data_movement* is called, so only one broadcast (as opposed to two) is needed in *MPI_Scatterv_data_movement* for sending the aggregate message.

```
(1)  DO i = 1, 1000
(2)      MPI_Scatterv(....)
```

(a) An example program

```
(1)  MPI_Scatterv_open_group(...)
(2)  DO i = 1, 1000
(3)      MPI_Scatterv_data_movement(....)
(4)  MPI_Scatterv_close_group(...)
```

(b) The compiler–assisted group management scheme

Figure 1: An example of compiler–assisted group management.

The *MPI_Bcast*, *MPI_Scatter*, and *MPI_Scatterv* with the static group management scheme are implemented as data transmission routines in *CC–MPI*. *MPI_Scatterv* with dynamic group management and *MPI_Scatterv_data_movement* are also data transmission routines. On the other hand, *MPI_Scatterv_open_group* and *MPI_Scatterv_close_group* are network control routines for *MPI_Scatterv*. Note that when compiled communication is applied, network control routines can sometimes be moved, merged, and eliminated to perform optimizations across communication patterns. The data transmission routines generally have to be invoked to carry out actual communications. Consider the example in Figure 1 (a), where *MPI_Scatterv* is performed 1000 times within a loop. Let us assume that the *MPI_Scatterv* sends to 5 nodes within a communicator that contains 30 nodes. When static group management is used, all 30 nodes must participate in the communication. When dynamic group management is used, only the 5 nodes will participate in the communication, which may improve reliable multicast performance. However, a multicast group that contains the 5 nodes in the communication must be created/destroyed 1000 times. With compiled communication, if the compiler can determine that the group used by the *MPI_Scatterv* is the same for all its invocations, it can perform group management as shown in Figure 1 (b). In this case, only 5 nodes are involved in the communication, and the multicast group is created/destroyed only once. This example demonstrates that by using separate routines for network control (group management) and data transmission, *CC–MPI* allows the user to directly manage the multicast groups and to amortize network control overheads over multiple communications. In addition, *CC–MPI* also allows more efficient data transmission routines to be

used when more information about a communication is known.

4.2 All–to–all and Many–to–many Communications

MPI_Alltoall, *MPI_Alltoallv*, and *MPI_Allgather* realize all–to–all and many–to–many communications. There are many variations in the implementation of these routines. One scheme is to implement these complex all-to–all and many-to-many communication patterns over simpler one-to-all and one-to-many collective communication routines. For example, for N nodes, *MPI_Allgather* can be decomposed into N *MPI_Bcast* operations. While multicast can obviously improve communication performance for one–to–all and one–to–many communications, it may not improve the performance for the more complex many–to–many communications on Ethernet switched clusters. Consider realizing a many-to-many communication where s_1, s_2, and s_3 each sends a message of the same size to d_1, d_2, and d_3. This communication can be realized with three multicast phases: Phase 1: $\{s_1 \rightarrow d_1, d_2, d_3\}$, Phase 2: $\{s_2 \rightarrow d_1, d_2, d_3\}$, and Phase 3: $\{s_3 \rightarrow d_1, d_2, d_3\}$. This communication can also be realized with three unicast phases: Phase 1: $\{s_1 \rightarrow d_1, s_2 \rightarrow d_2, s_3 \rightarrow d_3\}$, Phase 2: $\{s_1 \rightarrow d_2, s_2 \rightarrow d_3, s_3 \rightarrow d_1\}$, and Phase 3: $\{s_1 \rightarrow d_3, s_2 \rightarrow d_1, s_3 \rightarrow d_2\}$. Using an Ethernet switch, the unicast phase and the multicast phase will take roughly the same amount of time and multicast-based implementations may not be more effective than unicast based implementations. Our performance study further confirms this. Thus, while *CC–MPI* provides multicast based implementations for some of the all–to–all and many–to–many communication routines, we will focus on the techniques we use to improve the unicast based implementations.

Traditionally, these complex communications are implemented based on point–to–point communications [9, 22] without any scheduling. Such implementations will yield acceptable performance when the message sizes are small. When the message sizes are large, there will be severe network contention in the Ethernet switch and the performance of these implementations will be poor. *CC–MPI* optimizes the cases when the message sizes are large using *phased* communication [12]. The idea of phased communication is to reduce network contention by decomposing a complex communication pattern into phases such that the contention within each phase is minimal. To prevent communications in different phases from interfering with each other, a barrier is placed between phases. Next, we will discuss how phased communication can be used to realize *MPI_Alltoall* (for all–to–all communications) and *MPI_Alltoallv* (for many–to–many communications).

CC–MPI assumes that network contention only occurs in the link between an Ethernet switch and a machine. This assumption is true for a cluster connected with a single Ethernet switch. When multiple switches are involved, this assumption will hold when a higher link speed is supported for the links connecting switches. Under this assumption, the contention that needs to be resolved is in the links between a node and a switch.

To avoid network contention within a phase, each node receives at most one message in a phase (receiving two messages potentially results in network contention). All–to–all communication for N nodes can be realized with $N-1$ phases and $N-2$ barriers. The ith, $1 \leq i \leq N-1$, phase contains communications

$$\{j \rightarrow (j+i) \ mod \ N \mid j = 0..N-1\}$$

In the following discussion, we will call the phases that can form all–to–all communications *all–to–all phases*. Essentially, scheduling messages in an all–to–all communication according to the all–to–all phases results in no network contention within each phase. Notice that each source-destination pair happens exactly once in the all–to–all phases.

Using $N-2$ barriers potentially can cause a scalability problem. However, all–to–all communication itself is not scalable, and the extra barrier is swamped by data transmission as long as the message sizes are reasonably large. When the message size is large enough, phase communication reduces the network contention and achieves high communication performance. Note also that barriers can be very efficient with special hardware support, such as Purdue's PAPERS [6]. In our evaluation, we do not use any special hardware support, a barrier on 16 nodes takes about 1 milli-second.

Realizing many–to–many communication with phased communication is more difficult. Using *MPI_Alltoallv*, a node can send different sized messages to different nodes. This routine realizes many-to-many communication by specifying the size of some messages to be 0. The first difficulty to realize *MPI_Alltoallv* with phased communication is that the communication pattern information is not known to all nodes involved in the communication. In *MPI_Alltoallv*, each node only has the information about how much data it sends to and receives from other nodes, but not how other nodes communicate. To perform phased communication, however, all nodes involved in the communication must coordinate with each other and agree on what to send and receive within each phase. This requires that all nodes involved obtain the communication pattern information. *CC–MPI* provides two methods to resolve this problem. The first approach uses an *MPI_Allgather* to distribute the communication pattern information before the actual many–to–many communication takes place. The second approach, which can only be used when the user has additional information about the communication, assumes that the global communication pattern is determined statically for each node and stored in a local data structure. It is clearly more efficient than the first method.

Once the global communication pattern information is known to all nodes, a message scheduling algorithm is used to minimize the total communication time for the many–to–many communication. *CC–MPI* supports two message scheduling schemes for many to many communications: *greedy* scheduling and *all–to–all* based scheduling. The greedy scheduling algorithm focuses on the load balancing issue. It works in two steps. In the first step, the algorithm sorts the messages in decreasing order in terms of the message size. In the second

step, the algorithm creates a phase, considers each unscheduled message (from large size to small size) and puts the message in the phase if possible, that is, if adding the message into the phase does not create contention. Under our assumption, network contention is created when a node sends to two nodes and when a node receives from two nodes. If the sizes of the remaining messages are less than a threshold value, all messages are put in one phase. The greedy algorithm repeats the second step if there exists unscheduled messages. The operation to put all small messages in one phase is a minor optimization to reduce the number of barriers for realizing a communication pattern. The load in the phases created by the greedy algorithm is likely to be balanced because messages of similar sizes are considered next to each other.

```
Input: Communication pattern
Output: Communication phases
(1)Sort messages based on their sizes
(2)while (there exist unscheduled messages) do
(3)    if (the largest message size < the threshold) then
(4)      Put all messages in one phase
(5)    endif
(6)    Let all–to–all Phase i be the phase
         that contains the largest unscheduled message
(7)    Create a new empty phase P
(8)    Schedule all unscheduled messages that appear in
         all–to–all Phase i in P
(9)    For each unscheduled message in the sorted list
         if no conflict, put the message in P
```

Figure 2: All–to–all based scheduling algorithm.

The *all–to–all* based scheduling algorithm is shown in Figure 2. The main difference between this algorithm and the greedy algorithm is that messages are scheduled based on all–to–all phases first before being considered based on their sizes. This algorithm attempts to minimize the number of phases while putting messages of similar sizes in the same phase. It can easily be shown that this algorithm guarantees that the number of phases is no more than $N - 1$. The algorithm produces the most effective scheduling for all–to–all communication and will likely yield good results for communication patterns that are close to all–to–all communication.

Consider scheduling messages $(0 \rightarrow 1, 1MB)$, $(1 \rightarrow 3, 1MB)$, $(0 \rightarrow 2, 10KB)$, $(2 \rightarrow 3, 100B)$, $(1 \rightarrow 5, 100B)$, $(2 \rightarrow 1, 100B)$ on 6 nodes. Here, the notion (src, dst, s) represents a message from source node src to destination node dst of size s. Let us assume that the threshold value for the small message size is 0 and that the messages are sorted in the order as specified. The greedy scheduling works as follows: messages $(0 \rightarrow 1, 1MB)$, $(1 \rightarrow 3, 1MB)$ will be placed in phase 1 because they do not cause contention. After that, none of the remaining messages can be placed in this phase. For example, message $(2 \rightarrow 3, 100B)$ cannot be placed in this phase because node 3 receives a message from node 1 in message $(1 \rightarrow 3, 1MB)$. The greedy algorithm then creates phase 2 and places messages $(0 \rightarrow 2, 10KB)$, $(2 \rightarrow 3, 100B)$, and $(1 \rightarrow 5, 100B)$ in the phase. Message $(2 \rightarrow 1, 100B)$ cannot be placed in this phase because it conflicts with message $(2 \rightarrow 3, 100B)$, so a third phase is created for message

$(2 \rightarrow 1, 100B)$. The all–to–all based scheduling scheme schedules the messages as follows. First, the algorithm searches for the all–to–all phase that contains message $(0 \rightarrow 1)$. The algorithm then creates a phase and puts messages $(0 \rightarrow 1, 1MB)$ and $(2 \rightarrow 3, 100B)$ in the phase because these two messages are in *all–to–all phase 0*. After that, each unscheduled message is considered. In this case, message $(1 \rightarrow 3, 1MB)$ cannot be placed in this phase because it conflicts with message $(2 \rightarrow 3, 100B)$. However, message $(1 \rightarrow 5, 100B)$ will be placed in this phase. After this, a second phase will be created for messages $(1 \rightarrow 3, 1MB)$, $(0 \rightarrow 2, 10KB)$, $(2 \rightarrow 1, 100B)$; none of these messages conflict.

Depending on the availability of information about the communication, *CC–MPI* provides four different methods for many–to–many communications.

1. Simple point–to–point communication based implementation. This provides good performance when the message size is small and network contention is not severe.
2. Phased communication with the global communication pattern information distributed at runtime. In this case, the global communication information is distributed with an *MPI_Allgather* routine. After that, a message scheduling algorithm is executed at each node to determine how each communication is to be carried out. Finally, the message is transmitted according to the schedule. This routine is efficient when the user determines that large amounts of messages are exchanged with the communication; however, the details about the communication are unknown until runtime. We refer to this scheme as the *Level 1* compiled communication for *MPI_Alltoallv*.
3. Phased communication with the global communication pattern information stored in a data structure local to each node. The difference between this method and (2) above is that the *MPI_Allgather* is unnecessary. We refer to this scheme as the *Level 2* compiled communication for *MPI_Alltoallv*.
4. Phased communication with the message scheduling information (phases) stored in a data structure local to each node. Phased communication is carried out directly using the phase information. We refer to this scheme as the *Level 3* compiled communication for *MPI_Alltoallv*.

These different schemes are supported in *CC–MPI* with two network control routines and two data transmission routines. The first data transmission routine supports point–to–point communication based implementation. The second data transmission routine, *MPI_Alltoallv_data_trans2*, performs the phased communication with the assumption that the phases have been computed and the related data structures are established. The first network control routine, *MPI_Alltoallv_control1*, performs the *MPI_Allgather* operation to obtain the communication pattern and invokes the message scheduling routine to compute the phases. The second network control routine,

MPI_Alltoallv_control2, assumes that the communication pattern information is stored in local variables and only invokes the message scheduling routine to compute the phases. Depending on the availability of the information about the communication, different combinations of the network control and data transmission routines can be used to realize the function with different performance. For example, Level 1 compiled communication can be realized with a combination of *MPI_Alltoallv_control1* and *MPI_Alltoallv_data_trans2*, level 2 communication can be realized with a combination of *MPI_Alltoallv_control2* and *MPI_Alltoallv_data_trans2*, and level 3 communication can be realized with a single *MPI_Alltoallv_data_trans2*.

5 Performance Study

We have implemented *CC–MPI* on the Linux operating system. In this section, we evaluate the routines implemented in *CC–MPI* and compare the performance of *CC–MPI* with that of two MPI implementations in the public domain, LAM/MPI (version 6.5.4 with direct client to client mode) [22] and MPICH (version 1.2.4 with device *ch_p4*) [9]. The experimental environment is an Ethernet switched cluster with 29 Pentium III–650MHz based PCs. Each machine has 128MB memory and 100Mbps Ethernet connection via a 3Com 3C905 PCI EtherLink Card. All machines run RedHat Linux version 6.2, with 2.4.7 kernel. The machines are connected by two 3Com SuperStack II baseline 10/100 Ethernet switches as shown in Figure 3.

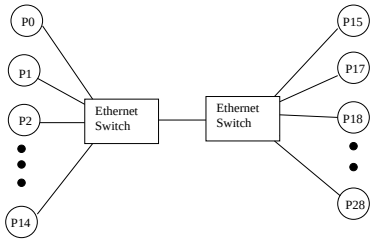


Figure 3: Performance evaluation environment.

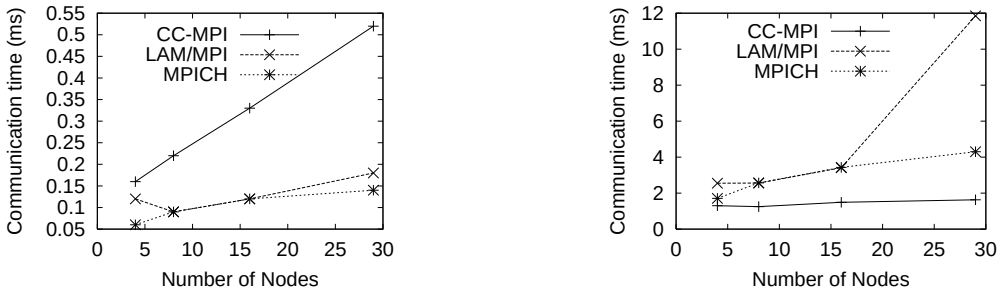
5.1 Individual MPI Routines

```
MPI_Barrier(MPI_COMM_WORLD);
start = MPI_Wtime();
for (count = 0; count < ITER_NUM; count ++) {
  MPI_Bcast(buf, s, MPI_CHAR, 0, MPI_COMM_WORLD);
}
elapsed_time = MPI_Wtime() - start;
```

Figure 4: Code segment for measuring the performance of an individual MPI routine.

We use the approach similar to Mpptest [10] to measure the performance of an individual MPI routine. Figure 4 shows an example code segment for measuring the performance. For the collective communication routines, we use the *average* time among all nodes as the performance metric. Because we are averaging the time over many invocations of an MPI routine, the average time is almost identical to the worst case time. Notice that most of the techniques developed in this paper optimize communications with large message sizes. Hence, although such measurement does not take into account application behavior, it should give a good indication about the performance of the routines when the message size is large.

CC–MPI contains a plain unicast (TCP) based implementation for each of the routines, which achieves a similar performance as the corresponding routine in LAM/MPI. We will omit the results for these implementations and only report the results of other implementations that improve performance for different situations. Since *CC–MPI* provides mechanisms to support compiled communication and relies on the user to select the most effective method for a communication, such implementations are efficient under some situations and not efficient under other situations. It should be emphasized that the performance improvement is the potential gain that can be obtained through compiled communication by employing alternative implementations while the situations where a particular *CC–MPI* routine performs worse can be avoided and should not be treated as the performance loss since another routine for the communication in *CC–MPI* can be selected.



(a) Small messages (1 Byte)

(b) Large messages (10 KB)

Figure 5: Performance of *MPI_Bcast*

Figure 5 shows the performance of the multicast based *MPI_Bcast*. As can be seen from Figure 5 (a), multicasting does not guarantee an improvement in communication performance, even for the broadcast communication. The reason that the LAM/MPI and MPICH broadcast implementations are more efficient than our multicast-based implementation when the message size is 1 byte is that LAM/MPI and MPICH use an efficient logical tree based broadcast implementation when the group is larger than 4 processes. This distributes the broadcast workload to multiple nodes in the system. In our implementation, the root sends only one multicast packet, but must process all acknowledgment packets from all receivers. As a result, for small sized messages, our multicast

based implementation performs worse. However, when the message size is large, the acknowledgment processing overhead is insignificant, and sending one multicast data packet instead of multiple unicast packets provides a significant improvement. In this case, our multicast-based implementation is much more efficient, as shown in Figure 5 (b).

MPI_Bcast only requires the static group management scheme. Next, we will evaluate the performance of one–to–many communication for which dynamic group management and compiler–assisted group management were designed. Figure 6 shows the performance of *MPI_Scatterv* with different implementations and group management schemes. In this experiment, the root scatters messages of a given size to 5 receivers among the 29 members in the communicator. As can be seen in the figure, the compiler–assisted scheme performs the best among all the schemes. The dynamic group management scheme incurs very large overheads and offers the worst performance among all the schemes. The static group management is in between the two. In this experiment, LAM/MPI outperforms both the dynamic and static schemes.

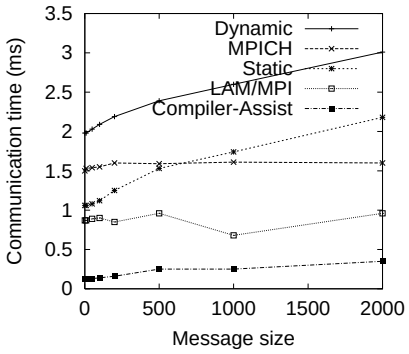
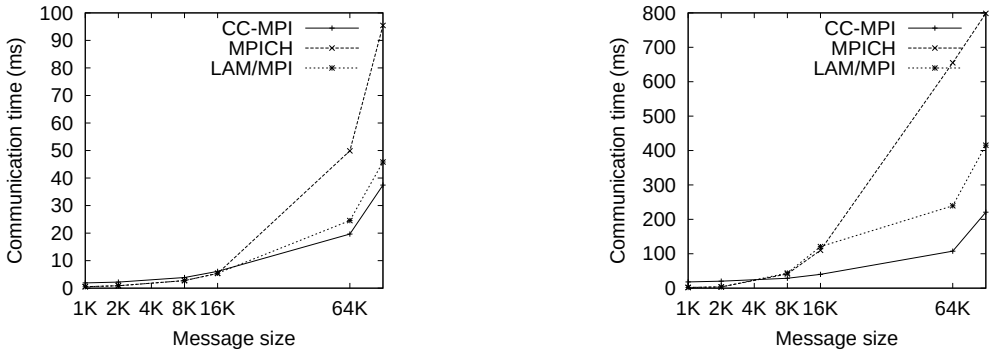


Figure 6: Performance of one–to–five communication using *MPI_Scatterv*.

Figures 7 shows the performance of phased communication based *MPI_Alltoall* in *CC–MPI*, which is designed to optimize the case when the message size is large. As can be seen from the table, even with 4 nodes, the network contention can still degrade communication performance, and our phased communication outperforms LAM/MPI and MPICH when the message size is larger than 16KB. For all–to–all communication over a larger number of nodes, the network contention problem is more severe, and the advantage of phased communication is more significant. With 16 nodes and a message size of 64KB, our phased communication completes an all–to–all communication about 2 times faster than LAM/MPI and 5 times faster than MPICH. The performance trend is similar for messages of sizes 256KB and 512KB.

As described in Section 4, *CC–MPI* provides a variety of schemes for *MPI_Alltoallv*. Two scheduling algorithms, greedy and all–to–all, are supported. For each scheduling scheme, three levels of compiled communication schemes are implemented; Table 1 shows their performance. In this experiment, we use *MPI_Alltoallv* to perform

all–to–all communication on 16 nodes. For this particular communication pattern, greedy and all–to–all based scheduling yield similar results, so only the results for all–to–all based scheduling are presented. As can be seen from the table, with more static information about the communication, more efficient communication can be achieved. The Level 3 implementation is about 15.7% more efficient than the Level 1 scheme when the message size is 4KB. As the message size becomes larger, the nearly constant cost of the *MPI_Allgather* and the scheduling operations become less significant. The Level 3 implementation is about 5.8% more efficient when the message size is 32KB. Notice that the message scheduling does not take a significant amount of time on 16 nodes. For a larger system, the scheduling overhead can be significant.



(a) 4 nodes

(b) 16 nodes

Figure 7: Performance of *MPI_Alltoall*

message size	*CC–MPI*				LAM/MPI	MPICH
	Level 1	Level 2	Level 3	point-to-point		
2KB	23.6ms	21.2ms	20.0ms	3.5ms	3.4ms	3.6ms
4KB	26.4ms	24.1ms	22.8ms	8.5ms	9.2ms	6.6ms
8KB	32.5ms	30.1ms	28.8ms	30.2ms	18.0ms	30.5ms
16KB	44.5ms	42.2ms	40.9ms	88.0ms	89.0ms	101.0ms
32KB	67.4ms	65.1ms	63.7ms	142.4ms	132.0ms	150.5ms
64KB	112.0ms	109.7ms	108.4ms	214.1ms	224.0ms	643.0ms

Table 1: Performance of different implementations of *MPI_Alltoallv*.

5.2 Benchmark Programs

In this subsection, we compare the performance of *CC-MPI* with that of LAM/MPI and MPICH using two benchmark programs, IS and FT from the NAS suite [20]. The Integer Sort (IS) benchmark sorts N keys in parallel and the Fast Fourier Transform (FT) benchmark solves a partial differential equation (PDE) using forward and inverse FFTs. These two benchmarks are presented in the NAS benchmarks to evaluate collective communication routines. Communications in other NAS benchmarks are either insignificant or dominated by point–to–point

communications. Both IS and FT are communication intensive programs with most communications performed by *MPI_Alltoall* and *MPI_Alltoallv* routines.

Table 2 shows the results for IS, and Table 3 shows the results for FT. We run both benchmarks on 4, 8, and 16 nodes with the three problem sizes supplied with the benchmark—the small problem size ($CLASS = S$), the medium problem size ($CLASS = W$) and the large problem size ($CLASS = A$). LAM/MPI and $MPICH$ do not have any special optimizations for Ethernet switched clusters. As a result, when the communications in an application result in network contention, the performance degrades and is somewhat unpredictable. Different ways to carry out communications may result in (very) different performance under different network situations.

Problem Size	MPI Library	Number of Nodes		
		4	8	16
CLASS=S	LAM/MPI	0.11s	0.09s	0.07s
	MPICH	0.10s	0.08s	0.07s
	CC–MPI	0.13s	0.16s	0.28s
CLASS=W	LAM/MPI	1.32s	1.02s	1.60s
	MPICH	2.69s	2.16s	1.57s
	CC–MPI	1.08s	0.69s	0.64s
CLASS=A	LAM/MPI	9.62s	5.88s	4.62s
	MPICH	21.92s	15.40s	11.60s
	CC–MPI	8.45s	4.90s	3.00s

Table 2: Execution time for IS with different libraries, different numbers of nodes and different problem sizes.

Problem Size	MPI Library	Number of Nodes		
		4	8	16
CLASS=S	LAM/MPI	1.00s	0.70s	0.75s
	MPICH	2.04s	1.63s	1.01s
	CC–MPI	1.10s	0.63s	0.42s
CLASS=W	LAM/MPI	2.15s	1.55s	1.42s
	MPICH	4.17s	2.77s	1.46s
	CC–MPI	2.20s	1.28s	0.77s
CLASS=A	LAM/MPI	146.50s	27.37s	12.75s
	MPICH	111.91s	46.71s	28.01s
	CC–MPI	40.19s	21.34s	11.23s

Table 3: Execution time for FT with different libraries, different numbers of nodes and different problem sizes.

As can be seen from the table, LAM/MPI performs much better than MPICH in some cases, e.g. the 'A' class IS on 16 nodes, while it performs worse in other cases (e.g., the 'A' class FT on 4 nodes). With *CC–MPI* we assume that the user determines that the communications will result in severe network contention with the traditional communication scheme and decides to use phased communication to perform *MPI_Alltoall* and *MPI_Alltoallv*. For *MPI_Alltoallv*, we assume that the Level 1 compiled communication scheme is used. As can be seen from the table, *CC–MPI* results in significant improvement (up to 300% speed up) in terms of execution time for all cases except for the small problem sizes. This further demonstrates that compiled communication can significantly

improve the communication performance. For IS with a small problem size, *CC–MPI* performs much worse than *LAM/MPI* and *MPICH*. This is because we use phased communication for all cases. In practice, when compiled communication is applied, a communication model selection scheme should be incorporated in the compiler to determine the most effective method for the communications. For the small problem size, the compiler may decide that the message size is not large enough for the phased communication schemes to be beneficial and resort to point–to–point based dynamic communication scheme to carry out communications. Notice that for IS with a small problem size, the execution time with *CC–MPI* increases as the number of nodes increases. The reason is that both communication and computation take little time in this problem, so the execution time is dominated by the barriers in the phased communications. As the number of nodes increases, the number of barriers for each phased communication increases, and each barrier also takes more time.

5.3 A Software DSM Application

In this section, we report our early work aimed at using *CC–MPI* to improve software distributed shared memory (SDSM) performance. Our initial *CC–MPI*-enabled SDSM is built within the Filaments package [18] and uses an eager version of home-based release consistency [28].

We tested the potential of using Level 1 compiled communication for *MPI_Alltoallv* to implement exchange of page information through a synthetic application that first modifies a set number of pages on each node and then invokes a barrier. The barrier causes all pages to be made consistent through collective communication. This process is repeated for 100 iterations.

Table 4 presents the results of this benchmark. We observe that with a small number of nodes, the advantage of Level 1 compiled communication versus dynamic communication (the point–to–point based implementation without message scheduling) is relatively small. In fact, on 4 nodes, Level 1 compiled communication sometimes results in worse performance than dynamic communication. However, as the number of nodes increases, the advantage of Level 1 compiled communication is significant (almost a factor of two when four pages per node are modified). As the message size becomes much larger (starting at eight pages per node), the advantage decreases somewhat, but is still significant.

6 Conclusion

In this paper, we present *CC–MPI*, an experimental MPI prototype that supports compiled communication. *CC–MPI* employs a number of techniques to achieve efficient communication over Ethernet switched clusters, including using multicast for broadcast type communications, supporting the compiler–assisted group manage-

Pages Modified Per Node	Communication Method	Number of Nodes		
		4	8	16
1	Level 1	0.93s	2.02s	4.57s
	Dynamic	0.90s	4.29s	6.75s
4	Level 1	3.07s	6.76s	15.8s
	Dynamic	4.13s	12.1s	27.5s
8	Level 1	9.46s	15.7s	35.5s
	Dynamic	8.35s	18.6s	48.4s

Table 4: Experiments with our prototype SDSM that uses *CC–MPI* for communication.

ment scheme that allows reliable multicast to be performed effectively, separating network control from data transmission, and using phased communication for complex many–to–many and all–to–all communications. We demonstrate that using compiled communication, the communication performance of Ethernet switched clusters can be significantly improved.

Compiled communication will likely be more beneficial for large systems, especially for massively parallel systems. In such systems, traditional dynamic communication is likely to generate significant network contention, which will result in poor communication performance. Compiled communication performs communications in a managed fashion and reduces the burden in the network subsystem. One difficulty with compiled communication is that it requires the user to consider network details, which is beyond of capability of a typical programmer. For the compiled communication model to be successful, it is crucial to develop an automatic restructuring compiler that can perform optimizations with compiled communication automatically. This way, programmers can write normal MPI programs and enjoy high communication performance achieved through compiled communication.

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