

## Abstract

Java's support for parallel and distributed processing makes the language attractive for metacomputing applications, such as parallel applications that run on geographically distributed (wide-area) systems. To obtain actual experience with a Java-centric approach to metacomputing, we have built and used a high-performance wide-area Java system, called Manta. Manta implements the Java RMI model using different communication protocols (active messages and TCP/IP) for different networks. The paper shows how wide-area parallel applications can be expressed and optimized using Java RMI. Also, it presents performance results of several applications on a wide-area system consisting of four Myrinet-based clusters connected by ATM WANs.

## 1 Introduction

Metacomputing is an interesting research area that tries to integrate geographically distributed computing resources into a single powerful system. Many applications can benefit from such an integration [11, 22]. Metacomputing systems support such applications by addressing issues like resource allocation, fault tolerance, security, and heterogeneity. Most metacomputing systems are language-neutral and support a variety of programming languages. Recently, interest has also arisen in metacomputing architectures that are centered around a single language. This approach admittedly is restrictive for some applications, but also has many advantages, such as a simpler design and the usage of a single type system. In [24], the advantages of a Java-centric approach to metacomputing are described, including support for code mobility, distributed polymorphism, distributed garbage collection, and security.

In this paper, we describe our early experiences in building and using a high-performance Java-based system for one important class of metacomputing applications: parallel computing on geographically distributed resources. Although our system is not a complete metacomputing environment yet, it is interesting for several reasons. The system, called *Manta*, has been optimized to achieve high performance. It uses a native compiler and an efficient, light-weight RMI (Remote Method Invocation) protocol that achieves a performance close to that of C-based RPC protocols [17]. We have implemented Manta on a geographically dis-

tributed system, called *DAS*, consisting of four Pentium Pro/Myrinet cluster computers connected by wide-area ATM links. The resulting system is an interesting platform for studying parallel Java applications on geographically distributed systems.

The Java-centric approach achieves a high degree of transparency and hides many details of the underlying system (e.g., different communication substrates) from the programmer. For several high-performance applications, however, the huge difference in communication speeds between the local and wide-area networks is a problem. In our DAS system, for example, a Java RMI over the Myrinet LAN costs about 40  $\mu$ sec, while an RMI over the ATM WAN costs several milliseconds. Our Java system therefore exposes the structure of the wide-area system to the application, so applications can be optimized to reduce communication over the wide-area links.

In this paper, we show how wide-area parallel applications can be expressed and optimized using Java RMI and we discuss the performance of several parallel Java applications on DAS. We also discuss some shortcomings of the Java RMI model for wide-area parallel computing. This experience will be useful for future (Java-centric) metacomputing systems and may also stimulate further research on programming support for wide-area applications. The outline of the paper is as follows. In Section 2 we describe the implementation of Manta on our wide-area system. In Section 3 we describe our experiences in implementing four wide-area parallel applications in Java and we discuss their performance. In Section 4 we look at related work and in Section 5 we give our conclusions.

## 2 A wide-area parallel Java system

In this section, we will briefly describe the DAS system and the original Manta system (as designed for a single parallel machine). Next, we discuss how we implemented Manta on the wide-area DAS system. Finally, we compare the performance of Manta and the Sun JDK 1.1.4 on the DAS system.

### 2.1 The wide-area DAS system

We believe that high-performance metacomputing applications will typically run on collections of parallel machines (clusters or MPPs), rather than on workstations at random geographic locations. Hence, metacomputing systems that are used for parallel processing will be *hierarchically* structured. The DAS experimentation system we have built reflects this basic assumption, as shown in Figure 1. It consists of four clusters, located at different universities in The Netherlands. The nodes within the same cluster are connected by 1.2 Gbit/sec Myrinet [6]. The clusters are connected by dedicated 6 Mbit/s wide-area ATM networks.

The nodes in each cluster are 200 MHz/128 MByte Pentium Pros. One of the clusters has 128 processors, the other clusters have

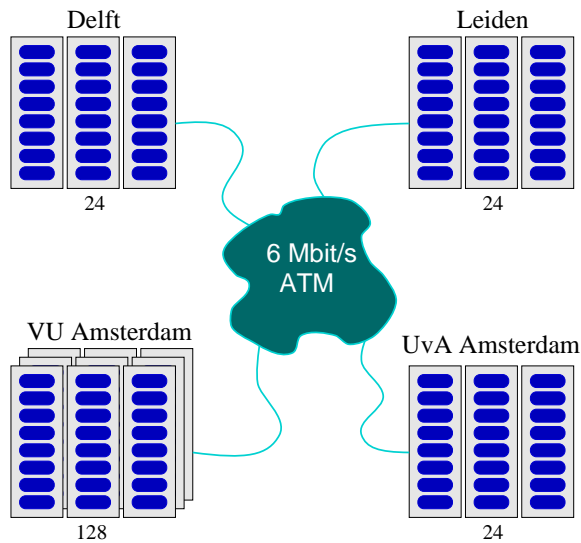


Figure 1: The wide-area DAS system.

24 nodes each. The machines run RedHat Linux version 2.0.36 and BSD/OS 3.0. The Myrinet network is a 2D torus and the wide area ATM network is fully connected. The system, called DAS, is more fully described in [20] (and on <http://www.cs.vu.nl/das/>).

## 2.2 The Manta system

Manta is a Java system designed for high-performance parallel computing. Like JavaParty [19], Manta uses a separate remote keyword to indicate which classes allow their methods to be invoked remotely. This method is somewhat more flexible and easier to use than inheriting from `java.rmi.server.UnicastRemoteObject` (the standard RMI mechanism). JavaParty requires a preprocessor for implementing this language extension; for Manta, we have modified our compiler. Except for this difference, the programming model of Manta is the same as that of standard RMI. Manta uses a native compiler and an optimized RMI protocol. The most important advantage of a native compiler (compared to a JIT) is that it can do more aggressive optimizations and therefore generate better code. The compiler also generates the serialization and deserialization routines, which greatly reduces the runtime overhead of RMIs. Manta nodes thus contain the executable code for the application and (de)serialization routines. The nodes communicate with each other using Manta's own light-weight RMI protocol.

The most difficult problem addressed by the Manta system is to allow interoperability with other JVMs. One problem is that Manta has its own, light-weight RMI protocol that is incompatible with Sun's JDK protocol. We solve this problem by letting a Manta node also communicate through a JDK-compliant protocol. Two Manta nodes thus communicate using our fast protocol, while Manta-to-JVM RMIs use the standard RMI protocol.

Another problem concerning interoperability is that Manta uses a native compiler instead of a byte code interpreter (or JIT). However, since Java RMIs are polymorphic [23], Manta nodes must be able to send and receive byte codes to interoperate with JVMs. For example, if a remote method expects a parameter of a certain class *C*, the invoker may send it an object of a subclass of *C*. This subclass may not yet be available at the receiving Manta node, so its byte code may have to be retrieved and integrated into the computation. With Manta, however, the computation is an executable program, not a JVM. In the reverse situation, if Manta does a remote

invocation to a node running a JVM, it must be able to send the byte codes for subclasses that the receiving JVM does not yet have. Manta solves this problem as follows. If a remote JVM node sends a byte code to a Manta node, the byte code is compiled dynamically to object code and this object code is linked into the running application using the `dlopen()` dynamic linking interface. Also, Manta generates byte codes for the classes it compiles (in addition to executable code). These byte codes are stored at an http daemon, where remote JVM nodes can retrieve them. For more details, we refer to [17].

The Manta RMI protocol is designed to minimize serialization and dispatch overhead, such as copying, buffer management, fragmentation, thread switching, and indirect method calls. Manta avoids the several stream layers used for serialization by the JDK. Instead, RMI parameters are serialized directly into a communication buffer. Moreover, the JDK stream layers are written in Java and their overhead thus depends on the quality of the interpreter or JIT. In Manta, all layers are either implemented as compiled C code or compiler-generated native code. Heterogeneity between little-endian and big-endian machines is achieved by sending data in the native byte order of the sender, and having the receiver do the conversion, if necessary.

To implement distributed garbage collection, the Manta RMI protocol also keeps track of object references that cross machine boundaries. Manta uses a mark-and-sweep algorithm (executed by a separate thread) for local garbage collection and a reference counting mechanism for remote objects.

The serialization of method arguments is an important source of overhead of existing RMI implementations. Serialization takes Java objects and converts (serializes) them into an array of bytes. The JDK serialization protocol is written in Java and uses reflection to determine the type of each object during run time. With Manta, all serialization code is generated by the compiler, avoiding the overhead of dynamic inspection. The compiler generates a specialized serialization and deserialization routine for every method. Pointers to these routines are stored in the method table. As explained above, Manta sometimes needs to load and compile classes dynamically, to implement polymorphic RMIs. In this case, the (de)serialization routines are also generated during run time. The Manta serialization protocol optimizes simple cases. For example, an array whose elements are of a primitive type is serialized by doing a direct memory-copy into the message buffer, which saves traversing the array. Compiler generation of serialization is one of the major improvements of Manta over the JDK [17].

## 2.3 Manta on the wide area DAS system

To implement Java on a wide-area system like DAS, the most important problem is how to deal with the different communication networks that exist within and between clusters. As described in Section 2.1, we assume that wide-area parallel systems are hierarchically structured and consist of multiple parallel machines (clusters) connected by wide area networks. The LANs (or MPP interconnects) used within a cluster typically are very fast, so it is important that the communication protocols used for intra-cluster communication are as efficient as possible. Inter-cluster communication (over the WAN) necessarily is slower.

Most Java RMI implementations are built on top of TCP/IP. Using a standard communication protocol eases the implementation of RMI, but also has a major performance penalty. TCP/IP was not designed for parallel processing, and therefore has a very high overhead on fast LANs such as Myrinet. For the Manta system, we therefore use different protocols for intra-cluster and inter-cluster communication.

To obtain a modular and portable system, Manta is implemented on top of a separate communication library, called Panda [3]. Panda

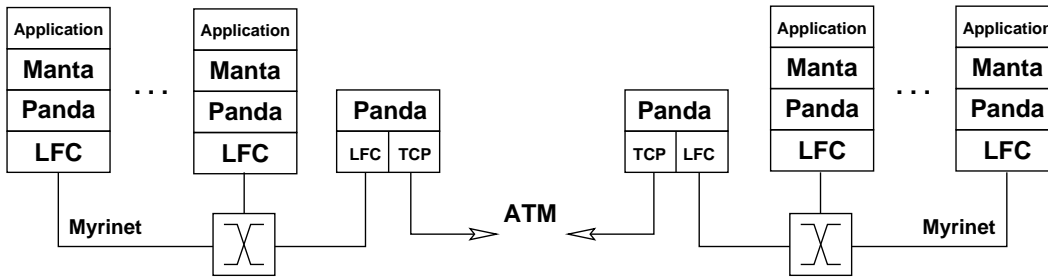


Figure 2: Wide area communication based on Panda

provides communication and multithreading primitives that are designed to be used for implementing runtime systems of various parallel languages. Panda’s communication primitives include point-to-point message passing, RPC, and broadcast. The primitives are independent of the operating system or network, which eases porting of languages implemented on top of Panda. The implementation of Panda, however, is structured in such a way that it can exploit any useful functionality provided by the underlying system (e.g., reliable message passing or broadcast), which makes communication efficient [3].

Panda has been implemented on a variety of machines, operating systems, and networks. The implementation of Manta and Panda on the wide-area DAS system is shown in Figure 2. For intra-cluster communication over Myrinet, Panda internally uses the LFC communication system [5]. LFC is a highly efficient, user-space communication substrate for Myrinet, similar to active messages.

For inter-cluster communication over the wide-area ATM network, Panda uses one dedicated *gateway* machine per cluster. The gateways also implement the Panda primitives, but support communication over both Myrinet and ATM. A gateway can communicate with the machines in its local cluster, using LFC over Myrinet. In addition, it can communicate with gateways of other clusters, using TCP/IP over ATM. The gateway machines thus forward traffic to and from remote clusters. In this way, the existence of multiple clusters is transparent to the Manta runtime system. Manta’s RMI protocol simply invokes Panda’s communication primitives, which internally calls LFC and/or TCP/IP.

The resulting Java system thus is highly transparent, both for the programmer and the RMI implementor. The system hides several complicated issues from the programmer. For example, it uses a combination of active messages and TCP/IP, but the application programmer sees only a single communication primitive (RMI). Likewise, Java hides any differences in processor-types from the programmer.<sup>1</sup>

As stated before, parallel applications often have to be aware of the structure of the wide-area system, so they can minimize communication over the wide-area links. Manta programs therefore can find out how many clusters there are and to which cluster a given machine belongs. In Section 3, we will give several examples of how this information can be used to optimize programs.

## 2.4 Performance measurements on the DAS system

Table 1 shows the latency and throughput obtained by Manta RMI and Sun JDK RMI over the Myrinet LAN and the ATM WAN. The latencies are measured for null-RMIs, which take zero parameters

<sup>1</sup>Manta supports the serialization and deserialization protocols needed to support heterogeneous systems, but the underlying Panda library does not yet support heterogeneity, as it does not do byte-conversions on its headers yet.

|               | Myrinet            |                      | ATM                |                      |
|---------------|--------------------|----------------------|--------------------|----------------------|
|               | Latency ( $\mu$ s) | Throughput (MByte/s) | Latency ( $\mu$ s) | Throughput (MByte/s) |
| Manta         | 39.9               | 38.6                 | 5600               | 0.55                 |
| Sun JDK 1.1.4 | 1228               | 4.66                 | 6700               | 0.35                 |

Table 1: Latency and maximum throughput of Manta and Sun JDK 1.1.4

and do not return a result. The maximum throughputs are measured for RMIs that take a large array as parameter.

For intra-cluster communication over Myrinet, Manta is much faster than the JDK, which uses a slow serialization and RMI protocol, executed using a byte code interpreter. Manta uses fast serialization routines generated by the compiler, a light-weight RMI protocol, and an efficient communication protocol (Panda). The maximum throughput of Manta (achieved with arrays of size 16 KByte) is 38.6 MByte/sec. A performance breakdown of Manta RMI and JDK RMI is given in [17].

For inter-cluster communication over ATM, we used the wide area link between the DAS clusters at VU Amsterdam and TU Delft (see Figure 1), which has the longest latency (and largest distance) of the DAS wide-area links. The difference in wide-area RMI latency between Manta and the JDK is 1.1 msec. Manta achieves a maximum wide-area throughput of 0.55 MByte/sec, which is almost 75% of the hardware bandwidth (6 Mbit/sec). The JDK RMI protocol is able to achieve less than 50% of the wide-area bandwidth. The differences in wide-area latency and throughput between Manta and the JDK are due to Manta’s more efficient serialization and RMI protocols, since both systems use the same communication layer (TCP/IP) over ATM.

## 3 Application experience

We implemented four parallel Java applications that communicate via RMI. The applications exploit the hierarchical structure of the wide-area system to minimize the communication overhead over the wide area links, using optimizations similar to those described in [4, 20]. Below, we briefly discuss the optimized applications and we give performance measurements on the DAS system.<sup>2</sup> We only present results for Manta, as other competitive Java platforms are not yet available for the DAS system. (Sun’s JDK 1.1.4 uses only interpreted code, the Kaffe JIT does not yet support RMI, and we were unable to run Sun’s JIT 1.1.6 on BSD/OS or Linux.)

<sup>2</sup>All applications except ASP are measured on the actual wide-area DAS system. ASP was measured on a local emulation system described in [20], which accurately emulates the wide-area system on a single 128-node cluster.

For each of the four programs, we will analyze its performance on the wide-area DAS system, using the following approach. The goal of wide-area parallel programming is to obtain higher speedups on multiple clusters than on a single cluster. Therefore, we have measured the speedups of each program on a single DAS cluster and on four DAS clusters. In addition, we have measured the speedups on a single cluster with the same total number of nodes, to determine how much performance is lost by using multiple distributed clusters instead of one big centralized cluster. (All speedups are computed relative to the same program on a single machine.)

The results are shown in Figure 5. The figure contains three bars for each application, giving the speedups on a single cluster of 10 nodes, four clusters of 10 nodes each, and a single cluster of 40 nodes. The difference between the first two bars thus indicates the performance gain by using multiple 10-node clusters (at different locations) instead of a single 10-node cluster. The difference between the second and third bar shows how much performance is lost due to the slow wide-area network (since the 40-node cluster uses the fast Myrinet network between all nodes).

### 3.1 Successive Overrelaxation

Red/black Successive Overrelaxation (SOR) is an iterative method for solving discretized Laplace equations on a grid. Here, it is used as an example of nearest neighbor parallelization methods. SOR is an iterative algorithm that performs multiple passes over a rectangular grid, until the grid changes less than a certain value. The new value of a grid point is computed using a stencil operation, which depends only on the previous value of the point itself and its four neighbors on the grid

The skeleton code for the wide-area parallel Java program for SOR is given in Figure 3. The parallel algorithm we use distributes the grid row-wise among the available processors, so each machine is assigned several contiguous rows of the grid, denoted by the interval  $LB$  to  $UB$  (for lower bound and upper bound). Each processor runs a slave process (a Java thread of class *SOR\_Slave*), which performs the SOR iterations until the program converges (see the *run* method). Each iteration has two phases, for the red and black grid points. The processes are logically organized in a linear array. Due to the stencil operations and the row-wise distribution, every process needs one row of the grid from its left neighbor (row  $LB - 1$ ) and one row from its right neighbor (row  $UB + 1$ ). (Exceptions are made for the first and last process, but we have omitted this from our skeleton code.)

At the beginning of every iteration, each slave process exchanges rows with its left and right neighbors and then updates its part of the grid using this boundary information from its neighbors. The row exchange is implemented using a remote object of class *Bin* on each processor. This object is a buffer of size one and contains synchronized methods to put and get data.

On a local cluster with a fast switch-based interconnect (like Myrinet), the exchange between neighbors adds little overhead, so parallel SOR obtains a high efficiency. On a wide-area system, however, the communication overhead between neighbors that are located in different clusters will be high, as such communication uses the WAN. The Java program allocates neighboring processes to the same cluster as much as possible, but the first and/or last process in each cluster will have a neighbor in a remote cluster. To hide the high latency for such inter-cluster communication, the program uses split-phase communication for exchanging rows between clusters. It first initiates an asynchronous send for its boundary rows and then computes on the inner rows of the matrix. When this work is finished, a blocking receive for the boundary data from the neighboring machines is done, after which the boundary rows are recomputed.

The optimization is awkward to express in Java, since Java

```
public class senderThread implements Runnable {
    private boolean filled;
    private Object o;
    private Bin otherSide; // Bin of remote cluster

    public synchronized void put(Object o) {
        if (filled) wait();
        filled = true;
        this.o = o;
        notify();
    }

    private synchronized void send() {
        if (!filled) wait();
        otherSide.put(o); // Send to remote cluster
        filled = false;
        notify();
    }

    public void run() {
        while (true) send();
    }
}

public remote class Bin {
    synchronized void put(double [] row) {
        // Wait until the bin is empty and save the new row.
    }

    synchronized double [] get() {
        // Wait until the bin is full and return the row.
    }
}

public remote class SOR_Slave extends RemoteThread {
    Bin leftBin, rightBin;
    senderThread leftSender, rightSender;

    void sendRows() {
        SOR_Row row = new SOR_Row();
        row.data = row LB of grid partition
        if (leftBoundary) { // Am I at a cluster boundary?
            leftSender.put(row); // asynchronous send
        } else {
            leftBin.put(row); // synchronous RMI
        }
        // Same for row UB to right neighbor ...
    }

    void receiveRows() {
        SOR_Row row;
        row = myLeftBin.get();
        row LB-1 of grid partition = row.data
        // Same for row UB+1 of right neighbor ...
    }

    public void run() {
        do { // do red/black SOR on the interval LB .. UB
            sendRows(); // Send rows LB and UB to neighbors
            Calculate red fields in local rows LB+1 ... UB-1
            receiveRows(); // Receive rows LB-1 and UB+1
            Calculate red fields in local rows LB and UB

            sendRows(); // Send rows LB and UB to neighbors
            Calculate black fields in local rows LB+1 ... UB-1
            receiveRows(); // Receive rows LB-1 and UB+1
            Calculate black fields in local rows LB and UB
        } while (... )
    }
}
```

Figure 3: Code skeleton for SOR.

lacks asynchronous communication. It is implemented by using a separate thread (of class *senderThread*) for sending the boundary data. To send a row to a process on a remote cluster, the row is first given to the local senderThread (using the *put* method); this

thread will then put the row in the Bin object of the destination process on a remote cluster, using an RMI. During the RMI, the original SOR\_Slave process can continue computing, so communication over the wide-area network is overlapped with computation. For communication within a cluster, however, the overhead of extra thread-switches outweighs the benefits, so only inter-cluster communication is handled in this way (see the method *sendRows*).

The performance of the SOR program is shown in Figure 5. The program obtains a high efficiency on a single cluster. Due to the latency-hiding optimization, the program is only 6% slower on the wide-area system than on a local 40-node cluster.

### 3.2 All-pairs Shortest Paths Problem

The goal of the All-pairs Shortest Paths (ASP) problem is to find the shortest path between any pair of nodes in a graph. The program uses a distance matrix that is divided row-wise among the available processors. At the beginning of iteration  $k$ , all processors need the value of the  $k$ th row of the matrix. The most efficient method for expressing this communication pattern would be to let the processor containing this row (called the owner) broadcast it to all the others. Unfortunately, Java RMI does not support broadcasting, so this cannot be expressed in Java. Instead, we simulate the broadcast using multiple RMI calls.

A naive implementation of broadcast, however, would send the same row many times over the same wide-area link, once to every destination machine. To avoid this, we use a separate *Coordinator* object per cluster. To broadcast a row, the row is sent to the coordinators of the different clusters, and these coordinators forward the message to the nodes in their cluster. This approach is illustrated by the skeleton code of Figure 4. Each machine contains a thread that executes the procedure *do\_asp*, which performs  $n$  iterations. At the beginning of iteration  $k$ , most threads block until they have received the row from its owner. The thread owning row  $k$  broadcasts this row by sending it (over the WAN) to the coordinator objects. It is important to use asynchronous communication for this, so the rows can be sent over the different WAN links in parallel. To implement this, we do the RMI call (to the remote method *forward*) from a newly created thread, of class *ForwarderThread*. The coordinator object forwards the row to the threads in its cluster, by invoking the remote method *transfer*; the latter method also wakes up the local computation thread.

The speedup of the wide-area ASP program for a graph with 2000 nodes is given in Figure 5. The program takes only 5% longer on four clusters of 10 machines than on a single 40-node cluster. Our implementation of the wide-area broadcast thus is fairly efficient. On a single cluster, the program also uses the coordinator mechanism to obtain some parallelism in forwarding multicast messages, which improves performance considerably compared to a serialized broadcast. A more general mechanism would be to use a spanning tree broadcast, as we have implemented, for example, in our MagPle wide-area collective communication library [13]. We have not implemented a general spanning tree algorithm for Java yet, however.

### 3.3 The Traveling Salesperson Problem

The Traveling Salesperson Problem (TSP) computes the shortest path for a salesperson to visit all cities in a given set exactly once, starting in one specific city. We use a branch-and-bound algorithm, which prunes a large part of the search space by ignoring partial routes that are already longer than the current best solution. The program is parallelized by distributing the search space over the different processors. Because the algorithm performs pruning, however, the amount of computation needed for each sub-space is not known in advance and varies between different parts of the search

```

remote class Coordinator { // 1 coordinator per cluster

    synchronized void forward(int[] row, int k) {
        for(all other threads T in this cluster)
            T.transfer(row, k);
    }
}

class ForwarderThread extends Thread {
    // This class is used to do asynchronous RMIs
    Coordinator dest;
    int[] row;
    int k;

    public void run() {
        dest.forward(row, k); // RMI over a WAN
    }
}

remote class asp_thread extends RemoteThread {

    int[][] tab; // The distance table
    int lb, ub; // The interval assigned to this process

    synchronized void transfer(int[] row, int k) {
        tab[k] = row; // This depends on call by value
        notifyAll();
    }

    synchronized void broadcast(int k, int owner) {
        if(this thread is the owner) {
            for(all remote cluster coordinators C) {
                // do asynchronous RMI using new thread
                new ForwarderThread(C, tab[k], k).start();
            }
            // Send directly to nodes in my own cluster.
            for(threads T in this cluster) {
                T.transfer(tab[k], k);
            }
        } else
            while (tab[k] == null) wait();
    }

    void do_asp() { // computation part
        int i, j, k;

        for (k = 0; k < n; k++) {
            broadcast(k, owner(k));
            for (i = lb; i < ub; i++) // recompute my rows
                if (i != k)
                    for (j = 0; j < n; j++)
                        tab[i][j] =
                            minimum(tab[i][j], tab[i][k] + tab[k][j]);
        }
    }
}

```

Figure 4: Code skeleton for ASP.

space. Therefore, load balancing becomes an issue. Load imbalance could be minimized using a centralized job queue, but this would also generate much wide-area communication. Instead, the program distributes the work statically over the different clusters, but within each cluster it uses dynamic load balancing. The program thus uses one FIFO job queue per cluster. The job queues are *remote* objects, so they can be accessed over the network using RMI. Each job contains an initial path of a fixed number of cities; a processor that executes the job computes the lengths of all possible continuations, pruning paths that are longer than the current best solution. Each processor runs one *worker* process, which is a remote object containing an active thread. The worker repeatedly fetches jobs from the job queue of its cluster (using RMI) and executes the job, until all work is finished.

The TSP program keeps track of the current best solution found

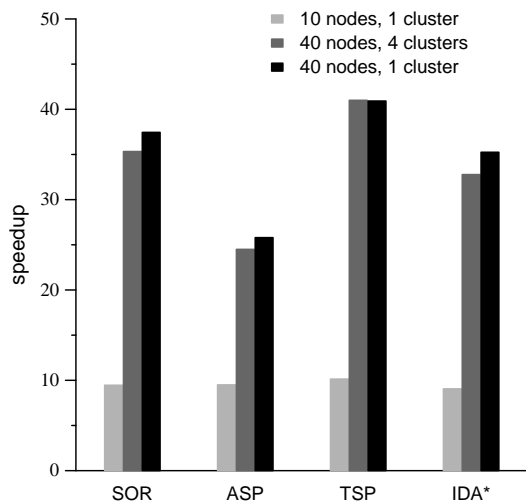


Figure 5: Speedups of four Java applications on a single cluster of 10 nodes, 4 clusters of 10 nodes each connected by a WAN, and a single cluster of 40 nodes.

so far, which is used to prune part of the search space. Each worker contains a copy of this value. If a worker finds a better complete route, the program does an RMI to all other workers to update their copies. (To allow these RMIs, the workers are declared as remote objects.)

The performance for the TSP program on the wide-area DAS system is shown in Figure 5, using a 17-city problem. As can be seen, the performance of TSP on the wide-area system is the same as that on a local cluster with the same number of processors. The reason is that the program is rather coarse-grained.

### 3.4 Iterative Deepening A\*

Iterative Deepening A\* is another combinatorial search algorithm, based on repeated depth-first searches. IDA\* tries to find a solution to a given problem by doing a depth-first search up to a certain maximum depth. If the search fails, it is repeated with a higher search depth, until a solution is found. The search depth is initialized to a lower bound of the solution. The algorithm thus performs repeated depth-first searches. Like branch-and-bound, IDA\* uses pruning to avoid searching useless branches.

We have written a parallel IDA\* program in Java for solving the 15-puzzle (the sliding tile puzzle). IDA\* is parallelized by searching different parts of the search tree concurrently. The program uses a more advanced load balancing mechanism than TSP, based on work stealing. Each machine maintains its own job queue, but machines can get work from other machines when they run out of jobs. Each job represents a node in the search space. When a machine has obtained a job, it first checks whether it can prune the node. If not, it expands the nodes by computing the successor states (children) and stores these in its local job queue. To obtain a job, each machine first looks in its own job queue; if it is empty it tries the job queues of some other machines. To avoid wide-area communication for work stealing, each machine first tries to steal jobs from machines in its own cluster. Only if that fails, the work queues of remote clusters are accessed. In each case, the same mechanism (RMI) is used to fetch work, so this heuristic is easy to express in Java.

Figure 5 shows the speedups for the IDA\* program. The program takes about 7% longer on the wide-area DAS system than on a single cluster with 40 nodes. The overhead is due to the work-stealing between clusters.

## 4 Related work

We have discussed a Java-centric approach to writing wide-area parallel (metacomputing) applications. Most other metacomputing systems (e.g., Globus [10] and Legion [12]) support a variety of languages. The SuperWeb [1] and Javelin [8] are examples of global computing infrastructures that support Java. A language-centric approach makes it easier to deal with heterogeneous systems, since the data types that are transferred over the networks are limited to the ones supported in the language (thus obviating the need for a separate interface definition language) [24].

Most work on metacomputing focuses on how to build the necessary infrastructure [2, 10, 12, 21]. In addition, research on parallel algorithms and applications is required, since the bandwidth and latency differences in a metacomputer can easily exceed three orders of magnitude [9, 10, 12, 20]. Coping with such a large non-uniformity in the interconnect complicates application development. The ECO system addresses this problem by automatically generating optimized communication patterns for collective operations on heterogeneous networks [16].

In our earlier research, we experimented with optimizing the performance of parallel programs for a hierarchical interconnect, by changing the communication structure [4]. Also, we studied the sensitivity of such optimized programs to large differences in latency and bandwidth between the LAN and WAN [20]. Based on this experience, we implemented collective communication operations as defined by the MPI standard, resulting in improved application performance on wide area systems [13]. Some of the ideas of this earlier work have been applied in our wide-area Java programs.

There are many other research projects for parallel programming in Java. Titanium [25] is a Java-based language for high-performance parallel scientific computing. The JavaParty system [19] is designed to ease parallel cluster programming in Java. In particular, its goal is to run multi-threaded programs with as little change as possible on a workstation cluster. Hyperion [18] also uses the standard Java thread model as a basis for parallel programming. Unlike JavaParty, Hyperion caches remote objects to improve performance. The Do! project tries to ease parallel programming in Java using parallel and distributed frameworks [15]. Java/DSM [26] implements a JVM on top of a distributed shared memory system. Breg et al. [7] study RMI performance and interoperability. Krishnaswamy et al. [14] improve RMI performance somewhat with caching and by using UDP instead of TCP. The above Java systems are designed for single-level (“flat”) parallel machines. The Manta system described in this paper, on the other hand, is designed for hierarchical systems and uses different communication protocols for local and wide area networks. It uses a highly optimized RMI implementation, which is particularly effective for local communication.

## 5 Conclusions

We have described our experiences in building and using a high-performance Java system that runs on a geographically distributed (wide-area) system. The goal of our work was to obtain actual experience with a Java-centric approach to metacomputing. Java’s support for parallel processing and heterogeneity make it an attractive candidate for metacomputing. The Java system we have built, for example, is highly transparent: it provides a single communication primitive (RMI) to the user, even though the implementation uses several communication networks and protocols.

Our Manta programming system is designed for hierarchical wide-area systems, for example clusters or MPPs connected by wide-area networks. Manta uses a very efficient (active message like) communication protocol for the local interconnect (Myrinet) and TCP/IP for wide-area communication. The two communication protocols are provided by the Panda library. Manta's lightweight RMI protocol is implemented on top of Panda and is very efficient.

We have implemented several parallel applications on this system, using Java RMI for communication. In general, the RMI model was easy to use. To obtain good performance, the programs take the hierarchical structure of the wide-area system into account and minimize the amount of communication (RMIs) over the slow wide-area links. With such optimizations in place, the programs can effectively use multiple clusters, even though they are connected by slow links. We also encountered several shortcomings of the RMI model. In particular, the lack of asynchronous communication and broadcast complicates programming.

In the near future we will extend the Panda library with support for heterogeneity, to allow RMI communication between different types of processors. In addition, we will do research on programming support that eases the development of efficient wide-area parallel applications.

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