

## A Quantitative Analysis of High Performance Computing with Amazon's EC2 Infrastructure: The Death of the Local Cluster?

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### Abstract

*The introduction of affordable infrastructure on demand, specifically Amazon's Elastic Compute Cloud (EC2), has had a significant impact in the business IT community and provides reasonable and attractive alternatives to locally-owned infrastructure. For scientific computation however, the viability of EC2 has come into question due to its use of virtualization and network shaping and the performance impacts of both. Several works have shown that EC2 cannot compete with a dedicated HPC cluster utilizing high-performance interconnects, but how does EC2 compare with smaller departmental and lab-sized commodity clusters that are often the primary computational resource for scientists? To answer that question, MPI and memory bandwidth benchmarks are executed on EC2 clusters with each of the 64-bit instance types to compare the performance of a 16 node cluster of each to a dedicated locally-owned commodity cluster based on Gigabit Ethernet. The analysis of results shows that while EC2 does experience reduced performance, it is still viable for smaller-scale applications.*

### 1. Introduction

The introduction of virtualized remote on-demand computing resources, Amazon's Elastic Compute Cloud (EC2) in particular, at reasonable prices has made many people question how computing should be delivered in the future. Will it be cheaper to simply lease time on remote resources rather than purchasing and maintaining your own? The emerging infrastructure-provider segment has been generally focused on business users and hosting web applications and services, but some researchers have begun to look at the cloud as a viable solution for scientific computing as well [1][2][7][8][10][11].

Utilizing cloud services for scientific computing opens up a new capability for many scientists: on-demand clusters with no queuing front-end and a

nearly-zero cost of entry. This allows scientists to satisfy their high-performance computing needs without resorting to entering their job in a queue with an hour or day long wait and the debugging headaches associated with queue-based systems. While this is certainly an exciting prospect, it must be recognized that cloud resources are not equivalent in processing power and network capability to custom-built high-performance systems such as the large clusters at the nation's supercomputing centers. For example, Walker has shown that EC2 simply cannot compete in terms of raw network performance with a dedicated high-performance cluster at NCSA called *abe*[2].

But, to date, there is an open issue that centers on the thousands of researchers who currently rely on their own small clusters: *How does EC2's performance compare against their existing (smaller, less cutting-edge, and much less expensive) cluster?* These scientists typically do not use national-scale supercomputers for a number of reasons, most notably potentially idiosyncratic operating environments (e.g., installed libraries), security issues, an unfamiliar queuing system, a generally daunting list of queued jobs, and a general belief that these shared clusters exist for "large jobs only". Even those scientist that use national-scale supercomputers for "production jobs" tend to do primary development, testing, and debugging on smaller clusters before switching to these shared supercomputers. EC2 resources are particularly attractive for this purpose because of the pay-as-you-go model and complete flexibility in the software stack. Thus, the question remains: Ignoring the potential benefits of *not* having to run, upgrade, and generally maintain a local cluster, does EC2 provide good enough *performance* to compete with local clusters owned by individual researchers? It is arguably "intuitive" to believe that EC2 does *not*, given its well-known use of virtualization and network shaping, *but it this actually true?* The answer to this question could have profound impact on the broad research community.

To answer these questions we have quantitatively evaluated EC2’s performance for the most common type of scientific application: the MPI program. We have run benchmarks of the memory systems and networks to compare Amazon’s performance to that of representative local departmental clusters. The purpose of the benchmarks is to evaluate EC2’s specific performance capabilities relevant to a commodity cluster. Our results show that EC2 competes surprisingly well with a commodity, Gigabit Ethernet-based, cluster in terms of memory performance and MPI performance. While we agree that the network performance of EC2 is not equivalent to that of a high-performance dedicated cluster with Myrinet or Infiniband interconnects, in terms of latency in particular, it does provide enough performance to be useful to a large class of scientific users which use the small to mid-sized departmental and lab commodity clusters often found in academia.

The rest of this paper will be organized as follows: the Related Work section will discuss other evaluations of the performance of EC2 and virtualized environments in general; the Evaluation Setup section will describe how the EC2 cluster was setup and configured as well as the configuration of the commodity clusters used as baselines; the Evaluation section will present our results from the various performance benchmarks; the Discussion section will address some observations made during this work as wells problems encountered and possible future work; finally, we give our conclusions on using EC2 clusters for MPI-based HPC computation.

## 2. Related Work

Edward Walker’s work [2] examines the feasibility of using EC2 for HPC, but compares it to high-end compute clusters at NCSA. This comparison pits EC2 against high-end clusters utilizing Infiniband interconnects. His work focuses on network latency and bandwidth in particular and unsurprisingly finds that the NCSA cluster has network latency that is more than an order of magnitude lower than that seen at EC2. We are focusing our evaluation on comparing EC2-based clusters to commodity clusters utilizing Gigabit Ethernet interconnects as would more likely be found in departmental and research-lab sized systems.

C. Evangelinos and C. Hill performed an evaluation of running couple ocean-atmosphere simulations on EC2 [1]. Their work focuses on 32-bit applications and as such they only examine two out of the five EC2 instance types. We have focused primarily on 64-bit platforms as this used for the majority of scientific computing. We also compare the performance of the

various EC2 instance types against each other to get a larger picture of EC2’s offerings.

Others have evaluated EC2 and its associated blob-storage, the Simple Storage Service (S3) [7], for applicability in data intensive eScience workloads [8][9]. We do not consider the I/O component in our evaluation and instead focus on CPU and network bound workloads based on message passing. We also do not primarily consider the question of cost-effectiveness of cloud-based clusters over locally-owned clusters. While we do feel that a performance-per-dollar comparison is valuable when deciding how to implement infrastructure, we leave that for future work as it can be very application specific.

General evaluations of the performance of virtualized systems such as Xen[10] have been studied extensively and Xen has been shown to impose negligible overheads in both micro and macro benchmarks [11][12]. However, these were evaluations of Xen itself in a controlled cluster environment whereas we are evaluating Amazon’s specific implementation and customizations of Xen and their overall product offering including networking. Amazon’s multiplexing of physical resources and networks introduces sources of performance limiters not found in these previous works.

## 3. Evaluation Setup

Our experimental setup included clusters composed of each EC2 64-bit instance type as well as our local 32-bit cluster. For creating and managing our EC2 clusters we utilized an existing project which provided Python scripts to handle most operations. We describe that project and the specifics of the EC2 instance types below. We also describe the configuration of our local resources that we used to compare the EC2 results against.

### 3.1. EC2 Overview

Amazon’s EC2 service has become the standard-bearer for Infrastructure-as-a-Service (IaaS) providers. It is the most popular and provides many different service levels. Machine instances are available in the following configurations:

| Instance Type              | CPU       | Mem (GB) | Disk (GB) | I/O Perf. | Cost /Inst-hr.** |
|----------------------------|-----------|----------|-----------|-----------|------------------|
| M1.Small<br>32bit,1 core   | 1*<br>ECU | 1.7      | 160       | Mod       | \$0.10           |
| M1.Large<br>64bit,2 cores  | 2*<br>ECU | 7.5      | 850       | High      | \$0.40           |
| M1.XLarge<br>64bit,4 cores | 2*<br>ECU | 15       | 1690      | High      | \$0.80           |

|                            |             |     |      |      |        |
|----------------------------|-------------|-----|------|------|--------|
| C1.Medium<br>32bit,2 cores | 2.5*<br>ECU | 1.7 | 350  | Mod  | \$0.20 |
| C1.XLarge<br>64bit,8 cores | 2.5*<br>ECU | 7   | 1690 | High | \$0.80 |

**Table 1. Amazon EC2 Instance Types**

\*1 ECU (EC2 Compute Unit) is equivalent to 1.0-1.2 GHz 2007 Opteron or 2007 Xeon processor capacity [6]. \*\* Indicates Linux pricing only, Windows Server prices are higher.

Amazon utilizes a customized version of Xen to host the AMIs. Instance operating systems available are: Windows Server 2003, Red Hat Linux, Fedora Core, openSUSE, Gentoo, Oracle Enterprise Linux, Ubuntu, and Debian Linux. While each instance has storage associated with it, the local instance storage is not persistent across instance termination, so other solutions, such as Amazons Simple Storage Service (S3) or Elastic Block Store (EBS) are required. However, for this work we did not to utilize either of those services since we are only evaluating the network and processing capabilities of EC2 rather than the storage capabilities.

In terms of service agreement terms, EC2’s service agreement states an availability level of 99.95% and Amazon will credit your account if it falls below that during a 365 day period. They also claim an internal network bandwidth of 250 Mbps regardless of instance type, although this is not included in the official instance type specification.

After working to build our own Amazon Machine Images (AMIs) we found a project called ElasticWulf [3], which in addition to providing a pair of AMIs that have multiple MPI libraries (MPICH2, LAM, and OpenMPI) and OpenMP already installed, also included scripts to start, stop, and monitor a cluster of EC2 machines. ElasticWulf requires only the installation of the Amazon command line tools and API libraries. It includes the basics to get a cluster up and running that has a shared NFS directory as well as the MPI runtime, various Python MPI libraries and tools, and Ganglia for monitoring the cluster via the web. The specific AMI’s that it uses are based on Fedora Core 6 and are 64-bit. The AMI numbers are: ami-e813f681 and ami-eb13f682 for the master node and the worker nodes respectively. ElasticWulf also works with any AMI, not just the supplied ones. There are also alternative 32-bit images provided although they do not include the NFS share and Ganglia. Our specific configuration was using MPICH2, *mpicc* version 1.0.6 specifically, on top of Fedora Core 6 and using *gcc* 4.1.2. for the x86\_64 architecture.

For our MPI tests we constructed a cluster of each of the instance types which are 64-bit. We feel that while

the 32-bit instances may be more cost-effective 64-bit is the standard for scientific computations as well as providing substantially more memory, which is often a large performance enhancer for CPU-bound applications. For the memory bandwidth tests we utilized a single node of each instance type.

### 3.2. Local Resources

To give context and a baseline to the EC2 performance numbers we ran the same benchmarks on our locally owned cluster. The Sunfire cluster is composed of nodes with 32-bit Intel Xeon processors has the following specifications: 2 Physical CPUs Intel Xeon 2.80Ghz with HyperThreading (CPU Family 15, model 2, stepping 7); 512KB L2 cache, 3GB RAM SDRAM, 400Mhz FSB, and Gigabit Ethernet NIC. The *mpicc* version was 1.0.8p1 and *gcc* was version 4.2.4. The platform was x86 32-bit and the MPI library used was OpenMPI 1.3 [15].

The other locally-owned resource we use for comparison is Camillus. Camillus is a 64-bit dual-CPU Intel Xeon E5345 Quad-Core machine (8 cores total) with a 1333 Mhz FSB, 16GB DDR2 RAM, and a Gigabit Ethernet NIC. We use this machine for comparison in the memory-bandwidth benchmarks since it represents current CPU designs better than the Sunfire cluster nodes do.

## 4. Evaluation

To evaluate the performance of EC2 clusters against that of a small commodity cluster we created clusters of each EC2 instance type and benchmarked their performance using the STREAM memory bandwidth benchmark and then Intel’s MPI Benchmark version 3.2[14]. We did not utilize a CPU ALU-op performance benchmark because Xen’s CPU performance has been studied extensively and in scientific applications which require a cluster the performance limiter is usually the interconnect or the memory bandwidth on each node since CPU performance has increase much more rapidly than either network or memory performance.

### 4.1. Memory Bandwidth

Many scientific applications involve operations on large amounts of data stored in memory. Thus, it is important to evaluate the memory-bandwidth of the EC2 instance types in order to see how they compare to non-virtualized resources. In this case we did not directly compare an EC2 instance’s performance to the performance of the same CPU in a non-virtualized environment. Others have examined the performance overhead of virtualization [11][12] on performance,

and part of the abstraction of EC2’s “Cloud” paradigm is that the underlying resources can change arbitrarily, so no single processor can be designated as the EC2 standard.

The results of running STREAM with array length of 10 million integers follow:

| Machine Spec | 1 Thread Bandwidth in GB/s |       |       |       |
|--------------|----------------------------|-------|-------|-------|
|              | Copy                       | Scale | Add   | Triad |
| M1.Large     | 2.058                      | 1.777 | 1.868 | 1.725 |
| M1.XLarge    | 2.551                      | 2.394 | 2.434 | 2.178 |
| C1.Medium    | 2.865                      | 2.852 | 3.114 | 3.097 |
| C1.XLarge    | 2.849                      | 2.840 | 3.126 | 3.120 |
| Camillus     | 2.834                      | 2.830 | 3.171 | 3.160 |
| Sunfire      | 1.341                      | 1.325 | 1.663 | 1.662 |

**Table 2. Single Thread CPU Memory Bandwidth**

The performance of the EC2 nodes is similar to Camillus, which is the most modern processor of the locally-owned machines. We see a definite advantage in the newer DDR and DDR2 memory architectures found and higher front-side bus clock-rates in the EC2 nodes as opposed to the older non-DDR systems of the Sunfire cluster and its 400Mhz FSB.

| Machine Spec | N Threads Bandwidth in GB/s |       |       |       | N  |
|--------------|-----------------------------|-------|-------|-------|----|
|              | Copy                        | Scale | Add   | Triad |    |
| M1.Large     | 3.244                       | 3.186 | 3.564 | 3.508 | 2  |
| M1.XLarge    | 3.748                       | 3.936 | 3.717 | 3.714 | 4  |
| C1.Medium    | 4.241                       | 4.494 | 4.840 | 4.796 | 2  |
| C1.XLarge    | 4.807                       | 4.788 | 5.149 | 5.161 | 8  |
| Camillus     | 4.653                       | 4.661 | 4.895 | 5.007 | 8  |
| Sunfire      | 1.441                       | 1.458 | 1.626 | 1.622 | 2* |

**Table 3. N threads (cores) CPU Memory Bandwidth. \*Sunfire is a Xeon processor with HyperThreading not 2 physical cores. These results are only for comparison.**

It is worth noting here that I am running 64-bit programs, not 32-bit as Evangelinos and Hill did. Thus, there are some discrepancies in the bandwidth numbers.

However, we see that the EC2 nodes perform as well or better than both the Centurion and Generals nodes in most of the tests. It is no surprise that they outperform the Centurion nodes due to their newer memory (DDR2), but they also hold their own against Camillus, which is a relatively new machine itself. This shows that we can expect reasonable to good memory

bandwidth performance even though the machines are virtualized.

## 4.2. Intel MPI Benchmarks v3.2

The most useful measure of the performance of a cluster is how well it performs on the specific code that it is being used for. Since a large proportion of scientific applications utilize MPI for inter-process communication, we have tested the various EC2 instance types using the Intel MPI Benchmarks (IMB) version 3.2[14]. We present here the results for the IMB-MPI1 suite of benchmarks which evaluate the MPI v1 specification. We believe that the common operations in most applications are covered in this suite and that the extensions provided in the MPI 2 specification while useful, would not paint a significantly different picture of the relative performance of EC2 instances compared to our local cluster. Thus, we have omitted those results for both brevity and clarity.

Each of the benchmarks presented here measures the average latency for messages passed of a given size. Each data point is an average of multiple runs (1000 for the smaller data points up to 32K and 10 for the 4 MB messages). These averages are reported by the IMB code itself. We do not present the minimums and maximums for sake of clarity.

There are three classes of benchmark: Single Transfer, Parallel Transfer, and Collective. The PingPong and PingPing benchmarks (Figures 1 - 4) compose the Single Transfer class while SendRecv and Exchange (Figures 5 - 8) compose the Parallel Transfer class with the remaining benchmarks (Figures 8 - 16) composing the Collective class. More information about each benchmark including the specific communication patterns in each can be found on the Intel MPI Benchmarks website [14].

Each of the benchmarks was run such that only a single MPI process was run on each node. Thus, even though some EC2 instance types have multiple virtual cores we did not match the number of MPI processes to the number of cores on the virtual machine because we are focusing on the network performance and co-location of MPI processes on nodes would not measure that accurately. Also, we were interested to see if requesting larger node types might reduce the possibility of being co-located with another user’s instances and thus reduce or eliminate contention for the I/O system, including the network.

In the following figures we show the results of running each benchmark on a cluster of 16 nodes of each EC2 64-bit instance type as well as our local cluster. The Single Transfer benchmarks (Figures 1 -

4) utilize only 2 nodes in each cluster for their measurements, but all other utilize the full 16 nodes. We conducted runs of the benchmarks using 4 and 8 nodes of each cluster as well but found that the results were not significantly different than for those run with 16 nodes.

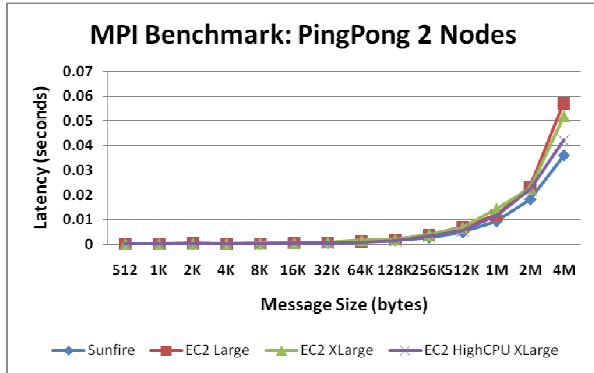


Figure 1. Average Latency of PingPong

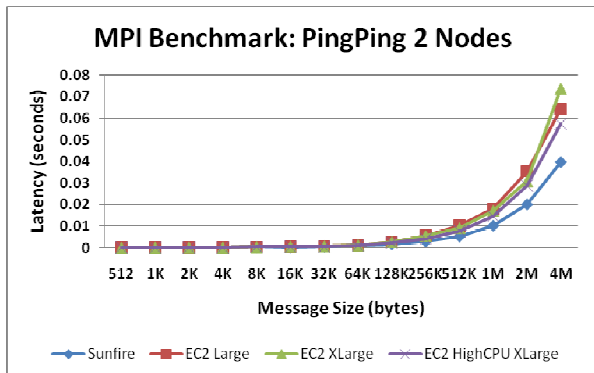


Figure 2. Average Latency of PingPing

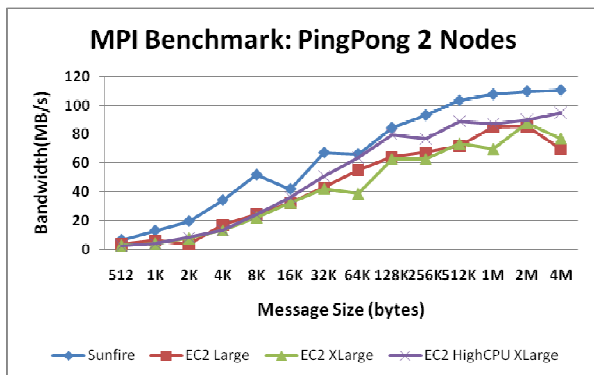


Figure 3. Bandwidth of PingPong

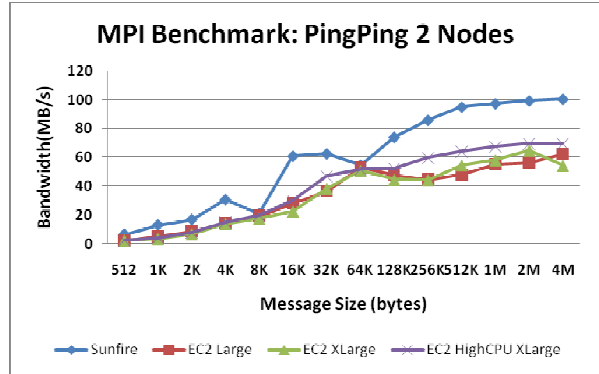


Figure 4. Bandwidth of PingPing

In the Single Transfer benchmarks (Figures 1 - 4) we see that the EC2 instance type is not a great determiner of performance. The message latency of the EC2 clusters, while not as low as that of the Sunfire cluster, is well below an order of magnitude lower and is generally below 2X higher than that of the Sunfire cluster.

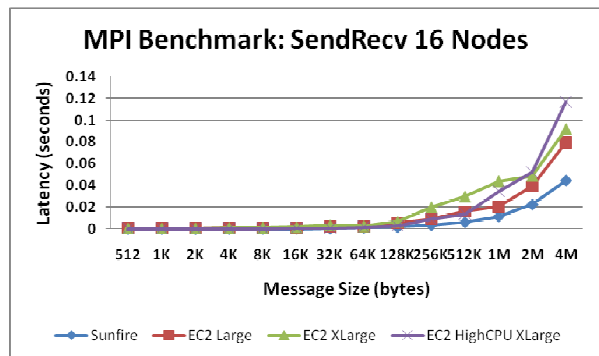


Figure 5. Average Latency of SendRecv

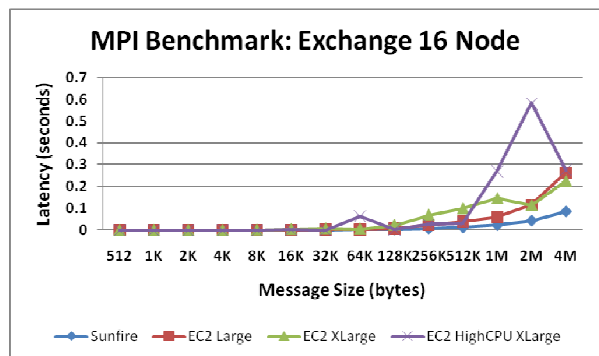


Figure 6. Average Latency of Exchange

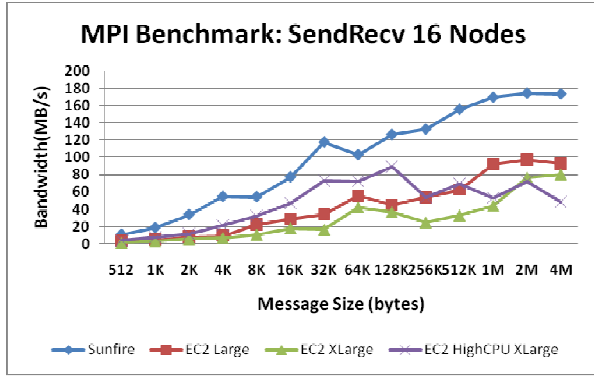


Figure 7. Bandwidth of SendRecv

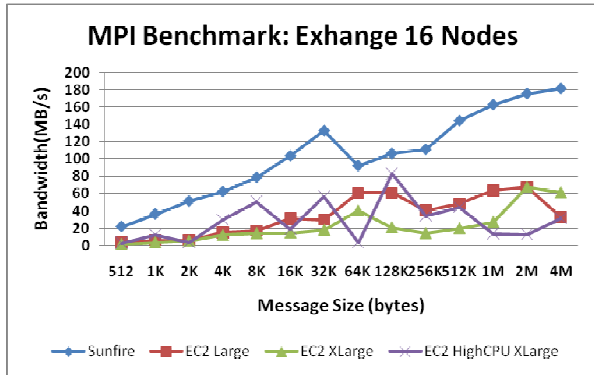


Figure 8. Bandwidth of Exchange

The Parallel Transfer benchmarks (Figures 3 & 4) show that again all EC2 clusters trail the local cluster, Sunfire, in terms of latency, but not by large margins. The spike seen in Figure 4 at the 2MB message size for the EC2 HighCPU XLarge instance-type cluster is interesting in that we do not expect to have I/O performance isolation issues in this instance type due to the fact that it occupies 8 cores which would fill a dual-CPU quad-core server. Thus, this abnormality could be either due to network contention, most likely, or evidence that performance isolation between hosted VMs is still an issue even when utilizing 8 virtual cores. Note that the results are averaged over 6 runs as opposed to the 20 that are normal used. This indicates that the benchmark experienced difficulty completing all the repetitions which most likely indicates network problems.

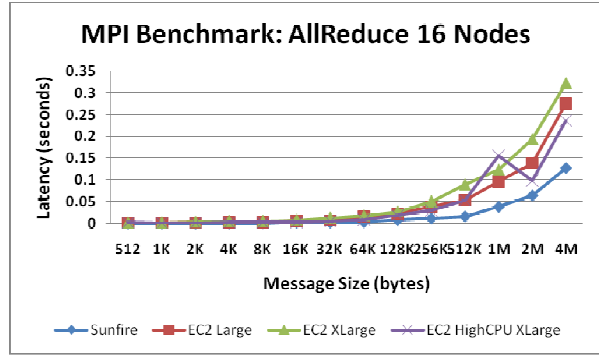


Figure 9. Average Latency of AllReduce

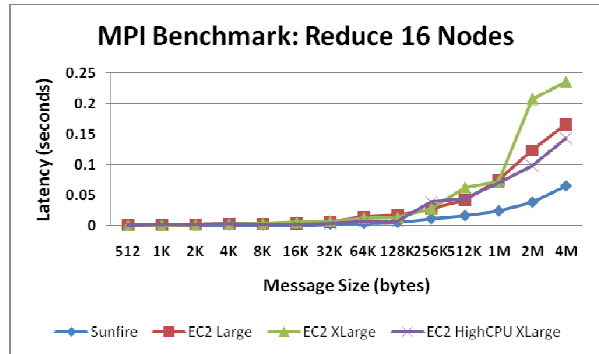


Figure 10. Average Latency of Reduce

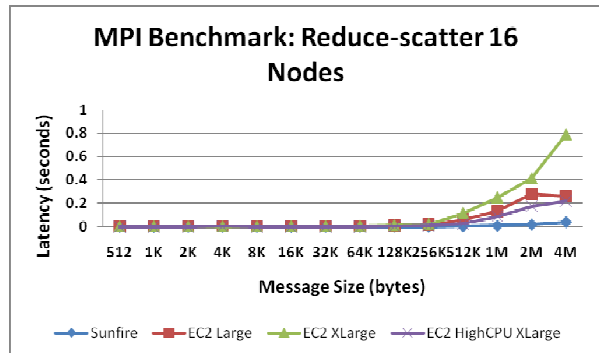


Figure 11. Average Latency of Reduce-scatter

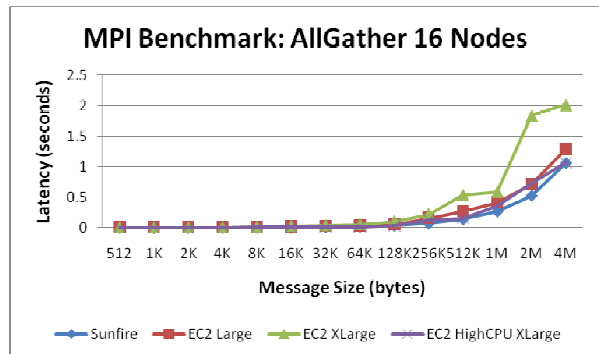


Figure 12. Average Latency of AllGather

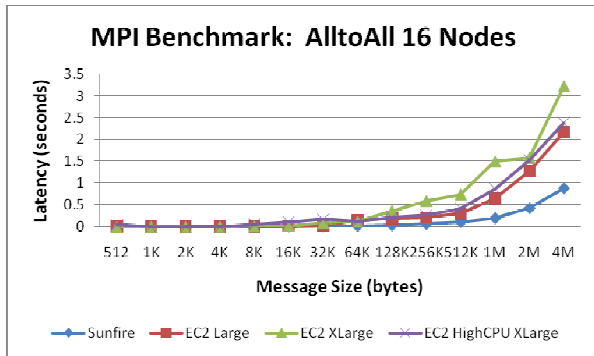


Figure 13. Average Latency of AlltoAll

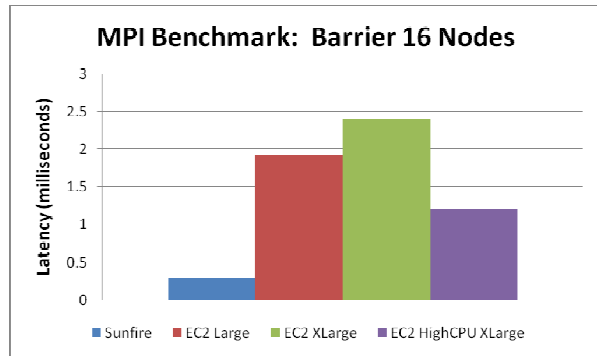


Figure 17. Average Latency of Barrier

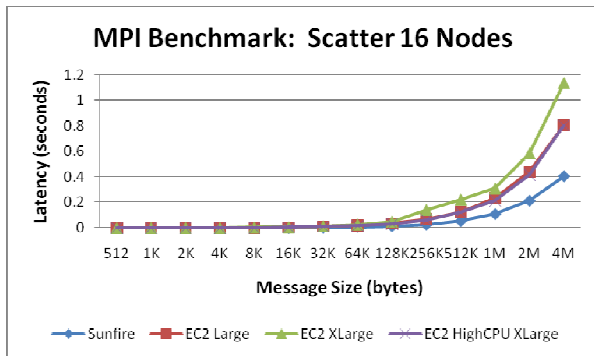


Figure 14. Average Latency of Scatter

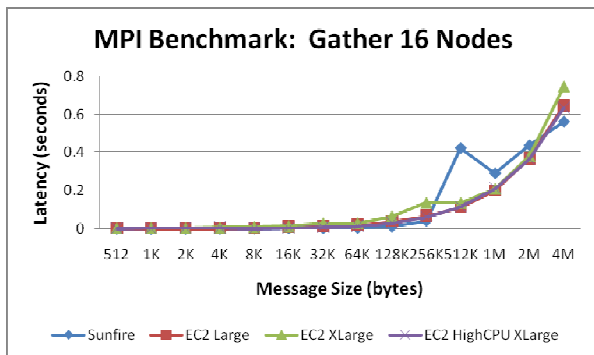


Figure 15. Average Latency of Gather

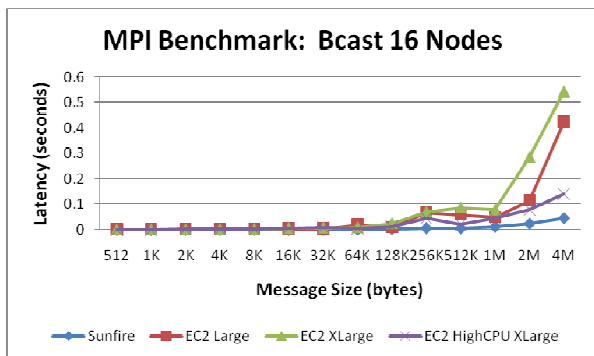


Figure 16. Average Latency of Bcast

The results for the Collective class of benchmarks generally show that the local Sunfire cluster still has a distinct advantage in network latency performance, and that while the EC2 “High-CPU X-Large” instance type usually has the highest performance of the EC2 clusters it is not a significantly better performer despite its virtual CPUs clock rate advantage. Also of note in all the results is that the “XLarge” EC2 instance type was almost always the worst performer despite having the same virtual clock rate as the “Large” instance type and twice as many virtual cores. While we did not expect the core count to directly impact the MPI results, because we didn’t schedule multiple processes on a single node, we did hope to see that requesting more cores would improve performance by reducing the possibility of a co-hosted instance from another user interfering with the I/O of our instances. This did not appear to be the case, however.

## 6. Discussion

There are several influences on performance which are of concern in virtualized environments such as EC2. These include: cache behavior, buffer-copy costs, and I/O sharing between instances. Cache behavior is critically important to the performance of programs, and good cache management can result in significant performance gains. The difficulty in a virtualized environment is that it is not clear how the caches are shared and whether cache-pollution is possible from other VMs. This is particularly the case for multi-core CPUs with shared L2 caches such as most Intel processors. Since the caches are not explicitly controlled by software (either the application or the operating system) this cannot be controlled by the VMM. Thus, in a pathological case where another VM instance is running on the same physical machine and is using a lot of the shared cache a user may see significantly slower performance than he would on a dedicated machine.

One potential solution to this is to simply pay for a larger instance in EC2, although our results did not reinforce this idea. The larger instances occupy more of the CPUs and cores than the smaller instances do. For example, the C1.XLarge instance type has 8 cores, which presumably is a single physical machine with two quad-core processors dedicated solely to that instance. Thus, even if you don't need more cores, by reserving them you may be able to stabilize performance since other VMs will not be hosted on the same physical machine. However, this cannot be guaranteed in the future as physical machines will have more cores and thus co-hosting may again take place even for large instance types.

A similar problem exists with the I/O subsystem of a physical machine. It necessarily must be multiplexed across the instances being hosted. Thus, one VM's I/O performance may affect that of another user. It is not clear whether Amazon has addressed this in their version of the Xen hypervisor, but this would require controlling I/O request routing to the hardware in the host operating system. The same solution as for the cache behavior may work for this case as well. By reserving larger instances you limit the amount of external interference that your VM instance can receive.

## 7. Conclusions

The emergence of EC2 and other cloud resource hosting platforms has enabled scientists to create clusters of machines on-demand and use them for small to medium scale computational science problems. We showed that while EC2 clusters are not the highest performers, they do provide reasonable performance which when coupled with their low cost and ease of use may provide an attractive alternative to dedicated clusters.

EC2 is not the best platform for tightly-coupled synchronized programs with frequent but small communication between nodes. The high latency kills performance. However, the bandwidth available between nodes suggests that less frequent but quite large data exchanges are acceptable and thus redundant computation may be a way to extract extra performance.

In all, EC2 is not a high-performance system which will replace *specialized* clusters any time soon, but it does offer on-demand capabilities which are very

useful for debugging and smaller scale computations. Using preexisting tools we were able to create and setup a cluster within minutes and using only three shell scripts. This is the beauty of EC2, its configurability and ease of use. We believe it would make a suitable small scale cluster for research groups, labs, and departments.

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