

# Worldwide Fast File Replication on Grid Datafarm

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The Grid Datafarm architecture is designed for global petascale data-intensive computing. It provides a global parallel filesystem with online petascale storage, scalable I/O bandwidth, and scalable parallel processing, and it can exploit local I/O in a grid of clusters with tens of thousands of nodes. One of features is that it manages file replicas in filesystem metadata for fault tolerance and load balancing.

This paper discusses and evaluates several techniques to support long-distance fast file replication. The Grid Datafarm manages a ranked group of files as a Gfarm file, each file, called a Gfarm file fragment, being stored on a filesystem node, or replicated on several filesystem nodes. Each Gfarm file fragment is replicated independently and in parallel using rate-controlled HighSpeed TCP with network striping. On a US-Japan testbed with 10,000 km distance, we achieve 419 Mbps using 2 nodes on each side, and 741 Mbps using 4 nodes out of 893 Mbps with two transpacific networks.

## 1. Introduction

Petascale data intensive computing wave has been coming such as high-energy physics data analysis, astronomical data analysis, and bio-informatics data analysis. More than ten petabyte storage needs to be shared and analyzed by world-wide users with high efficiency, high security, and high dependability.

The Grid Datafarm architecture [1] is designed for global petascale data-intensive computing to enable the process of large amounts of data at multiple regional PC clusters. The aim of this research is to establish a large-scale parallel filesystem by exploiting local storage of cluster nodes spread in the extensive area, a platform system needed to support a petabyte scale data intensive computing. The Grid Datafarm architecture enables high-speed access to a large amount of data by utilizing file access locality, and realizes fault tolerance of disks and networks by data replication.

This paper discusses about long-distance fast file replication on the Grid Datafarm. To improve the performance in high bandwidth-delay product networks, congestion control keeping efficient, fair, scalable, and stable plays a key role. The easiest way to improve the performance is to open multiple TCP connections in parallel, while this approach leaves the parameter of the number of connections to be determined by the user, which may result in heavy congestion with too much number of connections. There are several researches addressing this issue such as HighSpeed TCP [2], Scalable TCP [3], FAST TCP [4], and XCP [5]. HighSpeed TCP is an attempt to improve congestion control of TCP for large congestion windows with better flexibility, better scaling, better slow-start behavior, and competing more fairly with current TCP,

keeping backward compatibility and incremental deployment. It modifies the TCP response function only for large congestion windows to reach high bandwidth reasonably quickly when in slow-start, and to reach high bandwidth without overly long delays when recovering from multiple retransmit timeouts, or when ramping-up from a period with small congestion windows.

For file replication of large files in high bandwidth-delay product networks, it is also necessary to improve disk I/O performance not only the network performance. At this time, each cluster node has capability to transmit at a rate of 1 Gbps, while the performance of an IDE or a SCSI disk is at most 50 MB/s. To improve the disk I/O bandwidth, disk striping such as RAID-0 is effective.

This paper is organized as follows. In Section 2, the file replication on the Grid Datafarm is discussed. Section 3 evaluates the network performance and the file replication performance using a US-Japan Grid Datafarm testbed.

## 2. File Replication on Grid Datafarm

The Grid Datafarm provides a Grid file system that federates multiple local filesystems on a Grid across administrative domains. The Grid file system provides virtualized hierarchical namespaces for files having consistent access control with flexible capabilities management. There is a replica catalog to manage mappings from the hierarchical namespace for files to one or more physical file locations. This enables efficient, dependable, and transparent file sharing on a Grid.

The Grid Datafarm has a feature for data parallel execution. It manages a ranked group of files as a single Gfarm file. This makes it possible to manage a lot of distributed files as a single file, which will be analyzed in parallel. Each parallel process possibly generates a new set of output files also managed as a single file. File-affinity scheduling and new concept of a file view enable the “owner computes” strategy, or “move the computation to data” approach for the parallel data analysis.

When replicating a Gfarm file, each file of the Gfarm file, or a group of files, stored on a different filesystem node can be replicated in parallel and independently. File replication on the Grid Datafarm is considered to be a parallel file replication from multiple cluster nodes to (different) multiple cluster nodes.

In high bandwidth-delay product networks, multiple TCP streams, or network striping, is effective to improve the performance, while disk accesses to striping data decreases the performance of the disk I/O. It is necessary to utilize a modified TCP or other protocols to achieve high performance with a single stream. HighSpeed TCP is one of proposals of the modification of congestion control of TCP, which is utilized by the performance evaluation on a US-Japan Grid Datafarm testbed.

As described in Section 1, the disk I/O performance is poorer than the network bandwidth on each cluster node. One of requirements from the Grid Datafarm architecture is a dense and high-performance storage on each node for online petabyte-scale storage. To meet this requirement, each node of the AIST Gfarm cluster was designed to be a 1U server having a 3ware RAID card with four 120GB IDE disks in RAID 0 that achieves 480 GB storage capacity and over 110 MB/s for contiguous block reads and writes that is comparable with the network performance.

### 3. Performance Evaluation

#### 3.1. PC clusters and wide-area networks

During the international conference SC2002, held in Baltimore from November 16th to November 22nd of 2002, a Grid Datafarm Data Grid environment was set up linking seven PC clusters in both Japan and the U.S.

Seven systems of PC clusters, including the one at the SC2002 booth (a total of 190 PCs) were located in the research centers of both Japan and the U.S. (AIST, High Energy Accelerator Research Organization, Tokyo Institute of Technology, the University of Tokyo, Indiana University and San Diego Supercomputer Center (SDSC)). They were integrated with the Grid Datafarm Data Grid middleware [6] (Figure 1). Tsukuba WAN, APAN/TransPAC [7] and Maffin [8] supported in establishing the network.

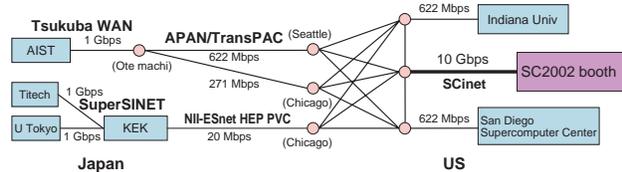


Figure 1: Network logical map of world-wide Grid Datafarm testbed. Four sites in Japan and three sites in U.S. are integrated with the Grid Datafarm Data Grid middleware.

The system had the peak floating-point performance of 962 Gflops. It was equipped with a large capacity file system of 18 TB at 6,600 MB/s access rate as a Gfarm wide-area filesystem.

This environment utilized multiple high-speed wide-area networks, that is, Tsukuba WAN and SuperSINET in Japan, APAN/TransPAC and NII-ESnet HEP PVC between Japan and the U.S., Abilene and ESnet in the U.S. and SCinet at the SC2002 booth. The bandwidth from SC2002 to both Indiana University and SDSC was 622 Mbps. In the transpacific network, it was 893 Mbps. Total theoretical maximum bandwidth of the network linking seven clusters was 2.173 Gbps one way (See Figure 1).

For the file replication, a large amount of scientific data taken from particle physics was generated mainly in the large-scale PC cluster of Tokyo Institutes of Technology and created data replicas of several hundreds of GB at each of the other clusters in a single filesystem image.

At the SC2002 booth in Baltimore, there was a 12-node AIST Gfarm cluster connected with gigabit ethernet that connects to the SCinet with 10 gigabit ethernet using the Force10 E1200 switch. Each node consisted of a dual Intel Xeon 2.4GHz processor, 1GB memory, and a 3ware Escalade 7500-4 RAID controller with four 120GB 3.5” HDDs, which was configured in RAID-0. The disk I/O performance for contiguous blocks achieved 109 MB/s for writes and 168 MB/s for reads. The network bandwidth of gigabit ethernet was 941 Mbps using the iperf bandwidth measurement tool [9]. File replication performance was 75 MB/s, that was equivalent to 629 Mbps, using the Gfarm Data Grid Middleware.

At the Grid Technology Research Center, AIST in Tsukuba, Japan, there was the same 7-node AIST Gfarm cluster that connects to the Tokyo XP with gigabit ethernet via Tsukuba WAN and Maffin networks.

At the Indiana University, there was a 15-node PC cluster connected with Fast Ethernet connects to Indianapolis GigaPoP with OC-12. The disk I/O performance for contiguous blocks was 9.3 MB/s for writes and 10.2 MB/s for reads.

At the SDSC in San Diego, there was a 8-node PC cluster connected with gigabit ethernet that connects

Table I Round trip time between the SC2002 booth and other sites. 'AIST (N)' and 'AIST (S)' mean that IP packets are transmitted via the northern route and via the southern route, respectively

AIST (N)	199 msec
AIST (S)	222 msec
Indiana	30 msec
SDSC	86 msec

to outside with OC-12. The disk I/O performance for contiguous blocks was 29.4 MB/s for writes and 20.0 for reads.

APAN/TransPAC transpacific network consisted of two links; the northern route (OC-12 POS) between Seattle and Tokyo, and the southern route (OC-12 ATM) between Chicago and Tokyo. The southern route was shaped to 271 Mbps. By default, all IP packets were transmitted via the northern route. To utilize the both routes, we configured a static route such that every traffic between specific three nodes at SC2002 booth and AIST was transmitted via the southern route.

The round trip time (RTT) of IP packets between the SC2002 booth and other sites is shown in the Table I.

### 3.2. HighSpeed TCP over transpacific network

Figure 2 shows the measured network bandwidth of the HighSpeed TCP from the SC2002 booth in U.S. to the AIST in Japan via the APAN/TransPAC northern route. The bandwidth was measured using the iperf from one node to one node with two HighSpeed TCP streams. The buffer size of each socket was 8 MB, which gave the theoretical peak bandwidth 337 Mbps for one connection with the RTT 199 ms. From the Figure 2, the measured peak bandwidth achieved 529 Mbps in 5-second average out of the physical network bandwidth 622 Mbps. Due to the packet loss, the bandwidth occasionally dropped, however, it was recovered reasonably quickly thanks to the HighSpeed TCP.

Figure 3 shows the measured HighSpeed TCP bandwidth from Japan to U.S. via the northern route. The machine and network configurations were the same as the previous measurement except the traffic direction. Because the traffic was slightly heavy at this time, the measured peak bandwidth was 443 Mbps. After the heavy packet loss, the bandwidth was recovered slowly just like the regular TCP.

Figure 4 is the case using the APAN/TransPAC southern route. Since the southern route was shaped to 271 Mbps, one HighSpeed TCP stream would be

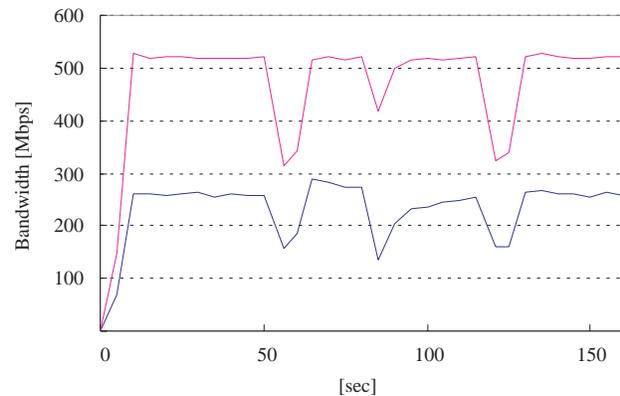


Figure 2: HighSpeed TCP bandwidth from U.S. to Japan via the APAN/TransPAC northern route (OS-12 POS).

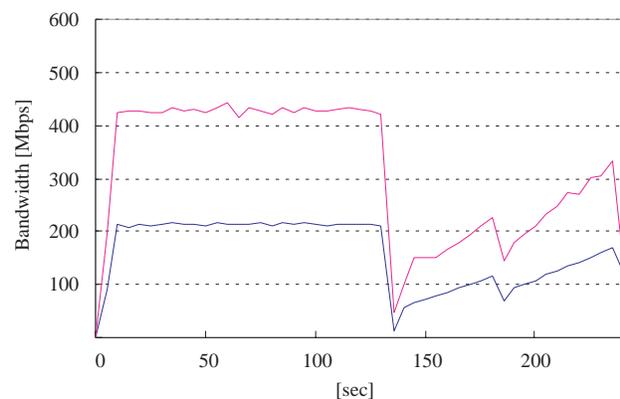


Figure 3: HighSpeed TCP bandwidth from Japan to U.S. via the APAN/TransPAC northern route (OS-12 POS)

able to fill the bandwidth. However, the stream suffered the critical packet loss, and only achieved 85.9 Mbps in 10-minutes average although 251 Mbps in 5-second peak bandwidth. One of reasons for the critical packet loss was the setting of an ATM switch configured without the random early drop. To cope with this problem, it is necessary to control the network traffic rate not to exceed the physical network bandwidth, that is, 271 Mbps.

When the maximum bandwidth of one HighSpeed TCP stream was limited to 100 Mbps, it was possible to achieve stable and high bandwidth shown by Figure 5. This rate control was realized by changing the network from gigabit ethernet to fast ethernet. This case achieved 166.1 Mbps in 10-minutes average, and 190.0 Mbps in 5-second peak bandwidth.

### 3.3. File replication

The performance of file replication of large files that do not fit the main memory is limited by the disk I/O performance and the network performance. When replicating between sites, the file replication perfor-

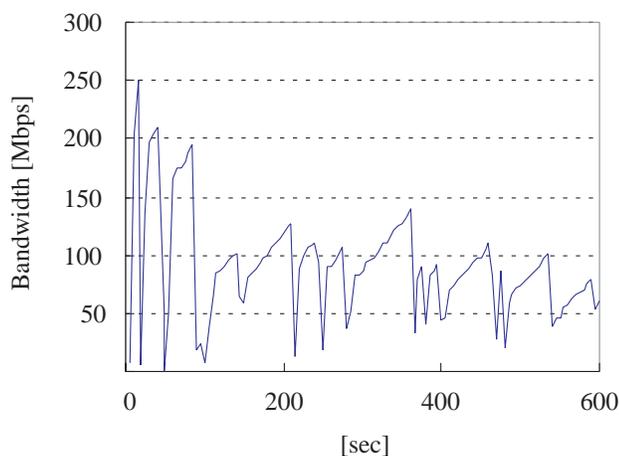


Figure 4: HighSpeed TCP bandwidth from Japan to U.S. via the APAN/TransPAC southern route (OC-12 ATM, 271 Mbps shaping) with one non-rate-limited HighSpeed TCP stream.

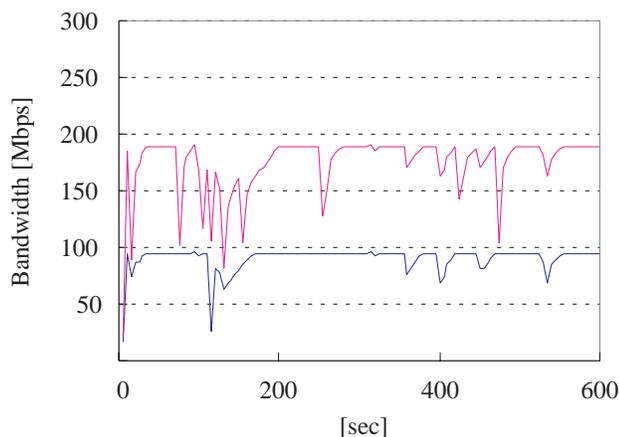


Figure 5: HighSpeed TCP bandwidth from Japan to U.S. via the APAN/TransPAC southern route (OC-12 ATM, 271 Mbps shaping) with two 100-Mbps HighSpeed TCP streams.

mance is also limited by the bandwidth of the wide-area network shown by Figure 1. Table II shows the performance limit of file replication with one node at each site.

Figure 6 shows the performance of file replication between one node at the SC2002 booth and various

Table II Performance limit of file replication using one node at each site in MB/s.

	To	From
Indiana	9.3	10.2
SDSC	29.4	20.0
AIST	109	112
SC2002	109	112

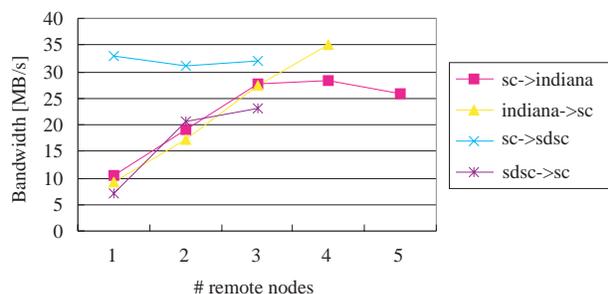


Figure 6: File replication performance between one node at SC2002 booth and several nodes at Indiana Univ. and SDSC.

number of nodes at Indiana Univ. and SDSC. Between the SC2002 booth and Indiana Univ., the file replication performance increased almost proportional to the number of nodes at Indiana Univ., and achieved the maximum performance of 34.9 MB/s, that is, 293 Mbps, from four nodes at Indiana Univ. to one node at the SC2002 booth with a 4GB file.

From the SC2002 booth to SDSC, the file replication performance of a 2GB file achieved 32.8 MB/s even with one node at SDSC. On the other hand, the performance from SDSC to the SC2002 booth showed a different tendency to increase scalable with respect to the number of nodes at SDSC. One reason was this direction requires multiple HighSpeed TCP streams to improve the network performance because one stream achieved only 1.1 to 2.3 Mbps. For the file replication from SDSC to the SC2002 booth, seven parallel streams were used in each node pair.

Table III showed parameters and the measured bandwidth of file replication from Baltimore in U.S. to Tsukuba in Japan at a distance of more than 10,000 km. As shown in the previous section, a High-Speed TCP stream achieved about 260 Mbps with socket buffer size 8 MB, while multiple rate-controlled streams were effective to stabilize the bandwidth.

To control and limit the traffic at any rate, the socket buffer size and the interval of sending data were adjusted. The interval of sending data was also needed to be adjusted to suppress too fast increase of the congestion window that causes the serious packet loss.

Using the northern route, 16 streams achieved the best bandwidth of 152 Mbps in average for file replication of a 2 GB file. Using the southern route, 8 streams achieved the best bandwidth of 93.9 Mbps in average for file replication of a 1 GB file. Using three node pairs for the northern route and one node pair for the southern route, the file replication of a 8 GB file achieved 458 Mbps in average, and 741 Mbps in 10-second peak bandwidth out of 893 Mbps.

For the SC2002 high-performance bandwidth challenge, parameters of Table IV was set up based on the previous measurement. In the remote site column, 'AIST N' means the AIST via the APAN/TransPAC

Table III Parameters and measured performance of US-Japan file replication

# node pairs	# streams	data size	10-sec average BW	Transfer time	Average BW
1 (N1)	1 (N1x1)	2 GB	n/a	162.6 sec	106 Mbps
1 (N1)	8 (N8x1)	2 GB	n/a	124.7 sec	138 Mbps
1 (N1)	16 (N16x1)	2 GB	n/a	113.0 sec	152 Mbps
1 (S1)	1 (S1x1)	1 GB	n/a	193.0 sec	44.5 Mbps
1 (S1)	8 (S8x1)	1 GB	170 Mbps	91.5 sec	93.9 Mbps
1 (S1)	16 (S16x1)	1 GB	n/a	173.3 sec	49.6 Mbps
2 (N2)	32 (N16x2)	2×2 GB	419 Mbps	115.9 sec	297 Mbps
3 (N3)	48 (N16x3)	2×3 GB	593 Mbps	139.6 sec	369 Mbps
4 (N3+S1)	56 (N16x3+S8x1)	2×4 GB	741 Mbps	150.0 sec	458 Mbps

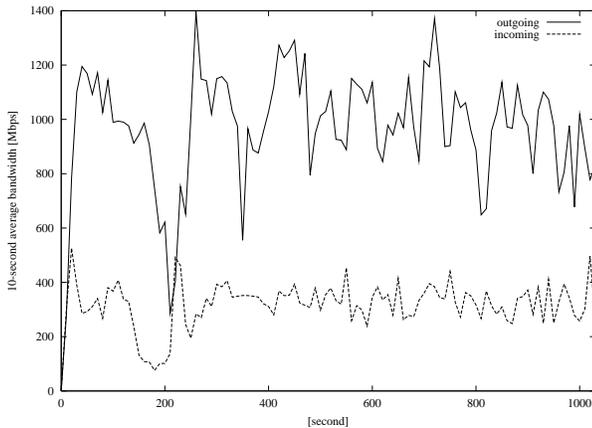


Figure 7: File replication performance in 10-second average between the SC2002 booth and other sites during the SC2002 high-performance bandwidth challenge.

northern route, and ‘AIST S’ means the AIST via the southern route. The ‘Measured BW’ column shows the measured average bandwidth of file replication of a 1 GB or 2 GB file, which is not the same as 5-second or 10-second peak bandwidth.

The average bandwidth in one to two minutes would be expected to be achieved over 1.43 Gbps for outgoing traffic and over 487 Mbps for incoming traffic, over 1.92 Gbps in total for both directions, if there were no unknown congestion and no unexpected packet drop by using several networks simultaneously.

As a result, the file replication performance was shown by Figure 7 in 10-second average bandwidth. The peak bandwidth was 1.40 Gbps for outgoing traffic, and 0.526 Gbps for incoming traffic. The 0.1-second average bandwidth measured by the SCinet showed 1.691 Gbps for outgoing traffic, and 0.595 Gbps for incoming traffic, 2.286 Gbps in total for both directions using 12 nodes in Baltimore.

## 4. Summary and Future Work

The Grid Datafarm is an architecture for petabyte-scale data-intensive computing providing online ten petabyte-scale storage, an I/O bandwidth scales to the TB/s range and scalable computational power, which is securely and dependably shared on a Grid. This paper discussed and evaluated the performance of file replication on the Grid Datafarm.

For the evaluation of the network performance in high bandwidth-delay product networks between U.S. and Japan, the HighSpeed TCP performed very well on the transpacific network of OC-12 POS, and achieved 529 Mbps in 5-second average using two streams of one node pair. On the other hand, the application-level rate-control of a HighSpeed TCP stream was necessary for the network of OC-12 ATM to achieve stable and high bandwidth.

Within the U.S., the file replication showed any performance problem, while between U.S. and Japan, application-level rate-control of a HighSpeed TCP were also needed for stability. As a result, using three node pairs for the northern route and one node pair for the southern route, the file replication of a 8 GB file achieved 741 Mbps in 10-second average out of 893 Mbps.

Between the SC2002 booth and other three sites including a Japan site, the peak bandwidth of file replication in 0.1-second average showed 1.691 Gbps for outgoing traffic, and 0.595 Gbps for incoming traffic, 2.286 Gbps in total for both directions using 12 nodes in the SC2002 booth.

The Grid Datafarm can be applied to theoretical or experimental science that calls upon large-scale data analysis and simulation. We are planning to evaluate it using large-scale production applications such as high-energy physics data analysis, analysis of observational data of all-sky multiple wavelength bands in astronomy, gene analysis in bio-informatics and so on on a world-wide Grid Datafarm testbed.

Table IV Parameters for file replication and expected bandwidth from and to a 12-node Gfarm cluster at SC2002 booth

Outgoing traffic					
# nodes in Baltimore	Remote site	# nodes at remote site	# streams /node	Socket buffer size, rate limit	Measured BW (1-2min avg)
3	SDSC	5	1	1 MB	> 60 MB/s
2	Indiana	8	1	1 MB	56.8 MB/s
3	AIST N	3	16	610 KB, 50 Mbps	44.0 MB/s
1	AIST S	1	16	346 KB, 28.5 Mbps	10.6 MB/s
9	S,I,A	5,8,4	-		> 171 Mbps (> 1.43 Gbps)
Incoming traffic					
1	SDSC	3	7	7 MB	23.1 MB/s
1*	Indiana	4	1	1 MB	34.9 MB/s
1*	AIST N	1	1	610 KB, 50 Mbps	n/a
1	AIST S	1	1	346 KB	n/a
3	S,I,A	3,4,2	-		> 58 MB/s (> 487 Mbps)

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