A Performance Analysis of the iSCSI Protocol

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Abstract

Fibre channel has long dominated the realm of storage area networks (SAN's). However, with increased development and refining, iSCSI is fast becoming an equal contender, which is causing many companies to reconsider how future storage networks shall be implemented. In addition to reduced costs and a unified network infrastructure, iSCSI allows for the deployment of storage networks over a commodity internet. Moreover, there are inexpensive software implementations of the iSCSI protocol that may provide compelling platforms for iSCSI deployment.

This paper discusses findings of a performance study on the iSCSI protocol in four different configurations. The first two consist of iSCSI in a more commercial setting, where specialized hardware is used for the iSCSI target and two different configurations are examined for the initiator. These results are contrasted with the performance of fibre channel in a similar setting. The second two configurations focus on iSCSI deployed purely in software in both SAN and WAN environments.

The performance results indicate that the iSCSI protocol can be severely limited by the implementation. This is due to either inefficient handling of the underlying network, or to not using sufficient system resources to take advantage of a network.

1. Introduction

Internet SCSI, or iSCSI is a newly emerging protocol within the realm of storage area networks (SAN) [1]. The protocol essentially encapsulates a SCSI subsystem within a TCP/IP connection. This allows for greater flexibility within storage area networks as they can now be implemented using less expensive components. For example, current prices for gigabit Ethernet interfaces range from $40-120, and high performance 24-port gigabit Ethernet switches can be purchased for $2500. Moreover, iSCSI may have greater flexibility, since remote access to a SCSI device can occur over any TCP/IP network infrastructure, with the remote device being treated by the operating system as a locally accessed block-level device. However, the response to block-level requests may encounter more delay depending on issues such as network traffic. In fact, one of the main challenges that faces iSCSI is its efficiency and performance against existing technologies such as fibre channel.

In this study, the iSCSI protocol is compared to fibre channel in a commercial environment. In this set of experiments, a commercial iSCSI software implementation and a hardware iSCSI implementation are compared against a fibre channel protocol. The iSCSI implementations are connected to a gigabit Ethernet which is in turn connected to a fibre channel switch. Thus, both the iSCSI and fibre channel requests arrive at the attached disk over fibre.

Having examined the performance of a commercial iSCSI environment, the performance of existing open-source implementations of the iSCSI protocol in a SAN as well as a wide area network environment are investigated. The overall performance of iSCSI in comparison with the performance of the underlying network is investigated, as well as the effect an attached device has on the protocol's performance.

Our evaluation indicates that within a SAN environment:

- The performance of a commercial iSCSI software implementation compared quite favorably with fibre channel. Surprisingly, the hardware initiator implementation did not perform very well.

- The performance of open-source iSCSI implementations is very dependent on the disk throughput, and high-performance iSCSI SAN's will benefit from specialized iSCSI target-specific hardware.

- Physical layer parameters such as Ethernet frame sizes have a significant role in overall performance.

- Network layer parameters such as TCP window buffer sizes affect performance minimally.

A wide-area network was emulated by interposing a router that causes specific degrees of packet loss, reordering and delay. For this network, we found that:

- Both network layer properties, such as TCP window buffering, and the implementation of the iSCSI protocol play a dominant role in overall performance.

- Physical and protocol layer properties appear to play a minor role in overall performance.

The experimental results also show that it is inadvisable to use a single set of network parameters for an iSCSI target when that target is likely to be used in a WAN environment; as with many other data transport protocols, network parameters such as the socket buffer size must be tuned to the bandwidth delay product of the underlying network.

Before describing the experimental test-beds and results, Section 2 briefly describes some of the tools and software systems that were used in running the experiments. This is followed by three major sections that describe a commercial iSCSI configuration in a SAN environment, an iSCSI configuration in a SAN environment using an open-source software iSCSI implementation, and a configuration using a software iSCSI implementation in a WAN environment. For each configuration, the hardware environment for that configuration is described, followed by a presentation and discussion of the experimental results for that configuration. Finally, our summary and conclusions are presented in Section 6.

2. Software Measurement Environment

This section details the tools used for gathering measurements from both the experimental environments used to profile iSCSI, as well as the iSCSI protocol itself. Additionally, a brief overview of the systems used in our analysis is provided.

2.1. Software Measurement Tools

The *Iometer* benchmarking kit was used within the exploration of the commercial implementations of iSCSI along with the fibre channel evaluation [2]. Iometer was simple to install on the platform used, and provided a comprehensive look at the performance of various configurations of the hardware based iSCSI tests.

The *NetPerf* benchmarking utility was used to analyze the raw performance of the TCP/IP network [3]. Netperf was chosen for its robustness and ability to segment data into specific block sizes. This allowed us to compare the network performance with the overall block transfer performance of iSCSI.

The *lmdd* block device measurement, which is part of the *lmbench* system benchmarking toolkit, was used to gather data from low-level block transfers [4]. Lmdd is much like dd, with the added feature of writing out statistics such as overall time taken and throughput.

Finally, the last benchmark utility used to profile iSCSI was the *Bonnie* file benchmarking utility [5]. Bonnie provided data from a series of sequential file I/O, file seek frequency, and file rewriting statistics. The sequential file I/O data allows us to compare iSCSI's performance with a filesystem sitting on top of it with its performance at the block level.

2.2. Software Environment

Here we define the general software environment. Unless otherwise noted, it is assumed that the servers used were configured in the way mentioned here.

In general each system was configured using Mandrake Linux 8.2, which uses the 2.4.18 kernel. The filesystem of choice on the individual platforms was ext3.

We were able to find two iSCSI target/initiator pairs that were publicly available. The first was designed and is maintained by the UNH Interoperability Lab iSCSI Consortium [6]. The second is maintained by Intel, and is available from Sourceforge [7]. After some preliminary evaluations it was determined that the two versions were similar in performance. Thus, it was decided that the Intel iSCSI implementation would be used exclusively in our software-based implementations. Additionally, the iSCSI target was modified so that it could be configured to simply drop write transactions, and send off zero filled read transaction response packets. This was done so the iSCSI protocol could be measured without any dependence on an underlying disk, thus allowing the protocol overhead to be analyzed.

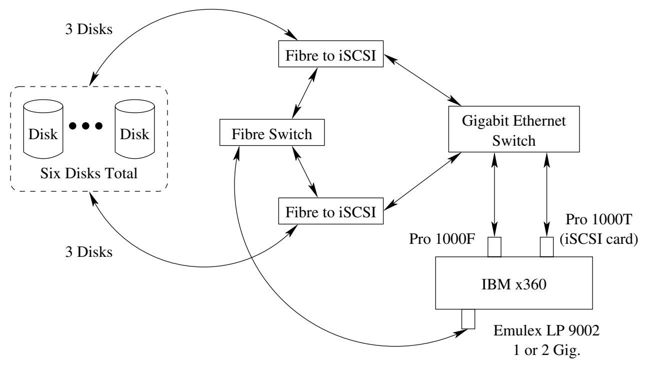

Figure 1. Experimental setup for commercially deployed analysis.

3. Commercial Deployment of iSCSI

This section discusses and analyzes the performance of iSCSI on a set of specialized hardware, and compares the results against a fibre channel environment.

3.1. Experimental Setup

Figure 1 is a diagram of the configuration used to evaluate the performance of iSCSI on specialized fibre hardware. At the bottom right of the figure is an IBM x-series 360 that is the initiator of requests to the disk array shown at the far left of the figure. The IBM server has dual XEON 1500 MHz processors with hyper-threading enabled. The server also has 2GB of RAM and a 64-bit/66MHz PCI bus.

The server has three cards attached to it. The Pro 1000F card is a gigabit Ethernet adapter that connects to a Dell 5224 gigabit Ethernet switch. iSCSI requests are generated using a CISCO iSCSI driver. The Pro 1000T card has a hardware implementation of the iSCSI protocol and appears to the server as a SCSI HBA. The Pro 1000T is also attached to the same gigabit Ethernet switch as the Pro 1000F.

The third card in the server is an Emulex LP9002 fibre channel HBA. This card is connected to the Sphereon 4500 fibre channel switch. This switch is inserted in the topology so iSCSI requests and fibre channel requests have the same number of network hops when going to or from the disk system.

Inserted between the fibre channel switch and the Ethernet switch are two CISCO SN-5428 Storage Routers. The SN-5428 is really a 16-port Qlogic switch with 8 external fibre channel ports and two internal ports connected to QLA 2300 fibre channel HBA's. The QLA 2300's provide the back-end for the fibre to iSCSI conversion. The SN-5428's have two gigabit Ethernet ports out the front. Finally, the network is connected via fibre to a storage array containing 6 disks.

While the Ethernet and fibre channel connections of the network are normally run at 1 gigabits per second, the fibre channel connection, through the Emulex LP9002, can also be run at 2 gigabits per second. The experimental results include performance data when this port is run at the higher rate.

3.2. Results

To exercise the test-bed described in the previous section, Intel's Iometer tool was used. A series of tests were performed in which different sized blocks of data were read from the target disks. For each block size, two sets of experiments were performed: one for sequential reads only; and one in which 50% of the requests were reads and 50% were writes. Thus, in the second set of experiments, the stream of requests was more random with a mix of reads and writes.

The two types of requests streams were each run on four test-bed configurations. The results of these experiments are shown in Figure 2. The vertical axis is throughput in megabytes per second. Across the horizontal axis are the different block sizes and and requests streams. Those labeled 50% seq. indicate the randomized streams. For each stream type and block size, a set of four bar graphs is shown. From left to right these correspond to a connection using the Pro 1000T, the Pro 1000F, the LP 9002 at 2 Gbps and the LP 9002 at 1 Gbps.

The configuration using the LP 9002 at 2 Gbps was used to ensure that the target disk system was not limiting the performance of the 1 Gbps network configuration. Looking at each set of bars, the 2 Gbps connection always performed as well or better than the other configurations. This meant that the disks could keep up with the requests coming through the network.

Looking at the Pro 1000T, the leftmost bar in each set of results, it usually performed worse than the other configurations. Recall that the Pro 1000T interface provides hardware support of iSCSI. The result is not as surprising as might be expected since the card was primarily designed to be used in lower-end systems. The Pro 1000T card contains an Intel 80200 processor, which is responsible for handling the TCP offloading. We believe that this processor was set at 200MHz, and thus could not handle the amount of traffic generated in a 1Gbps network, thus causing the performance to drop dramatically. However, even though the overall performance was poor, the Pro 1000T did accomplish some of its goals, the primary one being that TCP offloading reduced the servers CPU utilization greatly. It would be interesting to test the same card in a test-bed that uses 100baseT Ethernet.

Finally, comparing the Pro 1000F and the LP 9002 1Gbps configurations, at large block sizes, the two offer

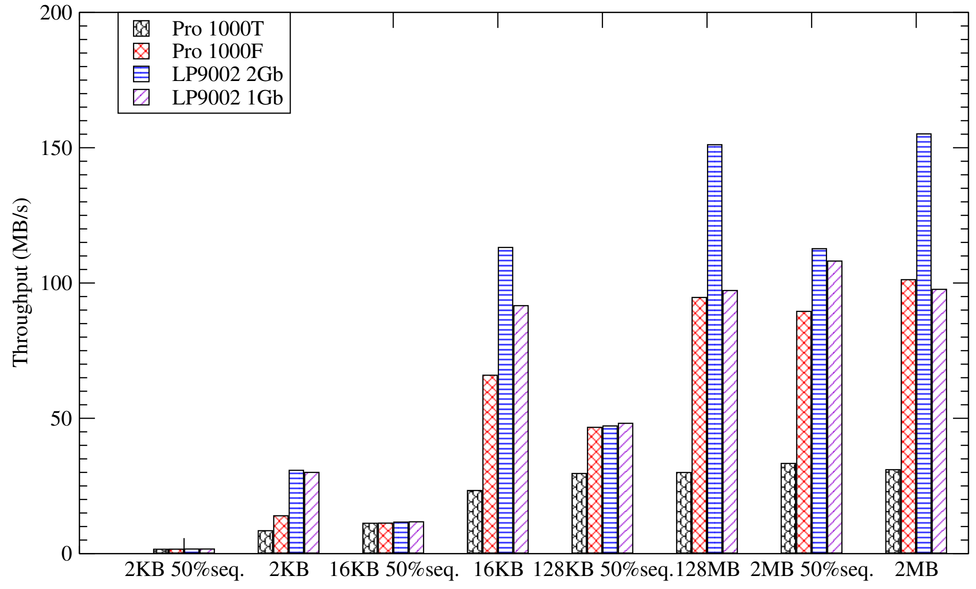

Figure 2. Throughput results for the commercially deployed test-bed.

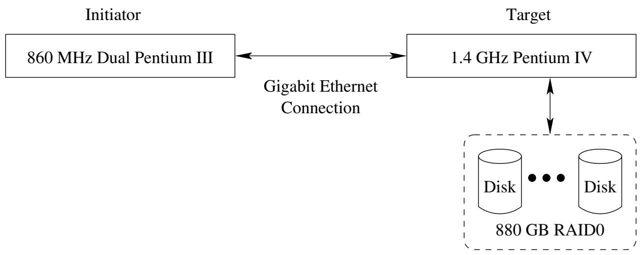

Figure 3. Experimental setup for Software SAN test platform.

very similar performance, with the LP 9002 slightly outperforming the Pro 1000F. At smaller block sizes, 2K and 16K, the LP 9002 substantially outperforms the Pro 1000F when sequential reads are performed. Once the request stream is randomized and writes are mixed with reads, both interfaces provide similar performance. With further experimentation, it may be possible to gain an understanding of the reasons for these performance results.

4. iSCSI in a Software-Based SAN Environment

One of the factors that has caught the attention of many regarding iSCSI is that it can be implemented in an existing network with little to no specialized hardware involved. This section is concerned with the performance of iSCSI in a SAN configuration, using existing hardware with software-based targets and initiators.

4.1. Experimental Setup and Configuration

For this particular SAN environment, two computers were directly connected via a gigabit Ethernet connection as shown in Figure 3. This configuration provides a network with no switch delay or overhead within the network. Both computers used D-Link DL2K gigabit NIC's.

The target machine contained a 1.4GHz P4 CPU, 256MB of RAM, and an 880GB RAID 0 array. The 2.4.19 kernel was loaded on the machine during all tests, as this was necessary to maintain a stable RAID configuration. The reason for this is that the RAID in question was constructed using a collection of 12 IDE disk drives spread across 4 firewire controller cards. Hence, a kernel was used that had a stable firewire implementation, and yet was compatible with the versions of iSCSI tested. Despite the somewhat unusual nature of the underlying RAID array, its performance was sufficient for our tests.

The computer upon which the initiator was hosted had a dual 860MHz PIII CPU, 256MB of RAM, and a 20GB hard drive. During all tests, the 2.4.18 kernel was run.

A number of different variables were examined during testing. In particular, the size of the Ethernet frame and the size of the socket buffers on the individual machines were varied, since these variables can have a significant impact on network performance.

One of the benefits of using a gigabit Ethernet was the ability to use jumbo frames, which expand the Ethernet payload from 1.5KB to 9KB [8]. It was determined that measuring iSCSI under both conditions would be best to see if there was a substantial increase in performance for iSCSI as the frame size increased.

4.2. Results

Figures 4 and 5 show the performance of different system configurations for a SAN environment using 9KB Ethernet frame sizes (Jumbo frames) and the largest socket buffer supported by the underlying operating system. Large socket buffers are necessary to achieve peak performance for networks with a large bandwidth-delay product. Both figures contain the overall network performance which indicate the peak performance achieved using Netperf with varying I/O transaction sizes. Except for the smallest transactions, the overall network performance rapidly reaches 111 MB/s; each measurement is shown with its respective 95% confidence interval. Figure 4 shows the behavior of iSCSI during sequential read operations, while Figure 5 graphs the iSCSI protocols performance for sequential writes. It is likely that the network performance plateaus at 111MB/s is due to the PCI architecture used in the study; the PCI bus architecture can deliver no more than 130MB/s, and most support chips have overheads that prevent maximum usage of the PCI bus bandwidth. The next data set immediately to the right of the network performance shows the peak I/O performance of the striped RAID disk array when the tests are run local to the target machine. One thing that immediately comes to attention is the extremely poor performance of the RAID array when the block transfer size is set to 512 bytes. While the reason for this could not be determined, it is believed that this performance anomaly is due to a read-modify-write cycle that occurs for writes smaller than the stripe width.

The next data set to the right of the local disk performance shows the performance of the Intel iSCSI target when all I/O transactions are actually discarded instead of processed. As shown, performance is approximately half that achieved by the network alone. The final set of data on the graphs shows the performance when I/O transactions actually make use of the RAID array; this decreases by another factor of two from the configuration that simply threw out I/O requests.

The additional performance hit seen when I/O requests are honored by the target is caused by the synchronous nature of disk writes. An initiator requesting an I/O transaction must wait for the target to receive the transaction. After the iSCSI target has received the request, the initiator must then wait for the disk to actually write the transaction successfully before the target sends the acknowledgement. Given the fact that the bandwidth for both the network and the disk are roughly equivalent, identical performance impacts from delay are expected, and, in fact, seen. An increase in the number of outstanding transactions would allow a greater degree of resource pipelining, thus improving the disk system throughput.

The delay imposed by synchronous writes in the iSCSI protocol could be reduced by acknowledging writes prior to committing the transaction to disk. This is not the case, since software-implemented targets are written for general purpose operating systems. However, a specialized iSCSI target may be able to buffer the writes in a non-volatile RAM buffer or in a battery backed up RAM, as is commonly done in current RAID implementations. This implies that a specialized implementation may be able to recover a substantial amount of lost bandwidth. Software implementations could, alternatively, acknowledge writes asynchronously, thus trading reliability for performance.

Figures 6 and 7 show similar measurements but with the size of the socket buffers within the operating system set to their default values. Interestingly enough, the network performance improves by an approximate 2MB/s. Further investigations are needed to determine the reason for this improvement. No other performance results are significantly affected.

Similar studies were conducted using a standard Ethernet frame size of 1.5KB. Other than observing a uniform performance drop of 10MB/s across all test configurations, there were no differences in performance trends, hence these results were omitted.

One interesting observation is how closely the performance of the diskless iSCSI configuration follows the performance trends of the target's local disk. At first one might assume that some erroneous disk access had occurred, except that when actually writing to the disk the performance dropped to half that of the diskless configuration. We can only speculate that this is due to the way in which the underlying system handles block sizes of 512 bytes. Using Bonnie, we measured the performance of an ext3 filesystem on the RAID array both locally (i.e. on the target) and remotely (using iSCSI). Figure 8 is a graph of the results obtained from both tests. Accessing the filesystem locally did better in all cases, as expected. File sizes from 100MB to 400MB experienced caching effects from the filesystem, as shown. Filesystem caching effects were reduced for those files greater than 400MB, as they were typically larger than the overall cache size. Those tests that did not benefit from file caching show that accessing the filesystem locally do anywhere from 5MB to 30MB better than the filesystem implemented on top of iSCSI. The results of the filesystem tests were significant in two ways. First, the difference between the block level tests and the filesystem tests show that caching effects still play a significant part of iSCSI's

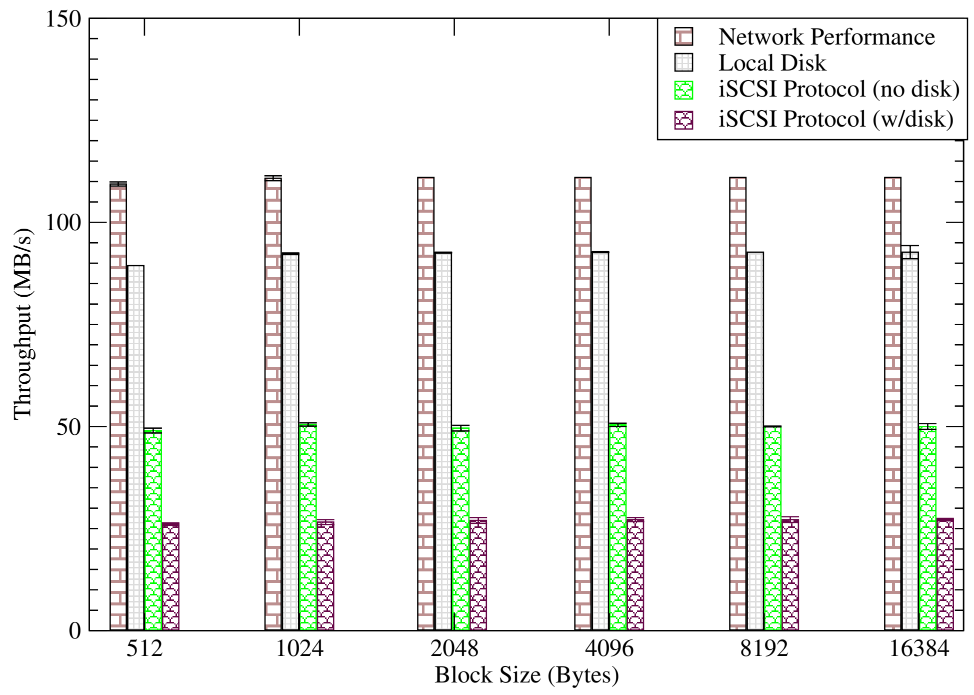

Figure 4. Throughput results for sequential reads in a software-based SAN environment using jumbo frames and maximum socket buffer sizes enabled.

performance, which would lead one to speculate that an increased cache could increase the performance of iSCSI in a real world environment. Second, most files on a system in use seldom reach 100MB, which nominally means that the majority of files accessed via iSCSI would greatly benefit from filecaching to such a degree that the fact that the file is on a remote storage device would not even be noticeable [9].

5. iSCSI Implemented in a WAN Environment

Given the fact that iSCSI was designed to be implemented over regular TCP/IP networks, there are many scenarios under which iSCSI may be deployed. One such scenario, which we analyze here, includes deploying iSCSI over an existing WAN infrastructure. First, an overview of how the WAN simulation environment was set up and configured is presented. This is followed by an examination of the collected data.

5.1. Experimental Setup and Configuration

Three identical machines were used in the WAN simulation. All three consisted of a single Pentium III 860MHz

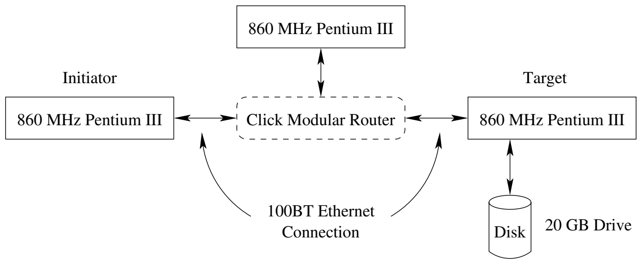

Figure 9. Experimental setup for WAN environment

CPU, 256MB of RAM, and a 20GB hard drive. As illustrated in Figure 9, the three machines were connected serially via a 100BaseT Ethernet, which was chosen due to the fact that most WAN's today operate over connection speeds much smaller than this (e.g. a T1 line, which has a throughput of 1.54Mbps).

The machine designated as the router between the initiator and target needed the capability to simulate a WAN environment successfully. It was to this end that the Click modular router was chosen as the routing mechanism [10]. The Click router, by its very design, is highly configurable and flexible. Click provides the machine upon which it was implemented the ability to simulate a WAN environment.

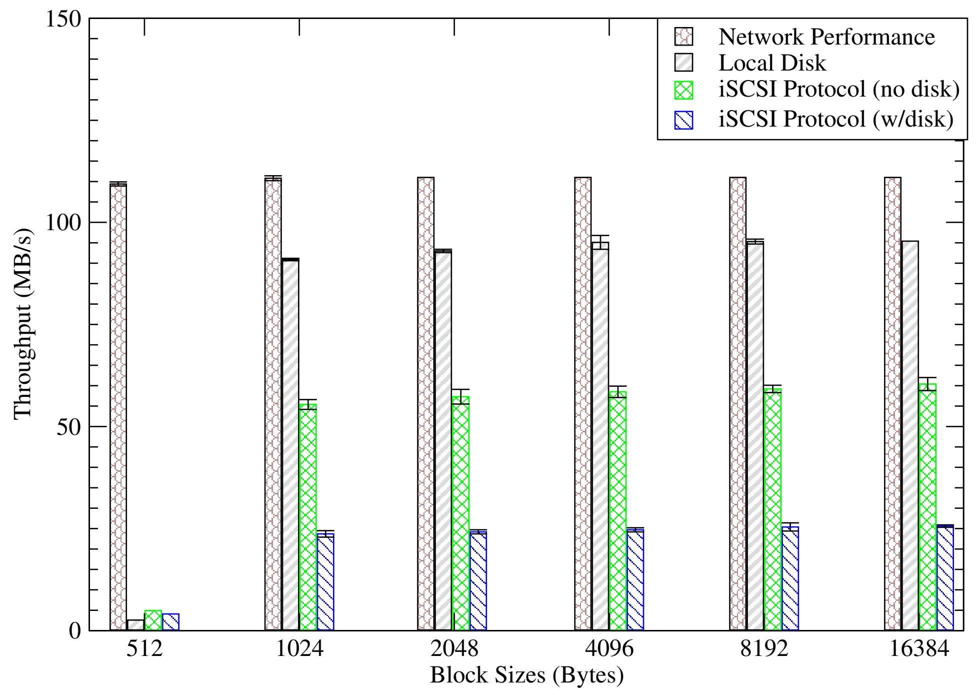

Figure 5. Throughput results for sequential writes in a software-based SAN environment using jumbo frames and maximum socket buffer sizes enabled.

Netperf Buffersize	Blocksize					
	512	1024	2048	4096	8192	16384
Standard	3.17±2.43	4.38±0.68	4.28±0.65	4.53±0.67	4.22±0.8	3.89±1.07
Maximum	4.37±0.4	4.24±0.61	4.52±0.49	4.12±0.54	3.36±2.55	3.68±2.85

Table 1. Network throughput performance in MB/s, with packet corruption and dropped packets.

Additionally, due to the modular nature of Click, network parameters could be adjusted on the fly. The WAN simulation was tuned in accordance with profiling information presented by Vern Paxson [11], which examined end-to-end characteristics of wide-area internet connections. That study found that over long time periods, the studied network connections suffered a 2.7% packet loss, a 0.02% packet corruption rate, and a 2.0% packet reordering rate. Network delay, which is a common variable in such a setting was varied from 0ms to 20ms. Performance measurements were calculated over the varying delay times for the case when the network environment exhibited no pathologies profiled by Paxson as well as when it did.

Socket buffers for both machines were set to a maximum value of 500,000 bytes. This value was set to be greater than the maximum network round trip time of 0.4s (which is twice the time it would take for a packet to be sent out from the initiator to the target and back again when the network delay is 20ms), multiplied by the maximum bandwidth of the network of 100MB/s.

5.2. Results

The results obtained from using the WAN environment support the results of Section 4. Initial examinations began by setting the packet drop rate, the reordering probability, and the corruption rate to zero for the purpose of examining iSCSI's performance as a network's bandwidth-delay product increases.

Figures 10 and 11 show the diskless iSCSI implementation's performance with various degrees of network delay. The performance of the network is shown for a network delay of 0ms and 20ms. All delays between 0ms and 20ms are omitted for clarity within the graph, but it should be known that the network's performance is constrained by those data sets. As network delay increased, the performance of the iSCSI protocol degraded rapidly. We believe again, as we

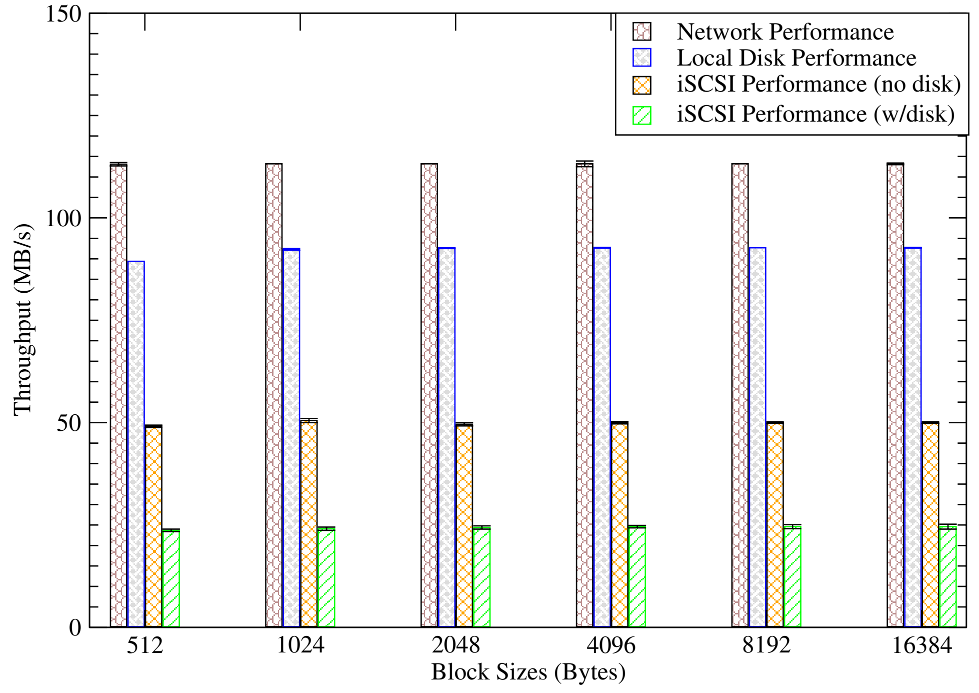

Figure 6. Sequential reads in a software-based SAN environment with jumbo frames enabled and standard buffer sizes set to the default size.

discussed in Section 4, that the cause of such a rapid performance decrease was due to the synchronous nature of iSCSI. In other words, only a limited number of outstanding requests are held until an acknowledgement is received, which essentially means that iSCSI is not making efficient use of a given network's bandwidth-delay product [12].

Again, as we saw in the software SAN environment, the diskless iSCSI configuration still patterns its behavior to that of the disk. This time, however, the block sizes whose transfer rates were poor included not only a block size of 512 bytes, but also 1KB, and 2KB.

Figures 12 and 13 show the impact of increasing network delay upon a filesystem implemented on top of iSCSI. For the sequential reads, the WAN environment equals out as the file size increases, much the same way that it did in the software-based SAN environment. This, we believe, is due to caching within the operating system. However, writing sequentially to the filesystem is very poor in comparison to the performance of writes occurring to the disk locally. While we believe that the combination of seek time at the disk, the delay imposed by synchronous writes in iSCSI, and the the lower overall bandwidth (when compared to the SAN environments) are the cause of this performance degradation, we cannot be completely sure without more testing.

Table 5.1 shows the impact of packet drop on network performance when emulating a wide-area network using two different TCP/IP socket buffer sizes. The increased TCP socket sizes actually improve performance in this configuration as they are used in reassembling and buffering partially delivered IP frames. As the rate of packet loss increased, larger buffers would be needed to achieve the same performance, even if the overlying iSCSI implementation did not change. However, as the network performance was poor, it was decided that iSCSI in this environment would perform at least a factor of two worse than the network.

6. Summary & Conclusions

In this paper several different iSCSI configurations were evaluated. The first investigated iSCSI in a commercial environment, where specialized hardware and drivers were used. This environment had a gigabit Ethernet iSCSI target that in turn used a fibre channel back end storage medium. It was found that for large block sizes, a software implementation of the iSCSI protocol was competitive with the fibre channel protocol. Interestingly, the hardware implementation of the initiator did not perform as well.

The second set of experiments evaluated open-source versions of the iSCSI protocol. This set of experiments was geared to evaluating a network constructed using inex-

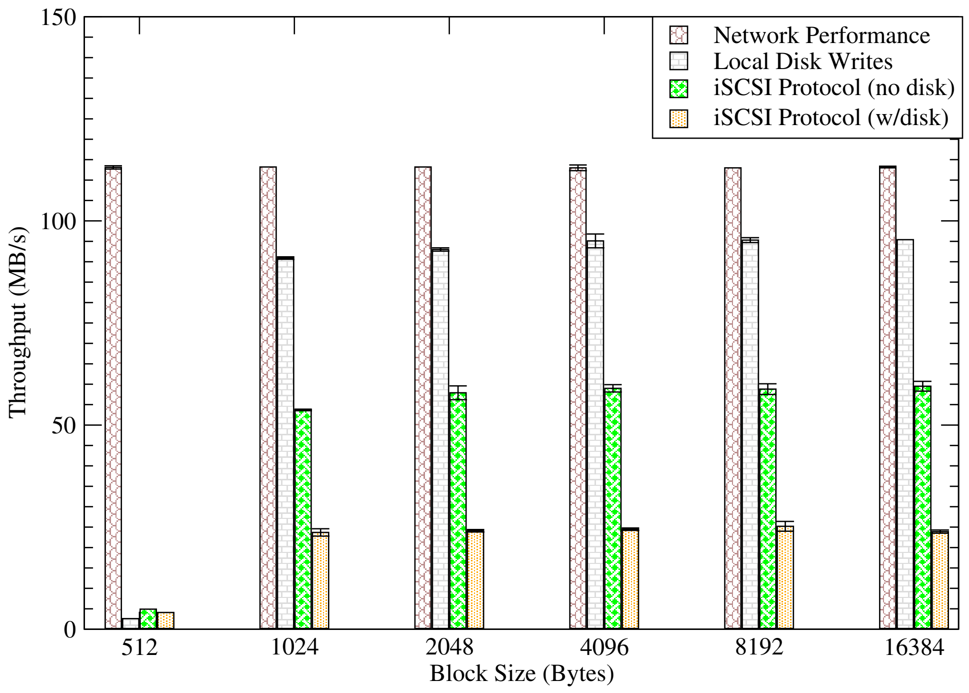

Figure 7. Sequential writes in a software-based SAN environment with jumbo frames enabled and default socket buffer sizes.

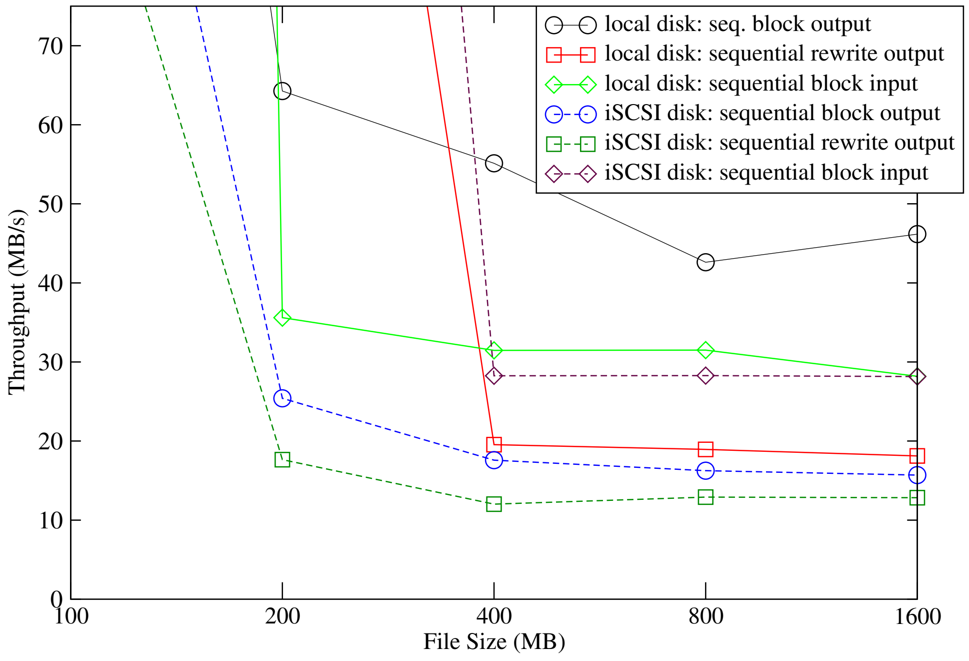

Figure 8. Bonnie results for the Software SAN Environment.

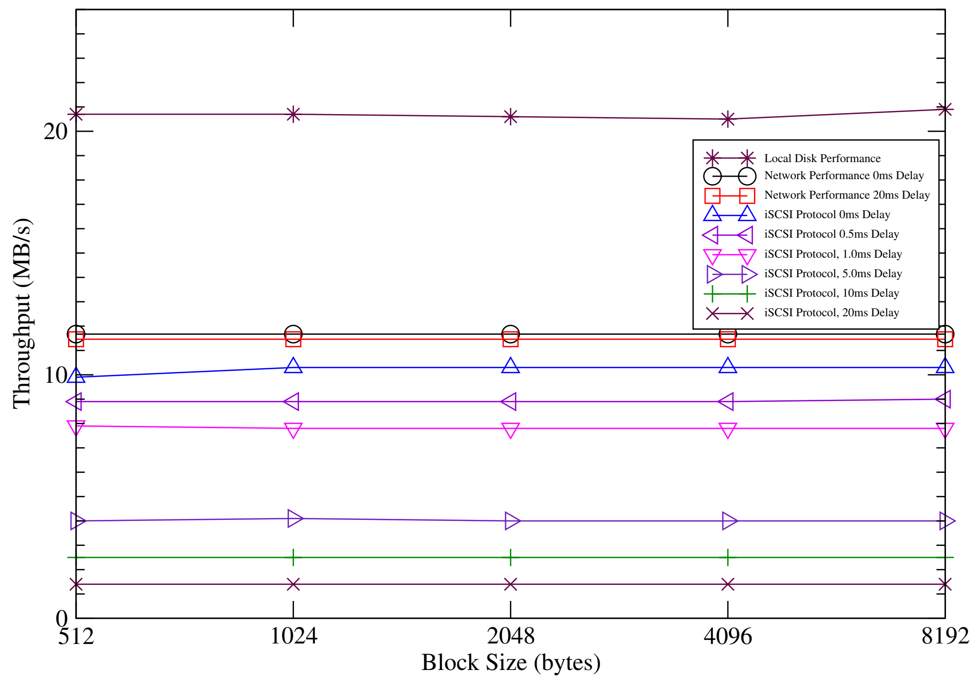

Figure 10. Throughput results using lmdd sequential read results for software WAN environment with varying block sizes and network delay

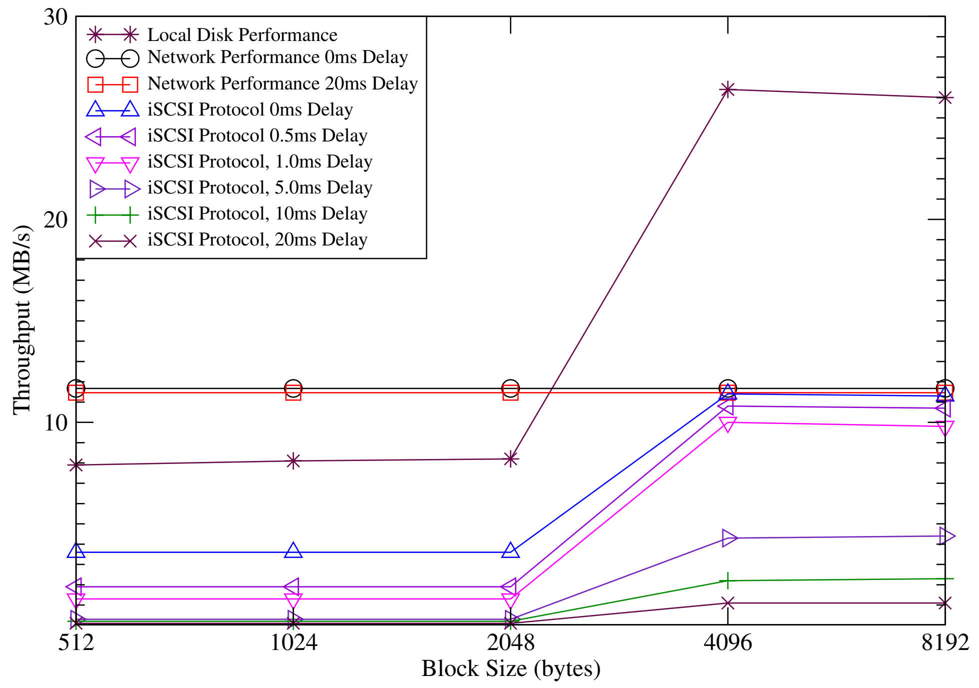

Figure 11. Throughput results using lmdd sequential write results for software WAN environment with varying block sizes and network delay

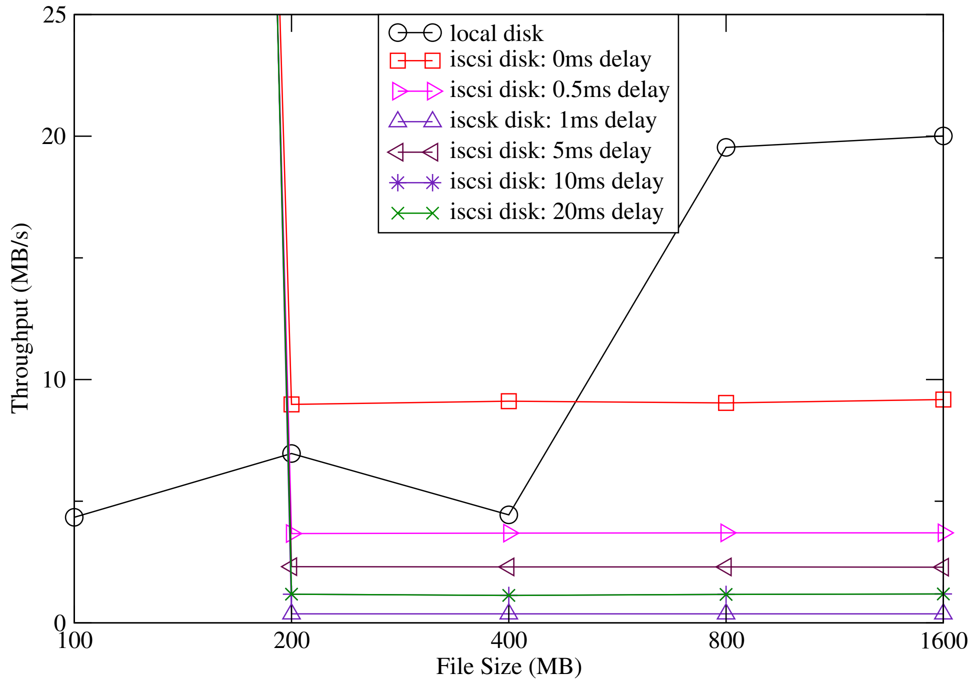

Figure 12. Throughput results for sequential file reads in a software-based WAN environment with increasing delay

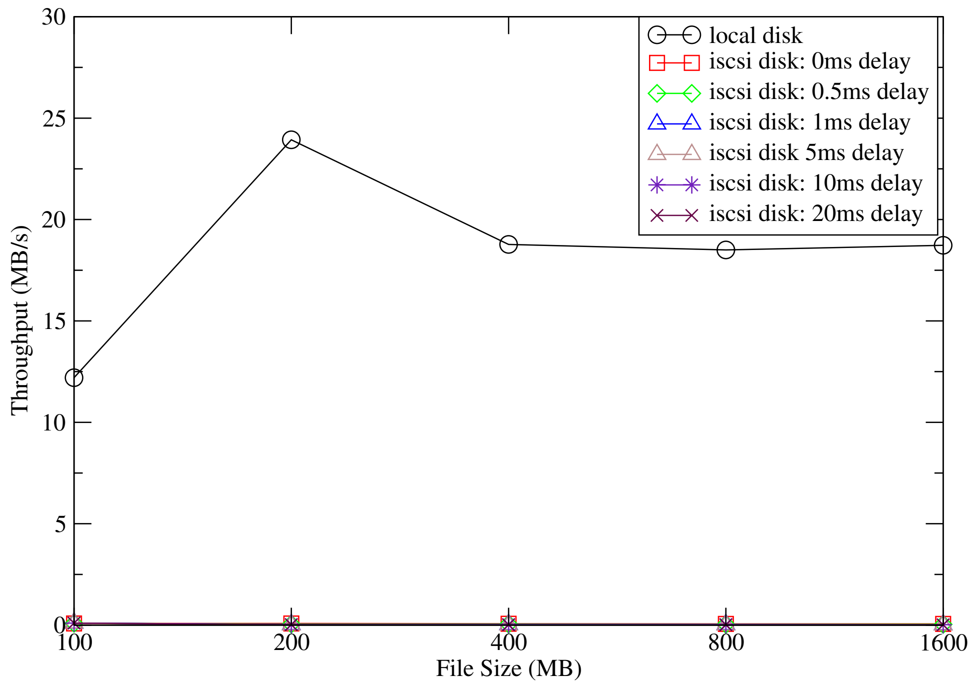

Figure 13. Throughput results for sequential file writes in a software-based WAN environment with increasing delay.

pensive commodity components. It was found that iSCSI in this configuration utilizes approximately half of the network bandwidth when performing raw reads and writes. However, when a filesystem is implemented on top of iSCSI, it performs nearly as well as a local disk. We hypothesize that this is due to filesystem caching within the operating system.

Finally, the open source iSCSI implementations were evaluated in a WAN environment. This was done using a 100 BaseT network and an implementation of the Click modular router. The results of these experiments indicate that network layer properties and the way in which iSCSI was implemented played a dominant role in overall performance. Unlike the SAN environment, the implemented filesystem on iSCSI performed poorly for writes occurring to the disk. We speculate that a combination of delays in both iSCSI and the disk are the cause.

References

[1] Julian Satran, et al. iSCSI. http://www.ietf.org/internet-drafts/draft-ietf-ips-iscsi-19.txt.

[2] Jerry Sievert. *Iometer: The I/O Performance Analysis Tool for Servers*. www.intel.com/design/servers/devtools/iometer/index.htm.

[3] Rick Jones. *The Public Netperf Homepage*. www.netperf.org.

[4] Larry W. McVoy and Carl Staelin. lmbench: Portable tools for performance analysis. In *USENIX Annual Technical Conference*, pages 279–294, 1996.

[5] Tim Bray. *textuality - Bonnie*. www.textuality.com/bonnie/.

[6] *UNH ISCSI Consortium*. www.iol.unh.edu/consortiums/iscsi/.

[7] Eric Blair, Michael Mesnier, and Quy Ta. *Intel iSCSI Reference Implementation*. sourceforge.net/projects/intel-iscsi.

[8] J. Chase, A. Gallatin, and K. Yocum. End system optimizations for high-speed TCP. *IEEE Communications Magazine*, 39(4):68–74, 2001.

[9] M. Satyanarayanan. A study of file sizes and functional lifetimes. In *Proceedings of the eighth symposium on Operating systems principles*, pages 96–108, 1981.

[10] Eddie Kohler, Robert Morris, Benjie Chen, John Jannotti, and M. Frans Kaashoek. The click modular router. *ACM Transactions on Computer Systems*, 18(3):263–297, 2000.

[11] Vern Paxson. End-to-end Internet packet dynamics. *IEEE/ACM Transactions on Networking*, 7(3):277–292, 1999.

[12] W. Richard Stevens. *TCP/IP Illustrated Vol. 1*. Addison-Wesley, 1994.