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Using TCP/IP traffic shaping to achieve iSCSI service predictability

Master thesis

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Abstract

This thesis reproduces the properties of load interference common in many storage devices using resource sharing for flexibility and maximum hardware utilization. The nature of resource sharing and load is studied and compared to assumptions and models used in previous work. The results are used to design a method for throttling iSCSI initiators, attached to an iSCSI target server, using a packet delay module in Linux Traffic Control. The packet delay throttle enables close-to-linear rate reduction for both read and write operations. Iptables and Ipset are used to add dynamic packet matching needed for rapidly changing throttling values. All throttling is achieved without triggering TCP retransmit timeout and subsequent slow start caused by packet loss. A control mechanism for dynamically adapting throttling values to rapidly changing workloads is implemented using a modified proportional integral derivative (PID) controller. Using experiments, control engineering filtering techniques and results from previous research, a suitable per resource saturation indicator was found. The indicator is an exponential moving average of the wait time of active resource consumers. It is used as input value to the PID controller managing the packet rates of resource consumers, creating a closed control loop managed by the PID controller. Finally a prototype of an autonomic resource prioritization framework is designed. The framework identifies and maintains information about resources, their consumers, their average wait time for active consumers and their set of throttleable consumers. The information is kept in shared memory and a PID controller is spawned for each resource, thus safeguarding read response times by throttling writers on a per-resource basis. The framework is exposed to extreme workload changes and demonstrates high ability to keep read response time below a predefined threshold. Using moderate tuning efforts the framework exhibits low overhead and resource consumption, promising suitability for large scale operation in production environments.

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Chapter 1

Introduction

1.1 Motivation

Consolidation of server and storage resources is an ongoing trend in the IT business, driven by economy-of-scale benefits [1, 2]. Consolidation of disk resources into SANs has been going on for 10 - 15 years, and centralized pools of storage resources are now the rule rather than the exception.

The University of Oslo is no exception to the trend, and has a growing number of centralized storage pools based on Storage Area Network (SAN) technologies from different vendors. On several occasions the lack of predictability of these devices' service availability has been suprising. The total performance benefit of spreading a workload across large physical resource pools is accompanied by a major cost with respect to load interference. Several times it was experienced that a few storage consumers' activity adversely affected a large amount of other consumers' ability to meet their performance requirements.

In order to utilize centralized storage pools, mechanisms for dividing a pool's resources into suitable chunks is needed. These mechanisms usually involve some kind of virtualization technology. Virtualization provides the elasticity and adaptability required to make consolidation feasible.

Early SAN technology exclusively utilized dedicated fibrechannel (FC) networks. Such networks use special purpose HBAs (Host Bus Adapters), switches and storage arrays. The cost of acquiring and operating such solutions was initially very expensive, but has become less expensive with increased adoption. FC SANs represented the only technology that could provide sufficient performance and capacity for the enterprise data storage purpose.

This is about to change. As the performance of standard Ethernet equipment is increasing, with its cost remaining low due to production volume and competition, new methods for accessing SAN storage have evolved. A recent and growing trend is to utilize standard Ethernet network equipment for transport of SCSI (Small Computer System Interface) commands. The most widely, and increasingly, used protocol for this purpose is the iSCSI (internetSCSI) protocol. Predictions from several storage analysts [3, 4] forecast that the market for iSCSI based storage solutions has definitely entered the mainstream adoption phase.

To achieve performance, optimal hardware resource utilization and flexible resource allocation, all SAN solutions imply some kind of resource sharing. This resource sharing is vital for the benefits mentioned, but there is a flip side to this "resource sharing model": storage consumers' behavior will impact available capacity for other consumers unless there is a prioritization mechanism in place and when utilization of a resource approaches 100% of its capacity, new consumer requests' response time increases dramatically.

The University of Oslo utilizes HP Storageworks EVA8000 SAN disk-arrays for storing large amounts of important application data. Despite many years of research within QoS for Storage, these storage devices illustrate how the ability to prioritize storage performance for consumers' disparate needs is still not an available option (See chap 2.8), even for expensive disk systems like the HP Storageworks EVA. At the University of Oslo there are several examples where single applications on single computers are able to monopolize all storage resources. This is particularly true for consumers sharing EVA disk-groups. The lack of ability to prioritize loads increases response time uncertainty for numerous important applications, a situation that potentially leads to downtime for a large number of users (See illustration in figure 1.1). At the time of writing, the previously mentioned disk systems does not come with efficient tools to discover which storage consumer is the culprit in such situations without expert knowledge.

Resource sharing is good for enabling large scale consolidation with the economy-of-scale benefits, but it also adds a cost: reduced predictability of service availability for any storage consumer sharing resources with others. Service Level Agreements (SLAs) presupposes predictability in service delivery (see also section 2.3). Lower predictability is caused by the lack of prioritization functionality in storage devices. This condition makes it hard, or impossible, to make keepable promises in the form of Service Level Agreements, and ultimately increases the risk for SLA violations.

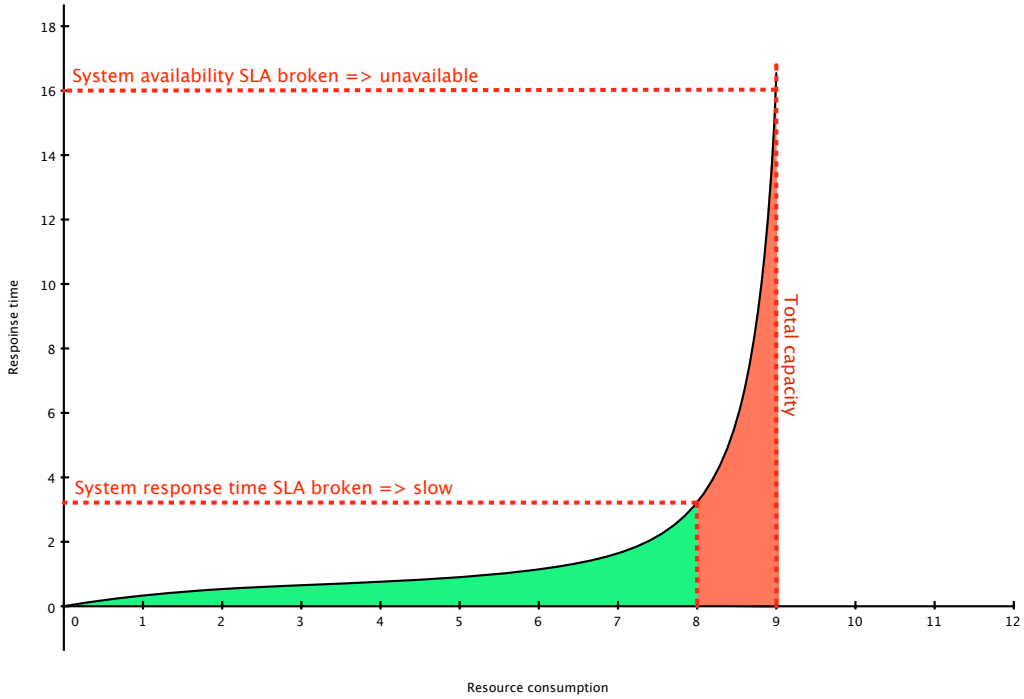


Figure 1.1: General example of resource saturation vs. response time

1.2 Problem statement

Motivated by chapter 1.1, this project explores novel methods of utilizing well known and trusted tools as a means to mend the reduced predictability introduced by resource sharing in iSCSI storage devices.

Even though most FC SAN storage appliances do not have mechanisms for prioritization, and implementing such mechanisms in FC SANs is hard, the emergence of IP-based SANs, with iSCSI as the most widely used variant, increases the solution space for implementing such mechanisms. Qualified speculations may suggest that the overhead introduced by allowing I/O requests to traverse an extra layer of abstraction, namely the TCP network layer, makes iSCSI unsuitable in high performance SAN environments. These speculations is analyzed and partly refuted in chapter 2. But what is just as interesting, is the opportunity to utilize well known QoS tools from the networking world to create a unified QoS picture including both storage and network resources.

Difficulties in trusting prioritization mechanisms to do the right thing, in a mission critical environment, can be an inhibitor for adopting them [5]. Many of the current approaches to storage QoS involve intrusive techniques (see

chap 2), imposing a new mechanism in between the client and the server. Intrusive approaches like this, and those which depend on client side scheduling/throttling, face a higher need for reasoning to convince users to trust the mechanisms. Also, the obvious disadvantage of needing to modify clients is the uncertainty about whether some clients have not been modified, since failure to do so let these clients bypass the QoS framework. The advantage of using TCP traffic shaping is that the same effect can be achieved by throttling the TCP traffic so that the client rates is adapted without the need to install extra software or drivers on clients.

The following problem statement guides the direction and experimental decisions in the thesis. The sole purpose of thesis is to answer these research questions with high confidence.

Formulate a non-intrusive approach for doing load prioritization in iSCSI SAN appliances utilizing multiple metrics and Linux traffic control for I/O throttling using a limited scope prototype.

1. Identify a suitable approach to use Linux Traffic Control as the throttling mechanism for iSCSI initiators.
2. Identify metrics for various resources of a Linux based iSCSI appliance in order to obtain continuous knowledge of their utilization.
3. Verify the anticipated effects of workload interference.
4. Verify the anticipated effects of workload throttling.
5. Design mechanisms for using this data to make prioritization decisions, including dynamic prioritization, when contention occurs.
6. Formulate an approach for making automatic policy decisions based on workload behavior.
7. Investigate any overhead of the TCP traffic shaping mechanism.

Chapter 2

Background material and previous work

This chapter introduces the reader to the concept of resource sharing, Quality of Services (QoS) relevant history of storage evolution and attempts of QoS in storage devices.

2.1 About resource sharing

In its most fundamental form, a resource can be thought of as collection of assets of some particular type. What characterizes any resource is its utility and limited availability. The limitation of it might be the total amount or the rate at which it is available (amount/time unit). We usually call this limit the capacity or capability of the resource.

Resources is closely tied to its consumers. If resource don't have any consumers it could hardly be called a resource, since it is lacking the core characteristic of utility. Consumers utilize resources and more often than not there are several consumers of any resource. Very often the consumers themselves offer some kind of utility to other consumers, which in turn is utilized as a higher level resource. For example, the power-supply of a computer utilizes the alternating current (AC) resource available from the power distribution network in order to supply the internal components (CPU/disks/memory, etc.) of the computer with direct current (DC) at suitable voltage levels. The CPU utilizes its DC power resources to provide computation resources to the operating system. The operating system provides available system calls to applications, and the applications usually provide some kind of utility to their users.

These levels can be thought of as abstraction levels because they each abstract their underlying resource from their own consumers. A chain reaction of change in resource consumption at all levels of abstraction happens when the top level changes its resource consumption due to utility-producing activity. Any such consumers/resource chain has a weakest link: a place where saturation first occurs. This place is called the bottleneck for obvious reasons. If we mend a bottleneck by increasing its available resources (by upgrading or adding components for instance), another bottleneck might appear in another place. The location of the bottleneck also varies with different workload types and usage patterns of the consumer at the top level.

Now, what is the relation between resources and performance? In computer science the terms capacity and performance are often used interchangeably, in particular when benchmarking and comparing different alternatives. Often the concept of efficiency is forgotten in this picture. Efficiency is the quantity of resources consumed in the process of creating the next level of utility. If the capacity of resources were infinite, it would be just a question of adding more resources in any necessary level to keep application performance high. Unfortunately, resources are finite. This means that any resource can be fully utilized in the sense that there is no more capacity left. This situation is called saturation. Finite capacity is a core characteristic of a resource. Therefore efficiency matters for performance, at least in the long term. The focus of this thesis, however, is not the efficiency of resource consumers, but the management (or lack thereof) of available resources. Thus, it is just acknowledged that the sum of resource consumption from a consumer is influenced by its efficiency before the the objectives of this project is pursued.

As previously stated, resources normally have several consumers. Also, the consumers of a resource may have differing ability (power) and need to consume the available capacity. A powerful consumer might be able to fully saturate a resource if it wants to. Processes like backups, report generation and data-movement or copying are typical examples of consumers that will take all available resources for a period of time. If the consumers are powerful enough, they will typically saturate available resources at the expense of all consumers. However, the nature of such jobs makes themselves suffer less from saturation than the other consumers they affect since the only thing they care about is getting the job done as fast as possible and not the response time of single requests. Other consumers might require access, with certain response time requirements to the same resource. In this case, the response time-sensitive application will not meet its requirements due to the resource saturation. If it was possible to say that a job should not be able to saturate more than a certain percentage of all resources, the response time sensitive application would not suffer, and the other job would merely take a bit longer time.

2.2 SAN history

2.2.1 The early days

Historically, data storage has been directly attached to the computers utilizing it. As the demand for storage capacity, performance and availability increased, new solutions emerged. A major and commonly utilized technique is the abstraction of resources from their providing hardware. The idea of abstracting storage resources from the actual hardware that provides it is a desirable feature that all consumers of storage want, and all suppliers of storage solutions strive to offer. This abstraction is the basis for achieving scalability, flexibility and availability in computer data storage. It is often implemented by some kind of virtualization technology. The term virtualization here means a general principle in a broader sense than just mechanisms for abstracting server resources.

Abstraction can be done on many different levels. For example it is possible to abstract filesystems and their actual block level layout using a volume manager like LVM (Logical Volume Manager) [6]. This way, even DAS (Direct Attached Storage) can be abstracted using software methods inside the host operating system. Another method involves virtualization inside a RAID (Redundant Array of Independent Disks) controller, where the attached physical disks are grouped into different redundancy groups and the device presents logical drives of suitable sizes to the operating system. The operating system sees the logical drives as single physical drives, while in reality even a small logical drive could be spread and mirrored over a number of physical disks.

It is increasingly common to place virtualization of physical storage media inside a dedicated storage array that can be accessed simultaneously by several hosts and is able to present tiered virtual disks from a larger pool of disk resources, allowing the actual storage to be closely adapted to the application capacity and availability needs. Thus, the application obtains the needed storage properties at the lowest possible cost. Also, when needs change (typically increases), abstraction makes migration of data between tiers possible. Access to such virtualized storage arrays is done through some kind of networking infrastructure. A collect term for such networks of storage arrays, the hosts utilizing them and the interconnecting infrastructure is Storage Area Networks, or just SANs.

Network Attached Storage (NAS) is a related term that is used for network-based storage technologies. NAS is also about accessing storage across the network. Although the two technologies have moved closer to one another

with the introduction of IP based SANs, there is a difference between them in the level at which the storage devices present the storage chunks. SAN devices present storage at the block device level while NAS devices present storage at the network filesystem level.

2.2.2 SAN technologies

At first, SAN technologies were almost exclusively used by large corporations for consolidating computing resources into large data centers. Such SANs were characterized by high price, reliability and performance. They were implemented as part of high availability clustering environments for core business applications with many simultaneous users. SANs made large scale host clustering possible with performance equal or exceeding the fastest direct attached storage (DAS) solutions at the time.

Over time, the prices of SAN equipment have decreased. Over the same time, the demand for storage capacity, availability requirements and performance has dramatically increased as most organizations run the majority of their business on some kind of computer based equipment today.

The most widely-used protocol for accessing storage is the SCSI protocol [7, 8]. The broad adoption of parallel SCSI as a standard for connecting DAS in a reliable way encouraged evolution of the well known SCSI command set to support other underlying interconnects [9], such as is the FC [10, 7] networking technology and common TCP/IP networks.

During the last few decades, an increasing amount of businesses' operational infrastructure has been migrated from manual, paper-based systems to IT infrastructure based on databases and applications. This move has increased the demand for application availability since unavailable operational applications can directly affect business revenue [1, 11].

As the demand for application availability increased, solutions offering failover clustering became popular for obtaining server hardware redundancy. A requirement of all such clusters is the ability to access the applications data from all nodes participating in the cluster. SANs fulfill this requirement, and is a major reason why SANs became so popular.

Today, most organizations utilize SANs in some form. The ongoing trend of data center consolidation is tightly woven in with the evolving SAN and server virtualization technologies; they reinforce and depend on each other. The flexibility of server virtualization seen today, would not be possible without the underlying SAN technologies which enabled simultaneous storage access. The

drive for consolidation enabled by virtualization further increases the need for higher performing, flexible and reliable shared storage solutions.

Back in the late 1990s, when SANs became a reality for production environments, FC networks were the only viable alternative to achieve the required performance and availability. However, the recent development of higher performing common Ethernet equipment makes it possible for low cost commonly-available equipment to compete with FC solutions also with respect to performance [12, 13].

One of the most widely used technologies enabling storage attachment using common ethernet equipment is iSCSI [4, 3, 14]. It utilizes TCP/IP protocol for bundling SCSI commands. The advantages utilizing iSCSI are: the equipment carries a low cost because of the volume and competition between vendors, it it easy to recruit staff with knowledge of standard TCP/IP networking technologies, contrary to specialized FC technology. The only reason for not utilizing iSCSI has been performance requirements, but this is now changing. With TCP/IP being a long distance routable protocol, it is also possible to access storage across the Internet. Of course, such transport is different from the concept of local high performing SANs and brings major challenges with respect to security and performance, however, it adds some interesting opportunities to utilize a single common technology for a vast amount of different purposes. One example is the ability to do backup and recovery operations over large geographic distances [13].

2.3 Aspects of storage consolidation

Large scale consolidation makes promises about lower total cost and the ability to closely tie the cost of resource consumption to the income of the business. This concept is exploited by businesses offering outsourcing services. Their business model is to run their customers' IT infrastructure as IT professionals, utilizing virtualization and flexible provisioning mechanisms to offer highly adaptable services to end customers, and let customers focus on their core business. The SAN solutions' contribution to this adaptability makes them a core component of any outsourcing company.

What makes the flexibility and adaptability properties of consolidation possible is the ability to share resources between their consumers. However, resource sharing benefits come with additional challenges with respect to reduced predictability of available capacity. The main problem with capacity starvation is the increased service times for all consumers utilizing a given resource. In a resource sharing environment with no control of who consumes

what, the result is highly unpredictable performance for any given consumer of that resource.

Surprisingly few SAN Storage arrays includes mechanisms for prioritizing consumers, or capping resource consumption, to prevent resource starvation as illustrated in Figure 1.1. Resource starvation increases the response time of all consumers dramatically. In [5] Wilkes is looking back in retrospect on 10 years of storage QoS research, reasoning that lack of real implementations could be caused by failure to build the needed trust that QoS will behave as expected.

To outsourcing companies and their customers, standardized agreements of service delivery are crucial. The most widely used standard for such service delivery is the ISO 20000 [15] standard. It formulates best practices for IT service delivery and support, and is used by most outsourcing companies and large organizations. A common method to specify deliverables between service providers and their customer, in ISO20000 and other standards, are service level agreements (SLAs): a set of agreements that define what services will be delivered, their quality and the consequences of non-compliances. To fulfill SLAs, the service provider needs predictable performance in the underlying infrastructure. They need to specify service level objectives (SLOs) for performance parameters like response time and throughput. To reduce the cost of providing services, the service provider also wants to maximize the utilization of their infrastructure (i.e. minimize over provisioning), hence increasing competition between workloads. Increased competition means increased risk that workloads interfere with each other, and the need for QoS mechanisms increase [16]. The requirements of utilization to keep cost down, and QoS guarantees to fulfill SLOs are contradictory in terms. Previous research shows that both requirements are seldom completely fulfilled [17].

The scope of SLAs varies greatly, and outsourcing companies tend to offer easily achievable and measurable deliverables in their contract templates. The inherent risk of consumers affecting each others' available resources of I/O capacity is seldom part of any agreement, making the customer the bearer of the risk introduced with the incentive of cost savings by the outsourcing provider. This again leads to unexpected and unacceptable situations for outsourcing customers, and ultimately lost business for outsourcing providers in the long run.

2.4 Traffic shaping (TS) and Quality of Service (QoS)

The QoS and traffic shaping terms is mainly known from the networking field, and they are closely related to each other. We can think of traffic shaping as the method used to achieve QoS. In its fundamental form, QoS means the ability to apply different priorities to to different entities like applications, users or data flows [18]. Traffic shaping is the tool that is used to to ensure that all entities gets the promised resource allocations. The promised resource allocations can be applied using traffic shaping policies by either limiting (capping) lower prioritized entities or raising the priority of other entities so they get processed first. By limiting lower prioritized entities, we indirectly make sure the prioritized entities have enough resources.

Before shaping can take place, decisions about prioritization must be made. It can be human value decision directly imposing differentiation, or it can be some kind of scheduling mechanism that automatically raises the priority of low consuming entities. An example of this is the flow based weighted fair queueing (WFQ) scheduler in Cisco IOS. WFQ and similar methods provide an easy way of ensuring consistent response times for heavy and light network traffic.

Traditionally, packet switched networks, such as the Internet in the early days, used a best effort service where no guarantees were made about packet delivery at all, and the communication parties had to be able to cope with packet loss and out of order delivery. Applications like e-mail and web browsing work well with the best effort model. They just wait until a complete message is transferred, and it can be further processed as a complete piece. Real time communication like telephony and video conferencing are examples where the best effort service delivery comes short. The increased utilization of the Internet to transport audio, video and other real-time-critical data introduced the need for more predictable delivery of IP packets, leading to QoS and traffic technologies [19].

Since QoS was introduced as a method of enabling transportation of such services, much research has gone into finding a best way of implementing it [20, 21, 19, 22, 23]. The research, and the amount of proposals, is so vast that the need for for a survey for getting a global overview became apparent. Guitart and coworkers offer a global perspective on previous research in this field [24].

2.4.1 QoS core models

The two major major core models for QoS found in the networking layer include differentiated services (DiffServ) [25] and integrated services (IS) [26]. DiffServ is a coarse grained mechanism for traffic management where individual packets are placed into different traffic classes. Routers along the travel path of the packets differentiate packet handling based on traffic class membership. Classification of packets normally happens on the ingress to a DiffServ domain: a collection of routers that implement commonly defined DiffServ policies. The classification is carried out by encoding the DSCP (Differentiated Services Code Point) into the lower six bits of the eight bit DS (Differentiated Services) field of the IP header, also known as the TOS byte. [27]. The disadvantage of DiffServ is that individual flows cannot be differentiated and that the classification processing adds delay to the packet travel time [28], the advantage is its simplicity and ability to work without other means than packet inspection along the network path.

Integrated services (IS) [26] is a more fine grained and predictable method than Diffserv when implemented along the whole packet path. The purpose of IS is that applications can make guaranteed resource reservations in the setup phase of a conversation. IS has a dedicated protocol, the Resource ReSerVation Protocol (RSVP), for signaling flow specifications across the network [29]. However, the amount of resources needed for keeping track of reservations in the routers along the path makes it scale poorly for large backbone routers handling many connections. This makes it less likely to find a complete IS supported path when traversing the Internet than relying on the less predictable, but easier to implement DiffServ [28].

There are other models as well. All of these models has led to tools for controlling almost any aspect of IP traffic based on any almost any properties of IP packets. This previous work will be useful in the following investigation on how to ensure SLA compliance in iSCSI based SANs.

2.5 Linux and QoS

2.5.1 The network layer

There exist many networking products offering QoS functionality in some way or the other. Often these are special purpose built components with a high price tag. A compelling alternative to such products is a computer running

GNU/Linux. The Linux kernel has advanced features for implementing QoS at different levels.

`Iproute2` [30] is the part of the kernel dealing with many aspects for control of the network stack. Setting up QoS policies is one of the many things `iproute2` is capable of. The user space utility for doing so is called `tc`, short for traffic control. `tc` has a range of different queueing disciplines (qdiscs) available. Some of them support classes, and can be used to build advanced decision trees about how to handle all kinds of traffic. The flexibility surpasses most of the available proprietary hardware based network products, with a surprisingly low overhead cost [31, 32].

Linux traffic control can be used to prioritize and control traffic based on a vast number of selection criteria. It is possible to limit bandwidth, introduce delay and make high priority traffic pass before others in the queue. The possibility of marking and/or classifying packets with `Iptables` prior to `Iproute2` processing comprises a powerful combination and extends the capabilities of Linux as a QoS machine further [31, 32].

`tc` can control NIC traffic in both directions, but controlling outgoing traffic is most easily done. Since the kernel is in control of what happens prior to the enqueuing of outbound packets on a NIC, it can control most aspects of how it is done and at which rate.

Controlling incoming traffic is more involved, and sometimes not possible at all. When we talk about single packets, it is not possible to shape incoming traffic. A packet arrived is a packet arrived; one cannot un-arrive it. However, it is possible to utilize the TCP protocol's flow control and its ability to adjust the senders' speed by the senders' observation of the receivers' capabilities. In the TCP protocol the receiver controls the sender by announcing its capabilities to the sender [33]. Thus it is possible to make the sender throttle down to a desired rate by dropping packets when the rate is above some limit set on the client. This can be accomplished using `tc`, and is called ingress policing [31]. (See also section 4.2 which discusses the approach more in-depth)

Another option for controlling inbound traffic is to use a virtual device to which incoming traffic is redirected enabling the whole toolbox of outbound qdiscs and classes to be utilized on the outbound side of the virtual device. The intermediate queueing device (IMQ) [31, 34] is often used for this purpose, as is its successor the intermediate functional block device (IFB) [35].

One objection against such methods of shaping incoming traffic is that they do not prevent inappropriate behavior by misbehaving and malevolent senders. Another problematic case occurs when there are large amounts of data already in flight and queued for delivery at an Internet Service Provider (ISP), and

the senders' sensing of the receivers capabilities might be delayed causing unwanted behavior.

These techniques of shaping can nevertheless be interesting in the context of an iSCSI SAN. An iSCSI SAN is a much more controlled and shielded environment than the Internet. To have any chance of being competitive against FC SANs, a dedicated iSCSI network is required. In this situation, the sender is close to the receiver and is able to immediately respond and adapt to changed situations. In contrast, for traffic traveling long distances over the Internet, the buffering and queueing along the packet path delays signaling between sender and receiver, introducing more uncertainty in the amount of packet loss and smoothness of throttling.

The best option is of course no packet loss. Methods for doing this is investigated as a part of this project.

2.5.2 The block layer

There is ongoing discussion about implementing improved QoS in the block layer of the Linux kernel [36] and the best approach for doing fair scheduling there.

The most important considerations are:

- Kernel invasiveness: the amount of kernel code touched by the change.
- Scope of control: should only user space processes be affected or kernel threads as well ?
- Consistency with I/O scheduler prioritization: can QoS mechanism defeat scheduler priority.
- Ability to influence the submitting process by letting it sleep for a while.

There are different patch-sets available for different approaches of QoS in the block layer. These include `dm-ioband`, `io-throttle` and `io-controller`.

`Dm-ioband` is located in the virtual block driver layer; hence one must use device-mapper to utilize it. It needs the `blkio-cgroup` patch to form control groups (groups of processes to operate on) and implements a best effort way of ensuring that each group get a certain percentage of the bandwidth.

`Io-throttle` is able to enforce absolute bandwidth limitations onto control groups. The advantage of `io-throttle` is that it is located on the top of block-layer where requests are issued and is able to signal processes that it wants to throttle down to sleep rather than letting it fill up the queues in memory.

Unfortunately, neither `dm-ioband` nor `io-throttle` are integrated with the lower level I/O scheduler, a design that makes it possible to defeat the scheduler's policies.

The only current alternative that is consistent with scheduler policies and is capable of applying bandwidth limitations at the same time is the `io-controller` patch-set. A consensus was reached that the right place to implement such functionality is in the I/O scheduler level [37]. Version one of `io-controller` was implemented for the completely fair queueing (CFQ) scheduler and included in kernel version 2.6.33 released on February 24, 2010.

2.6 SCSI

SCSI, which originated from Selector Channel in IBM-360 computers, became an ANSI standard in 1986. Originally it was both a hardware specification for parallel interfaces and a command set [38].

The main purpose of SCSI was to make devices connected to computers speak the same language and thereby achieve interoperability between different vendor products . The common language and interface specifications enabled modularity and reusability of the common communication layer, thereby reducing the development effort for writing new device drivers by not having to design and implement a full stack every time [38].

There are two kinds of devices in SCSI: targets and initiators. Initiators start an I/O process and targets responds to them in much the same way as clients and servers. In this sense, the initiator is analogous to the client and the target is analogous to the server. Targets and initiators are called endpoints, and the communication taking place between them is called a SCSI transport [38, 39].

All communication starts by the initiator sending the target a command descriptor block (CDB). The target then processes it and sends back the appropriate response. Each target can further be subdivided into logical unit numbers (LUNs) [38, 39]. The mechanism of logical block addressing (LBA) makes it possible to have a uniform way of dividing devices into logical chunks of data storage, without knowing the cylinder/sector/heads layout of the de-

vices . The target takes care of finding the correct location by translating LBA addresses into cylinder/head/sector addresses internally [38].

2.7 iSCSI

iSCSI is a protocol for SCSI targets and initiators to utilize standard TCP network connections for transportation of SCSI CDBs. iSCSI packages CDBs into protocol data units (PDUs), before handing them to the TCP layer [14]. A PDU adds the necessary wrapping for a SCSI CDB to be handed over to TCP.

2.7.1 Performance of iSCSI

The main weakness of iSCSI based SAN solutions have been their weaker performance in comparison with the more established fibre channel (FC) technology. However, past research demonstrates that these differences can be reduced, and in some cases iSCSI can even outperform FC SANs [12].

Intuitively, the most likely source of the performance degradation from utilizing TCP/IP is the added latency due to computation of checksums and reassembly of packages. This is supported by experiments done by Aiken and coworkers [12]. Their comparison of iSCSI and FC shows decreasing throughput differences as block size of operations increases. The performance differs most, in favor of FC, on workloads where there are many small I/O operations.

Just like ordinary SCSI, iSCSI also utilizes targets and initiators as endpoints forming a SCSI transport over TCP. iSCSI initiator implementation varies a lot but can divided into two main categories: software based and hardware based. The hardware based iSCSI initiator presents itself to the operating system directly as a SCSI adapter, and its function is implemented in the adapter hardware. The software-based iSCSI initiator is implemented as a kernel driver between the block layer and the network layer, and presents itself as a virtual SCSI adapter. When it comes to performance many would argue that functionality implemented in hardware is always performing better. Aiken and coworkers [12] demonstrates that for larger block sizes the software based iSCSI initiator significantly outperforms the hardware based iSCSI initiator, refuting the conventional wisdom that hardware always performs better than software based implementations in the case of iSCSI initiators, a somewhat unexpected result.

Implementing iSCSI in software also has the benefit of being maintainable and flexible in conjunction with the operating system. It scales better with CPU clock speeds and increased number of processing units, and it has no need for specialized hardware. When using a TCP offloading engine (TOE) and/or the full iSCSI stack implemented in hardware, throughput can be excellent but at the expense of smaller requests of smaller size [13].

The motivation for using TOE is to speed up Cyclic Redundancy Check (CRC) which improves performance. Performance can also be improved by looking at where processing cost occurs and alleviating this in software. CRC generation and data copying have been identified by Joglekar and coworkers [13] as a primary bottleneck in iSCSI processing. They suggests replacing the industry standard CRC [40] with a new slicing-by-8 algorithm. The new algorithm is 3 times faster than the industry standard CRC algorithm, and yields significant performance improvement [13].

Caches play an important role in enhancing performance of storage systems. Performance of iSCSI attached storage no exception to this rule. Both the local buffer cache in the operating system and the storage device controller cache will help by enabling delayed merged writes and read ahead for sequential read access, but there exists additional approaches to caching. An interesting approach to caching in an iSCSI environment is proposed by He and coworkers [41]. A SCSI-to-IP cache for storage area networks (STICS) is an intermediate cache that caches data traveling in both directions. The cache device speaks SCSI on the host side and can be implemented in software or as separate plug-in card. On the other side, it speaks to another STICS instance over the IP network, effectively converting SCSI protocol to be transported across the network, thereby bridging the protocol and speed disparities between SCSI and IP. Techniques found in log file structured file systems are used for caching data in both directions. The main benefit of using STICS over using ordinary iSCSI lies in the caching mechanism that is smoothing out the traffic in similar manner to what CPU cache does for CPU memory accesses. Comparisons using I/O benchmark tools like PostMark, IOzone and vxBench [42, 43, 44] shows a performance increase by a factor of 2 to 4 using STICS compared to pure iSCSI [41]. Most of the write performance gain can be explained by the write requests being acknowledged as soon as they reach the local log NVRAM storage instead of having to travel across the net. Read requests that are not satisfied locally must be fetched from remote storage in any case, and any differences are likely to be caused by differing pre-fetch techniques for predicting what data is to be read next. If prediction fails, there is little to be gained from read caching.

2.7.2 QoS and iSCSI

In section 2.4, QoS is seen from from a global Internet perspective, where it is tightly bound to the routers' handling of packets. In the context of SANs, however, routing is normally not involved at all. Most high performance IP based SANs are dedicated, relatively small networks with no IP routing between initiators and targets for minimum overhead and maximum throughput. This thesis the focuses on QoS within limited unrouted iSCSI SANs. Previous work related to QoS and storage, including iSCSI, is discussed in section 2.8 below.

2.7.3 iSCSI stability and enterprise readiness

At the core, iSCSI is an application level Internet protocol. Just like other popular application level protocols, like SMTP and HTTP, the widespread adoption of it, and many implementations, are what make it increasingly interesting. The maturation and adoption of new technologies often involves rapid development efforts in free software projects, the Linux kernel project being the most prominent example. Together with interest from IT industry, companies which implements their own products, and/or sponsor free software projects with commercially exploitable aspect, exercises strong influence on the direction of technology emergence. The amount of companies involved in free software iSCSI projects is increasing. This is a signaling the relevance of iSCSI to the industry.

Customers are attracted by utilizing commodity network equipment for functionality that was previously only possible with expensive equipment requiring special knowledge, following the same reasoning for moving away from expensive mainframe and proprietary Unix solutions during the last decade. By building resilient software solutions that account for failures and limitations in the underlying infrastructure, cheaper commodity hardware can be substituted for more costly special purpose hardware, driving costs down.

There are several competing free iSCSI software stacks available for free operating systems like GNU/Linux [45, 46] and ones based on Berkeley Software Distribution [47]. Among the examples are the iSCSI Enterprise Target (IET) [48], the Generic SCSI Target Subsystem (SCST) [49] and the Linux SCSI target framework [50]. The latter two also implement SCSI targets for other underlying transports like FC, infiniband (IB) and FibreChannel over Ethernet (FCoE), and are mostly implemented in user space. At the moment, it is SCST which is included in the official Linux kernel.

The Linux-iSCSI project is slightly different from these [51]. It is a free project

but is entirely developed by the company Rising Tide Systems [52]. The company's vision is to outperform FC SANs completely by combining the highly scalable and stable iSCSI target stack utilizing specialized 10GB ethernet adapters from Neterion [53] with QoS features particularly directed towards virtualized/cloud computing environments.

When it comes to client side, the initiator, there are many options that range from purpose made iSCSI cards with the whole initiator stack implemented in the hardware to free, pure software implementations that layer on top of any NIC. There used to be two competing free iSCSI initiator implementations, open-iSCSI [54] and Linux iSCSI [55], until they joined forces and became the new Open-iSCSI project [56]. At the time of this writing it seems that Open-iSCSI is not a part of the official kernel, but several popular distributions include its modules and user space tools, RedHat Enterprise Linux is an example of such.

All these loosely knit iSCSI free software projects plays a role in further development of new features and stable operation for enterprise usage. Many ideas and elements from these projects make their way to commercial or semi-commercial products, and experiences from utilizing them are fed back into further improvements of the software and products. Several commercially successful companies has emerged offering enterprise level iSCSI solutions with competitive price and performance. It is interesting to see that large FC SAN vendors like HP and Dell are buying companies producing low cost enterprise iSCSI storage arrays, further acknowledging and promoting their enterprise readiness. Hewlett Packard Company announced their acquisition of LeftHand Networks [57] , a company producing mid range scalable iSCSI storage appliances, nine months after Dell announced the acquisition of a similar company, EqualLogic [58]. Such moves by large storage vendors increases expectation that iSCSI based storage is on the rise, thus making it an interesting and relevant research subject.

2.8 QoS in SAN/NAS

Research about QoS in SAN and NAS (Network attached Storage) devices is an ongoing effort, and there has been numerous approaches to design of such systems [59, 60, 61, 2, 62, 63, 64, 65, 66, 67, 68, 69, 70]. They all start out by acknowledging, in more or less detail, the same challenges about resource sharing, and the need for mechanisms for mending them, as mentioned in sections 2.3 and 2.1, namely the interference between storage consumers and consequently the lack of predictability that comes with it. Popescu and Ghanbari

has made a thorough comparison of performance isolation approaches in [17]. This section will summarize the most relevant of these.

2.8.1 Stonehenge

Stonehenge is the name of a comprehensive project running over several years [59, 60, 62]. It comprises a high performance storage cluster able to make promises about QoS for the presented storage chunks. It is motivated by opportunities presented by previous research, such as Chuang and Sirbu [71] whose work serves as a starting point for community discussion about storage QoS, and Raniwala with coworkers [72, 73] who designed and implemented a prototype for a fault tolerant cluster whose main QoS feature is maintaining the same level of QoS during failure as it is when no failure is present. Stonehenge takes one step further by introducing a mapping scheme that takes both capacity and QoS requirements as input. It further utilizes measurement based virtual disk admission control and includes a real time disk scheduling algorithm.

Three classes of service is supported: guaranteed service, predictive service and best effort service. For guaranteed service, all requests have to be serviced within their deadline which is specified during virtual disk setup. The predictive service class takes an additional parameter that specify the percentage of requests that must be within the deadline over time, and the best effort service utilizes remaining capacity to service the least important consumers.

Stonehenge utilizes storage objects as intermediate means to allocate needed disk blocks with the needed QoS requirements for virtual disks. Given that QoS for the virtual disk is done at create/registration time, the achievement of Service Agreement Objectives is obtained through allocation of the servicing storage objects onto physical disk groups with sufficient amount of striping and redundancy level. The QoS guarantee then is fulfilled by the virtual disk as result of its allocation. There can be several users with different priorities sharing the same virtual disk, and each user can have several applications each with different QoS requirements within the bounds of the virtual disk. Application level granularity of QoS objectives requires application integration with the Stonehenge API.

Given that all virtual disks have static service level objectives that need to be met simultaneously (if necessary), it is reasonable to think that this is achieved by dedicating static pieces of underlying hardware resources in the cluster to the virtual disks. The storage manager maintains global overview of available capacity and accepts or rejects virtual disk creation requests based on their

wanted constraints and available resources in the cluster. The scheduling dynamic lies in making sure that QoS objectives are met by tagging requests with deadline time stamps and making sure there is always enough capacity for storage servers to fulfill requests within the deadline.

The central scheduler, in the management server, is responsible for tagging I/O requests with deadline time stamps before forwarding them to appropriate storage servers. The real time storage servers are responsible for servicing I/O requests within the deadline time stamps, answering requests directly to storage clients.

The suggested implementation of [60] implies a front end target driver (FETD) that presents an iSCSI port at the client side. The main objection against such approach is the need for client side modifications. Also, FETD lies in the data path of disk request scheduling, managing all aspects of disk communication. The handling of I/O requests in FETD necessarily adds overhead compared to regular iSCSI connections.

It is proposed by [60] to more aggressively share spare disk bandwidth by admitting more virtual disks utilizing more of the underlying capacity. It is likely that this will have an effect of decreasing the likelihood of 100% compliance of all QoS objectives by this overcommitting.

Hang and Peng [59] present a Stonehenge prototyp and their evaluation of of it, as well as some design improvements. The main design improvement is the introduction of a dual queue real time disk scheduler for maximizing utilization at the same time as complying with QoS guarantees for virtual disks. The difficulty of quantifying available disk bandwidth is pointed out, together with the effect this has on service level objectives regarding latency of I/O requests. To address this, the Stonehenge implementation implies extensive run time measurements as a basis for disk service time predictions. Also, the dual queue real time scheduler is a means to fulfill request deadlines even if one queue is filled with requests, hence increasing likelihood of latency objectives also being met. Tests shows that for three types of load traces replayed, QoS latency objectives are met 97% of the time for the improved Stonehenge implementation, but only 75% with the initial Stonehenge design. The improved design adapts better to burstiness of workloads, fulfilling the latency objectives better than the initial design.

Further enhancements to Stonehenge has been made by Peng in [62], adding improved fairness in QoS guarantees to storage users. An improved algorithm that better caters for differences in I/O patterns is proposed to prevent intensive head-moving workloads jeopardizing workloads with high data locality.

2.8.2 Cello

Shenoy and coworkers present Cello, an operating system disk scheduling framework, in [74]. Cello comprises a two level disk scheduling architecture: a class independent scheduler for coarse grained bandwidth allocation to application classes and an interleaving, class specific scheduler for fine grained request control to align application requirements to the service provided. The core concept is proportional sharing of bandwidth combined with weighting of applications. Idle bandwidth is reassigned to the best effort class when not needed by higher priority classes, thus, improving utilization of resources (work conservation).

The prototype used for measuring the scheduler overhead was integrated into a filesystem driver on in SUN Solaris. Experiments demonstrates an overhead $<$2ms by interposing Cello.

Comparison between Cello and other algorithms were done using simulations.

The main outcome of the work, is a proposal for an algorithm utilized in application-QoS aware disk schedulers of subsequent operating system versions. Simulations shows that Cello gives better response time for interactive requests, when interfered with large sequential access, than algorithms that don't take differing application requirements into consideration.

2.8.3 Façade

Façade [75] is a throttling mechanisms sitting between a storage device and its consumers. A primary goals is performance isolation between consumers: the performance perceived from one consumer must not suffer from activity caused by other consumers. Performance isolation between workloads is achieved by throttling down consumers in order to shorten queue lengths of the physical drives servicing requests with tight latency service level objectives (SLOs). The implementation of SLOs is done through a combination of real-time scheduling and feedback-based control of the storage device queue. Control is based on simple assumptions of the storage device: reducing the length of the device queue reduces the latency at the device and increasing the device queue increases the throughput. Façade does not have admission control to make sure the total workloads presented actually can be serviced. Additional capacity planning tools is needed for this purpose.

The Façade prototype is implemented as a software layer between the workload generator and the storage devices. It could also be implemented as a

shim box, a thin controller that sits between the consumers and the storage device. Experimental evaluation demonstrates negligible overhead by introducing Façade. Also, it exhibits high probability of meeting SLOs, thus demonstrating its usefulness for performance isolation between consumers, sharing the same underlying resources, by the use of throttling.

2.8.4 Triage

Triage [2] is a solution that ensures predictable performance for storage access. It uses a control-theoretic approach, utilizing a feedback loop, and sees the storage devices as a black box with no prior knowledge about it. At the core lies the general assumption that increased throughput results in increased latency, similar to assumptions described in Façade [75]. The throttling of loads is the means to achieve performance goals also in Triage. It utilizes an adaptive controller approach which infers the model used for decisions solely based on storage device behavior as seen from the outside.

The workload throttling is done on the client side. For the experiments, a Lustre clustered filesystem is used. Each client node is running a modified IOZone [42] with built in throttling capabilities, taking signals about throttling from the controller that makes throttling decisions.

Experiments show that adaption speed of Triage is close to models specifically designed for certain operation points, i.e. they contain knowledge about the device and workloads. Triage adapts, with the same speed, without this knowledge.

2.8.5 Argon

Argon [64] is a QoS aware storage server, part of the Ursa Minor [76] based storage distributed cluster system. It focuses on efficiency by avoiding cache interference between applications, by aggressive prefetching and cache partitioning, to obtain amortization. This is mainly done to avoid unnecessary head movement in competing workloads where one of them is sequential and will benefit from not moving the head away. Fair sharing is obtained such that no user get less than $\frac{T}{n}$ (where T=total resources and n=number of users) but allows users to borrow capacity when there is no contention.

2.8.6 Chameleon

Chameleon [63] utilizes a combination of performance models, incremental feedback and constrained optimization. It mends broken SLAs by throttling down competing clients (with lower or no SLA) to free up enough resources to rectify the broken ones. Chameleon reacts to workload changes and minimizes the number of QoS violations. A balance between maximum utilization and no QoS violation is achieved by continuos monitoring and throttling / un-throttling of loads. Dynamic internal performance models are built using performance samples. A reasoning engine computes throttling values with statistical confidence based on internally generated black box models. Predefined policies serve as a fallback applying coarse grained arbitration when the generated models falls short. That is when confidence of statistical calculations are below a certain threshold.

2.8.7 SARC/AVATAR

Zhang and coworkers use an interposed scheduler that services all incoming requests, in a similar manner as [61, 2, 75]. It takes a black box approach to the storage device and uses monitoring to obtain knowledge about device state. The higher level of the architecture implements a rate controller called SARC. SARC controls workloads to meet rate requirements and isolation of workloads. AVATAR is the lower level of the architecture, and controls the flow of requests between two queues. It carries out work conservation by utilizing spare bandwidth to aggressively serve throughput requests. AVATAR monitors "spareness" and balances high priority latency bound requests with servicing the higher level SARC for maximizing bandwidth consumption. Simulation based verification of operation, that assumes Poisson distributed request arrivals, is used for verification, an approach that idealizes the actual situation artificially [17].

2.8.8 AQUA

Aqua is the QoS component of the CEPH petabyte-scale high performance storage cluster [68, 69]. The workers of the CEPH cluster are the object based storage devices (OSDs). AQuA makes OSDs QoS-aware and able to make bandwidth reservations based on client requests. Requests are grouped into QoS classes of different priorities by tagging them on the client side. The OSDs prioritize their scheduling based on the requests' QoS-tags, similar to DiffServ in networks [25].

The QoS requirements of CEPH are different from other storage clusters in the way that relatively small amounts of data can be spread across many OSDs. Hence, its QoS knowledge needs to be global and equally enforced on all OSDs.

This work points out the inherent challenges of proportional sharing mechanisms for bandwidth allocation: disk bandwidth is not constant. Rather, it varies with its load and access pattern because access times vary not only with data location on disk but also the current location of the disk head, a component of access time that is workload dependent and highly unpredictable.

Because of the highly unpredictable data locations for incoming requests, AQuA has chosen to implement a distributed adaptive throttling approach for solving the QoS task at hand. The fundamental augmentation AQuA provides to CEPH is the throttling ability of OSDs. Each OSDs simply makes individual throttling decisions to support the higher level QoS goals.

A Hierarchical Token Bucket filter (HTB) is used to slice up the disks' total bandwidth, thus creating bandwidth classes that are able to borrow bandwidth from each other while still enforcing capping in case of contention. The calculation of total bandwidth is based on profiling disks according to a certain workload type. The workload type from which total disk bandwidth should be profiled is centrally configurable. This semi-dynamic adaption of total bandwidth makes the underlying assumptions of the HTB creation more accurate by directly influencing the total token rate of each HTB.

Small scale experiments illustrates intended behavior of the new throttling-augmented OSD disk scheduler. Performance isolation is achieved between competing workloads on a single-OSD level. The experiments only consider QoS of throughput.

VMware research on storage QoS

Gulati and Ahmad [65] propose using I/O request latency on the consumer side as a measure of disk array contention. Their idea is inspired by the loss probability calculation of packets in TCP. The latency measure is used to decide the throttling of local outgoing I/O requests, thereby influencing the saturation level at the storage array. If all consumers abide to the same throttling scheme, this approach ultimately would prevent array saturation. However, there is nothing that prevents a machine that doesn't participate from monopolizing all resources. In fact, it would make it easier for a non-abiding host to monopolize resources because any abusive behavior would drive up the array latency. While the abuser doesn't care, the throttlers will detect high latency

caused by the abuser and throttle themselves down, thereby freeing even more resources for consumption by the abuser.

The method is targeted towards host computers running VMware virtual machines, and fairness is calculated by aggregating virtual machine weights for each host computer. The outgoing queue length is determined by a moving average of request latencies, calculated using the Exponentially Weighted Moving Average (EWMA), an upper limit and a threshold triggering change. The threshold is the limit describing the intersection between normal array operation and array overload.

Initial investigations carried out in the research show it is possible to distinguish between the latency due to an array's normal workload and the higher latencies caused by array overload.

In [67], Gulati and coworkers present a QoS framework for VMware ESX server: proportional allocation of resources for distributed storage access (PARDA). PARDA is a software system that implements the basic ideas from [65] with some enhancements. Testing the findings more thoroughly, [65] found that virtual disks sharing the same underlying disk-group exhibited differing performance running the same load. The differing locally measured latencies lead to throttling that made the environment diverge, creating a persistent performance gap between otherwise equal hosts. Thus, a measure of average latency from all hosts was used as input signal. This was done by aggregating values through interconnects between the hosts utilizing the same storage system. Experiments show that the system is able to keep close to the set latency value, describing the saturation point, hence avoiding array saturation altogether. PARDA seems to make significant overall QoS improvement for a dedicated VMware environment sharing a storage array.

Furthermore Gulati and coworkers present a storage resource scheduler [66] for deciding what virtual disks are a suitable storage location for different loads. It does this by profiling workloads and available virtual disks to find suitable storage performance for workloads. Locations of workloads are moved by the means of VMware's VMotion storage product. Workloads are characterized at the hypervisor level by having lightweight probes reporting on individual request properties, such as seek distance, I/O sizes, read-write ratio and average number of outstanding I/O operations. A rather simplistic approach was taken for modeling virtual disks performance: a performance factor based on the constant linear relation between rate and latency. In special cases where a single disk-group has only one virtual disk utilizing it, this is likely an adequate representation of the performance. However, once sharing of the underlying resource with other virtual disks begins, this assumption can't be made. Basing storage relocation on such a model could lead to wrong

decisions.

2.8.9 Four-tag SFQ

Jin and coworkers [61] propose an interposed request scheduler in the network path between clients and server. It uses a modified start time first Queueing (SFQ), called Four-tag Start-time Fair Queuing or FSFQ, and its main focus is on improving the scheduling algorithm by using FSFQ over SFQ and other previous algorithms.

The experimental evaluation utilizes a modified NFS proxy that maintains per client queues that implements SFQ and FSFQ for comparing their fairness. The test is synthetic, utilizing on/off constant rate and Poisson arrival rates.

The weakness of the study seems to be that it assumes constant rate-capacity of the storage server as the base measure for dividing resources between clients (constant cost prediction). Other studies demonstrate that this assumption is incorrect [17, 69, 70]. Remaining capacity, and hence distance from saturation, is just as much influenced by the nature of the workload (read/write mix and randomness, for example) as the rate. Basing scheduling decisions merely on rate could result in wrong decisions.

2.8.10 Modeling iSCSI delay bounds

Ramaswamy [39] proposes an analytical model to estimate maximum delay bounds for iSCSI requests. While the ideas underlying the model are excellent, unfortunately the assumptions made in the model design are insufficient for real life usage, including the following:

- Schedulers have negligible servicing time.
- Schedulers can be characterized as systems in a steady state where the number of departed requests equals the number of the requests arriving into the system: requests are rearranged and merged unless the NOOP scheduler is used.
- Steady state operation of the network.
- Resources are able to accommodate aggregate traffic classes.

The model presented is not verified by experiments, and, with the insufficient assumptions made, the model is likely to misrepresent real situations.

2.8.11 Adaptive SFQ

Jin and Buyya [70] recently presented a modified SFQ algorithm that adapts the fairness calculations to the performance of the underlying resources by utilizing a performance monitor. The objective of the performance monitor is to detect unfairness between flows. This is done by comparing each flow's rate with its SLO, which is a reasonable foundation for deciding throttling. Also, it attempts to relate storage object location to performance level, given that data locations have different I/O capacity. For example, blocks located on the outer edge of the disk plates have faster access than inner locations, due to different rotational speeds. An assumption that previous measurements of block location performance can predict future performance of the same block location could be flawed however. The case or a virtual disk sharing underlying resources that constantly has its data blocks redistributed to optimize overall performance would be an example where such an assumption is too simple. Hence, it remains to be seen whether the unfairness calculations based on device profiling will work as expected in such environments.

2.8.12 Modeling RAIDs

As pointed out by previous work [17, 63], the complexity of RAID systems makes it difficult to model their behavior when loaded with different kinds of workload patterns that interact with the underlying resources and influence each other. The most successful approaches seem to be the ones that take a black box approach and don't try to make detailed assumptions about behavior.

However, Lebrecht and coworkers present a response time distribution model for zoned RAID [77]. The model implies modeling of single disk drive's properties and combines these into queueing networks that represents their RAID setup. High accuracy is demonstrated in experimental verifications carried out as part of the work.

This work is a first step in the process of creating a model that takes into consideration caching mechanisms at different levels and workload arrival patterns other than the Markovian arrivals used in their experiments. It remains to be seen, though, whether it will be possible to extend the model to predict individual virtual disk behavior when a number of consumers are sharing the underlying RAID resource.

2.9 Summary

Previous research includes a vast amount of approaches to the problem of storage QoS, and the amount of work is descriptive of this problem. Previous work varies from full blown storage clusters with QoS as a part of the storage provisioning [60] to simple feedback based control loop approaches. All approaches involve some kind of interposed throttling or scheduling functions. Some involve feedback from storage devices as a means to make scheduling/throttling decisions, and some try to use a predefined model of behavior instead. Many of the experiments done, using close to real world workloads, indicate that relying on a predefined model behavior is not sufficient. Chameleon uses an interesting approach that utilizes dynamically generated models of behavior from measurement observations if able, and uses ordinary feedback with statistical confidence as a fallback for making throttling decisions. Gulati and Ahmad [65] present an interesting and simple approach to resource saturation detection by measuring request response-times.

Other important aspects of the research are work conservation vs. isolation of workloads. These are contradictory in terms, and previous research shows that it is hard to combine the two. In their comparison of different performance isolation approaches [17], Popescu and Ghanbari conclude that non-work-conserving approaches are better choices for isolation of workloads sharing the same physical storage.

All of these approaches utilizes some kind of workload generation. The problem is that they use different workloads and different tools for generating it. Many also lack a detailed specification of how the workload is generated and reasoning about why the particular workload is chosen. This impression is supported by Traeger and coworkers [78], a thorough survey of papers utilizing I/O benchmarks, commenting on their approaches and suggesting improvements.

The ability to specify service level objectives (response time and bandwidth), among other data management features, has been the subject of a decade long research at HP Labs Storage Systems department. Looking back in retrospect, Wilkes [5] points out the challenges of incorporating the research results into real production implementations. The challenge is to persuade users to trust the systems to do the right thing. This is a human challenge, one perhaps rooted in general healthy skepticism to new technology and bad experiences from earlier implementations that turned out to not fully take all real life parameters into account. Wilkes points out the need to remember that systems are built to serve people, and the success of technical accomplishments is dictated by how comfortable people ultimately are with them [5].

Despite all the research done in the field, specifications regarding QoS functionality are seldom found in the specification sheets of storage devices.

iSCSI based storage devices are the major competitor to FC based storage devices at the moment. With its lower cost, easier configuration and maintenance and increasingly competitive performance, iSCSI seems to be the enabler of large scale adoption of IP based SAN devices. The introduction of IP as a transportation layer introduces an additional, well known and well trusted toolbox for enforcing policy and fairness amongst storage consumers. Tools for traffic shaping in the TCP/IP layer have been around for many years. The combination of well known and trustworthy throttling mechanisms and an extended knowledge about storage system internals makes an appealing pragmatic and non-intrusive approach to the problem of QoS in storage systems. Instead of introducing the need to build trust towards interposed scheduling algorithms, bound to add uncertainty and overhead, this project suggests utilization of previously known and trusted tools to obtain workload prioritization in case of resource saturation. Lumb and coworkers point out the lack of a traffic shaper in storage systems [75] (presumably FC based storage systems). However, when utilizing TCP/IP as transport mechanisms, traffic shapers are available.

Chapter 3

Methodology

This chapter will introduce the reader to the methods, tools and equipment used in this project.

3.1 System model

Figure 3.1 shows the conceptual overview of the lab setup. Five machines are involved in the execution of the experiment: four IBM blade servers acting as iSCSI initiators and one Dell 6650 acting as iSCSI target. The iSCSI target server has 10 external SCSI disks connected via a parallel SCSI connection. Physically all five servers are connected via their `eth1` interface to the blade center switch described in Table 3.3. The Iperf [79] utility was used to verify simultaneous gigabit link speeds in all directions with TCP traffic between all servers before experiment's start. The logical volumes serve as back end storage for iSCSI target devices. The iSCSI target software makes the mapping between LUNs presented on TCP port 3260 and the logical volumes that stores the data. To simulate resource sharing, the logical volumes are striped across the ten physical disks with a stripe size of 64 KB. Hence I/O traffic (of sufficient size) to any of the logical volumes will effectively be spread across all ten disks, equally sharing the collective back end I/O capacity of physical disks.

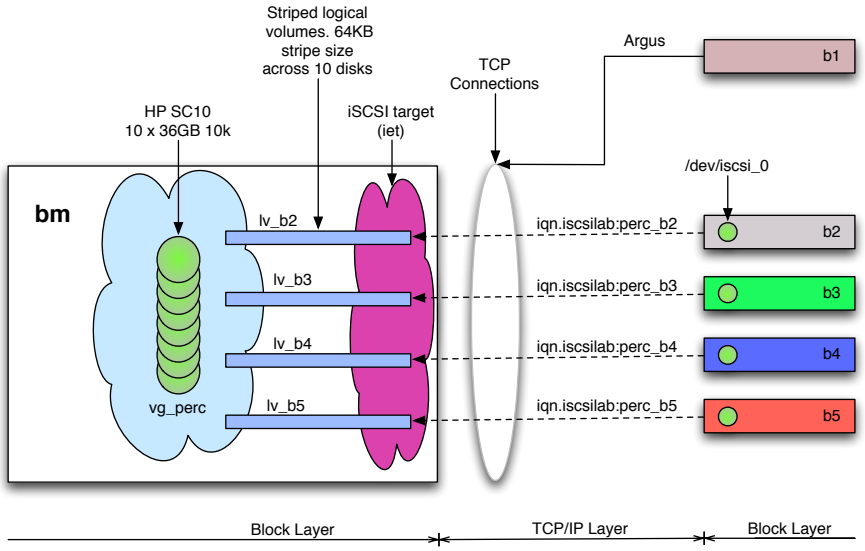


Figure 3.1: Concept sketch of the lab setup

3.2 Tools and equipment

3.2.1 Generating workload

Flexible I/O tool (`fio`) [80] is a versatile tool for generating a wide variety of workload mixes. The tool is written by Jens Axboe [81], who is the current maintainer of the Linux block layer, as a facility to aid the development work of it. `Fio` was the tool used to produce the workload that broke through the 1 Millon IOPS barrier in an experiment done by HP and Fusion IO [82, 83, 84]. Simple configuration files are used for setting up any number of worker threads for generating simultaneous workload of a wide variety. A generated workload is reproducible using the same configuration files. While the main task of `fio` is to produce workloads, it can also produce latency and bandwidth traces for every single I/O request it issues. This is useful to the get an overview of I/O subsystem behavior without having to add any external monitoring. In a real system, I/O requests would be caused by applications running on the iSCSI initiator machines. In the experiment I/O requests will be synthetically generated using `fio`.

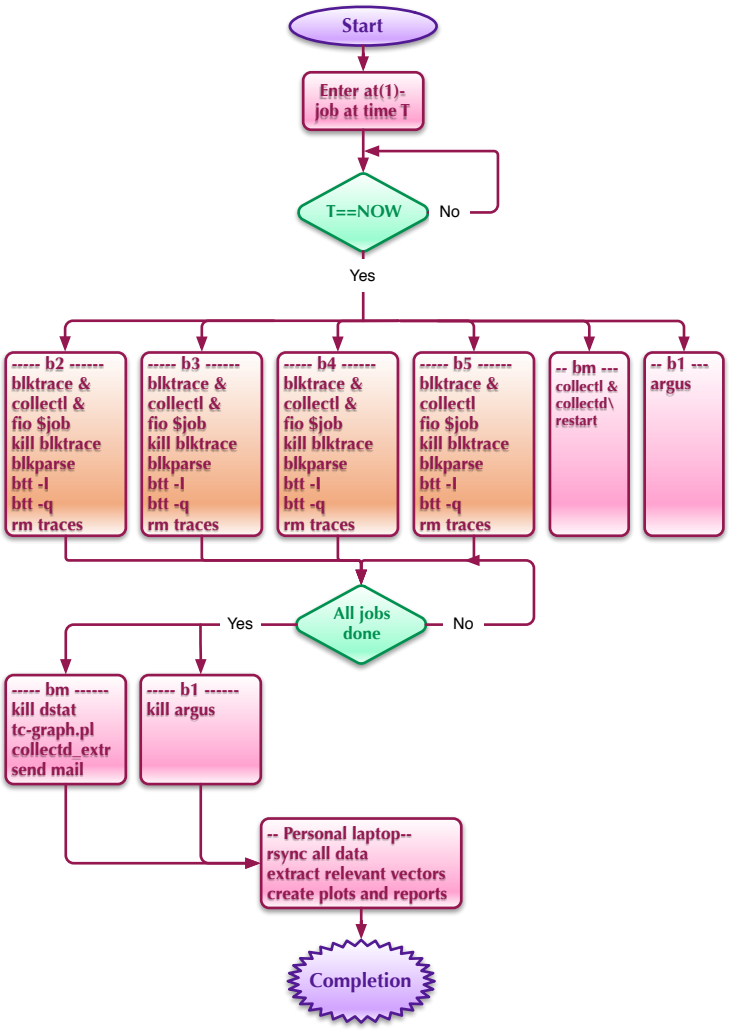


Figure 3.2: Experiment automated workflow. The workflow and collected data is the same for all experiments, except those in chapter 5.4.

3.2.2 Measuring system behavior

To characterize system behavior during experiments, a number of different tools are utilized. The most important task is monitoring metrics about the I/O requests traveling through the system. Some important measuring points include:

- The iSCSI block device on the initiator machines.
- The I/O subsystem on the iSCSI target machine.
- The network subsystem on the iSCSI target, including the different QoS mechanisms.

Different performance tools collect various aspects of system behavior during experiment execution. The data collection is started, stopped, post-processed and collected using shell and perl scripts. The concept of this orchestration is depicted in Figure 3.2.

The following data is collected on the iSCSI initiator nodes:

- Total elapsed runtime of the load, using the /usr/bin/time command.
- Iostat-like time stamped data, using btt -I option.
- Trace of the queue-to-completions (q2c) latencies, using btt -q option.
- Btreplay files, created using btrecord.
- A one second interval data file, containing various performance data, produced by collectl.

The following data is collected on the iSCSI target node:

- A copy of the script collection during the run.
- A graph representing the tc setup during the run.
- An extract of queueing discipline and class statistics, produced by collectd.
- A one second interval data file, containing various performance data, produced by collectl.

The intention of the data collection is to automate a large amount of sensors producing as much data as possible without affecting the produced results in any noticeable way. Earlier experience with lab experiments has shown that unexpected results can call for additional data to explain them. If the extra data is already collected in advance there is no need to redo the experiment.

Preliminary tests were used to get an impression of resource consumption and effect of different measurement approaches. An example of measurements that noticeably affected results was the attempt to run `blktrace` on all ten SCSI disks serving the striped logical volumes. These measurements made throughput drop by more than 10% . The tools and techniques described here were found to be as much data as could be gathered on general basis without affecting the system's performance.

To exactly measure how I/O requests are being serviced, as seen from the iSCSI initiator side, `blktrace` [85] is used to record all there is to know about requests passed to the iSCSI initiator device. The `blktrace` framework consists of three major parts: the kernel event logging interfaces, the blktrace user space utility to access and store the in-kernel events and utilities for parsing and viewing recorded data. The framework also includes utilities to create playback files that can be used to re-play an exact sequence of the traced I/O requests at a later point in time: `btrecord` and `btreplay`

`Blktrace` produces per CPU trace files, so the first part of post processing is to run `blkparse` on the separate traces gathering them into one file. This file can be used for extracting various pieces of information using the `btt` tool. In the experiments, the resource consumption impact by monitoring is minimized by extracting data after the workload has finished running.

Although I/O requests can be examined in great detail from `blktrace` files, two types of information are most relevant to this experiment: rates and latencies of I/O requests (read and write). `Btt` produces output similar to `iostat` using the `-I` option. All measurements of iSCSI initiator devices on the blade servers are extracted from this file.

In the experiments all workloads are started simultaneously on all blade servers using `at(1)`. `Ntpd` is running as a client on all machines to ensure correct time. The scripts that start the workloads first start `blktrace` on the iSCSI device, tracing the behavior of all I/O requests passed to it during workload application. When the workload has finished, the tracing process is killed, and automatic post processing of the trace files is carried out before the traces are deleted for space conservation.

Collectl [86] is a very useful tool with its capability to log performance data into compressed text files. The compressed files can be replayed later to ex-

tract different metrics as needed. Most of the disk and network data from the target server comes from files collected by collectl. Collectl supports the measurement strategy of this project very well: low overhead collection with vast amount of information available for extraction at later points in time. This strategy was beneficial when double-checking packet loss, using collectl's TCP statistics, since Argus turned lost some capture data (See section 3.2.9). Collectl was run in record mode on all machines during experiments from the experiment in section 5.4) and onwards.

The tool `collectd` [87] is used for gathering statistics about data flowing through the `tc` queueing disciplines (qdiscs). `Collectd` is a lightweight plug-in based data collection tool. The `netlink` plugin of `collectd` was the only pre-made collection facility found for collecting qdisc statistics (except from tc -s). All plugins other than the netlink plugin were disabled, the sample interval was decreased to 1 second, and only the CSV output plugin was enabled. To capture only the relevant data for the experiment period, all collectd files were deleted at the start of each experiment run, and collectd was restarted so that output CSV files reflect the actual qdisc and class setup active in that particular experiment. As a part of the experiment post processing on the iSCSI target server, a script collects these files and places them in the results folder. This script is found in appendix C.8.

The `job_template.sh` script starts monitoring, runs the I/O load and does post processing on all blade servers. The script is designed to be reused with different I/O loads just by creating symbolic links named `jobname.sh` which point to the script. The job name matches the `fio` job definition file in the `jobdefs` subdirectory. The last part of the `fio` job definition (after the underscore) defines which host the job definition will be run on. This way the `job_template.sh` script can be reused with different I/O loads just by creating symbolic links and creating a set of `fio` jobs that match the script name and the host it is supposed to run on, ensuring that all monitoring and post processing is done consistently.

The job scripts are run by `at(1)`, and scheduled by the `scheduler.pl` script. Together with `b1-mon.sh`,`bm-mon` `postproc.sh`, these scripts comprise the workflow of all experiments which is conceptually depicted in Figure 3.2. The scripts are found in listings C.15, C.6, C.14, C.13 and C.12 respectively.

The Plot [88] tool is used for creating all plots except for Figure 4.3 which is created using Mathematica, and Figures 5.5 and 5.6 which are created using R.

Item	Specifcation
hostnames	b2,b3,b4 and b5
Machine model	IBM HS20 Blade server , Type: 8843, Model E8G
CPU amount and type	2 X Intel(R) Xeon(TM) CPU 2.80GHz Cache:2MB, Family:15, Model:4, Stepping:3, 32bit
Memory	2 X 512MB
Operating system	CentOS release 5.4 with package-sets @core @base @development-tools
Network interface Card	Broadcom NetXtreme BCM5704S GBit, driver:tg3 (kernel-provided), driver version: 3.96-1, tcp-segment-offlod-(tso)=off, flow-control=(rx=off,tx=off)
Kernel version	2.6.18-164.11.1.el5
iSCSI initator	CentOS provided package iscsi-initiator-utils-6.2.0.871-0.10.el5 (iscsid version 2.0-871)
iSCSI login command	iscsiadm –mode node –targetname iqn.iscsilab:vgname_'hostname' bm:3260 –login

Table 3.1: IBM blade server specifications

3.2.3 Hardware specifications

Tables 3.1, 3.2 and 3.3 list the specifications of the Blade servers, the iSCSI target server and the interconnecting switch, respectively.

3.2.4 Monitoring the network connection

Access to all the network traffic is essential in order to detect the effect of traffic shaping on the network link. The BNT blade center switch, used to interconnect the experiment servers, has an option to mirror port traffic. Port INT1 was chosen as the port for monitoring because the server connected to it (host b1) is running any workload in the experiments leaving host b1 to concentrate on the capturing process. It was decided to mirror ingress traffic of ports INT2-INT5 (hosts b1-b5) and EXT1 (host bm) onto port INT1 (host b1). The setup of port mirroring was done according to the Alteon OS application guide [89].

Next, a tool for capturing network statistics on the mirror port was needed. The first tool considered was `tcpdump` [90], and tcptrace [91] for plotting various aspects of the TCP communication. However, it turned out that `tcpdump` is unable to keep up with the traffic rate between the five machines during

Item	Specifcation
hostname	bm
Machine model	Dell 6650
CPU amount and type	4 X Intel(R) Xeon(TM) MP CPU 2.50GHz Cache:1MB, Family:15, Model:2, Stepping:5, 32bit
Memory	8 X 1024MB physical, 4GB Utilized
Network interface card	Broadcom NetXtreme BCM5700 Gigabit, driver:tg3, driver-version:3.92.1, tcp-segment-offlod-(tso):off, flow-control:(rx=off,tx=off)
Operating system	Debian Lenny minimal install
SCSI HBA external disks	Dell PERC 4/DC Ultra 320 SCSI external port (Used up to section 5.4)
SCSI HBA external disks	Adaptec AHA-2940U/UW/D / AIC-7881U (Used in section 5.4) and onwards
External diskshelf	HP SC10 Shelf with 10x36GB 10k rpm disks
OS version	Debian Lenny with kernel 2.26.2 (Used up to section 5.4)
OS version	Cent OS 5.4 with kernel 2.6.18-164.15.1.el5 (Used in section 5.4 and onwards)
iSCSI target	Debian provided package iscsi-target (ietd version 0.4.16) (Used up to section 5.4)
iSCSI target	IET version iscsitarget-1.4.19 from [48] (Used in section 5.4 and onwards)
ipset version	ipset v4.2, protocol version 4, kernel module protocol version 4
iptables version	1.4.6

Table 3.2: Dell iSCSI server specifications

Item	Specifcation
Switch model	BNT Layer 2/3 Copper Gigabit Ethernet Switch Module for IBM BladeCenter
Firmware versions	Boot kernel: v1.5.9, software image version:1.5.9
Flow control	Turned off on all ports
Port mirroring	Ports INT2,3,4,5 and EXT1 mirrored to Port INT1

Table 3.3: IBM Bladecenter switch specifications

iSCSI workload. `Tcpdump` kept losing packets, hence, it did not capture a full picture of what was going on. `Tcptrace` is very useful for generating detailed plots and statistics from reading `tcpdump` files. Plot files are generated in a format called xpl and can be plotted with the special purpose xplot program. However, the plot files generated from `tcptrace` were rather large, and when trying use `gnuplot` to plot files generated with xpl2gpl [92] (which took about 5 minutes), all 4GBs of memory were consumed on the laptop and no plots were produced.

Obviously, a more lightweight solution was needed. Argus [93] seemed to fit the purpose. Argus is connection oriented and is geared towards security audit trails but it also captures various performance related metrics which are adequate for the purpose of this project. Argus is run as part of the experiment orchestration shown in Figure 3.2, on host b1. Host b1 does not take part in the experiment, it only monitors the mirrored port of the switch during experiment execution.

During experiments, it was discovered that Argus too was loosing packets hence not representing a full picture of the network traffic. See section 3.2.9 for further discussion about this.

3.2.5 Getting persistent device names

Most Linux distributions now use `udev` [94] to dynamically populate the `/dev` directory with the correct contents. Unfortunately the default device naming scheme of SCSI disks still is the old `sda,sdb,sdc` and so on, which contain no persistent binding to target and LUN numbers.

Since blade server b3 has an additional internal disk, compared with the others, the device naming of iSCSI disks was not consistent across all four blade

servers. To alleviate this, a small udev trick was enabled. The following custom udev rule creates iSCSI device files that is persistent with LUN numbers (/dev/iscsi_#).

```
BUS=="scsi", SYSFS{vendor}=="IET", SYSFS{model}==
   VIRTUAL-DISK", KERNEL=="sd*", PROGRAM="/lib/udev/
   getlun.sh $id", NAME="iscsi_%c%n"
```

The program /lib/udev/getlun.sh returns the LUN number, and its output is substituted for %c in the name of the device.

The getlun.sh script:

```
#!/bin/bash
echo $1 | awk -F":" '{print $NF}'
```

Since all LUNs have LUN number 0, and no partitions is used, the device to run I/O-load towards is named /dev/iscs_0 on all blade servers.

3.2.6 Setting up bandwidth limitation

Linux Traffic Control has many built-in modules for traffic shaping. The Hierarchical Token Bucket (HTB) queueing discipline (qdisc) can be used to set up a complex hierarchy of bandwidth classes. This project utilizes the HTB qdisc as a means to create the bandwidth classes for iSCSI read throttling seen in figure 5.2. Figure 3.3 shows a graph depicting the class hierarchy of which the iSCSI interface is divided into. In order to keep a small size of the figure, only the two first classes is shown. The next class indicates the pattern of further classes.

In order to enforce any bandwidth limitations, packets need to be placed in the desired bandwidth class. Packet classifications is done with filters. In `tc` the `fw` filter module is used to match packets with marks (a hexdecimal number) placed by `Iptables`. Thus, the class hierarchy can be set up once, and `Iptables` used to dynamically select bandwidth by its powerful matching capabilities.

Filters are attached to the root qdisc, in order to inspect all outgoing traffic. The blue lines in figure 3.3 depicts the filter with their associated `fw` mark-match along the lines.

The script for setting up the bandwidth hierarchy, depicted in figure 3.3, is located in listing A.4.

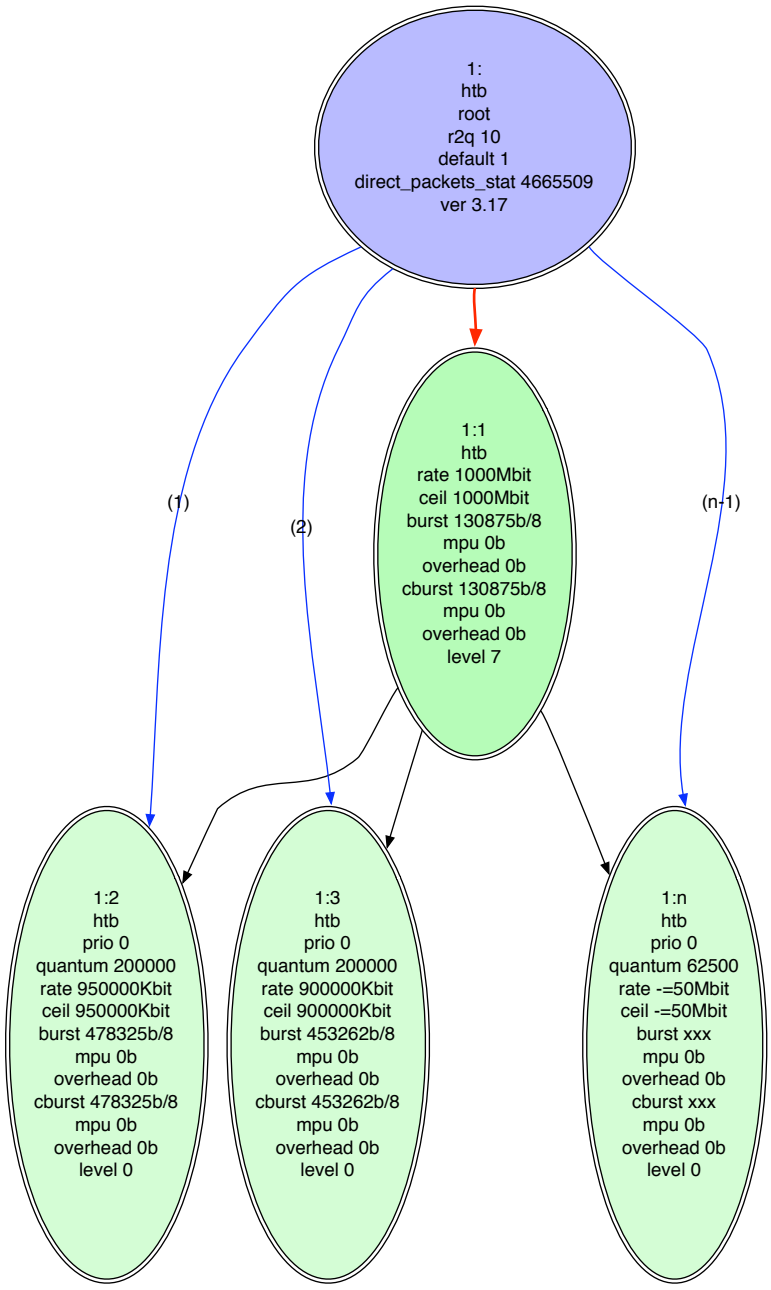


Figure 3.3: Graph depicting the egress queues used for bandwidth outgoing limitations

3.2.7 Delay limitation

The concept of the delay class hierarchy is similar to the bandwidth class hierarchy; a set of classes that covers the needed throttling scope in a sufficiently granular manner. The `netem` module of `tc` is used to enforce artificial packet delay. The HTB qdisc is used to create the hierarchy, but rather than HTB bandwidth limiters as leaf qdiscs, `netem` qdiscs with predefined delay is used instead. Figure 3.2.7 shows what this class hierarchy looks like. Filters are attached to the root qdisc in order to inspect all traffic. Upon mark match, packets are sent to the corresponding delay class.

The script that sets up the packet delay hierarchy depicted by figure 3.2.7 is located in listing A.5.

3.2.8 Using Iptables and Ipset to classify traffic

`Iptables` has more powerful and dynamic matching capabilities than `tc`. This project utilizes a set of static `tc` delay classes with filters only checking packets for marks placed by `Iptables` (see section 3.2.7). This way, the packet classification task is carried out by `Iptables` by utilizing `tc` classes for applying the delay. The scripts wanting to utilize packet throttling need to know the valid range of marks with corresponding `tc` delay filters. The scripts then have a means to throttle iSCSI initiators within the pre-configured delay classes in `tc` by altering `Iptables` rules. The script used to demonstrate throttling effect on throughput uses this altering of `Iptables` rules to throttle individual iSCSI initiator IP addresses (Figures 5.2,5.3, 5.4 and Listing A.1).

While throttling of individual consumers is sufficient for demonstrating the effect, more matching capabilities are needed for the next step: a dynamically maintained list of consumers that are deemed throttleable. Ideally `Iptables` should be able to match against this list directly, and apply marks if a consumer is found in the list. `Iptables` does not have built-in capabilities for matching against lists, however, the `Ipset` patch-set enables this feature [95]. The PID controller program (Listing A.2) utilizes `Ipset` in order to have only one `Iptables` rule to change when packet marks needs altering. The `Iptables` rule always match against the set of throttleable consumers while this set also can be dynamically updated.

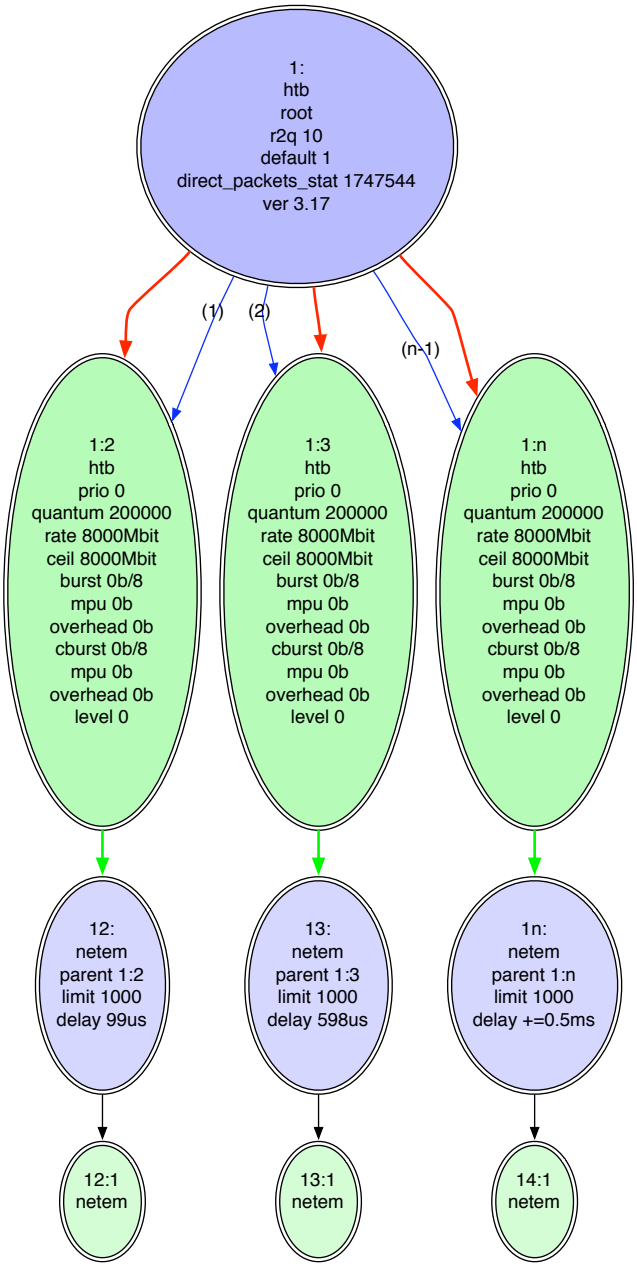


Figure 3.4: Graph depicting the egress queues used for packet delay in both directions

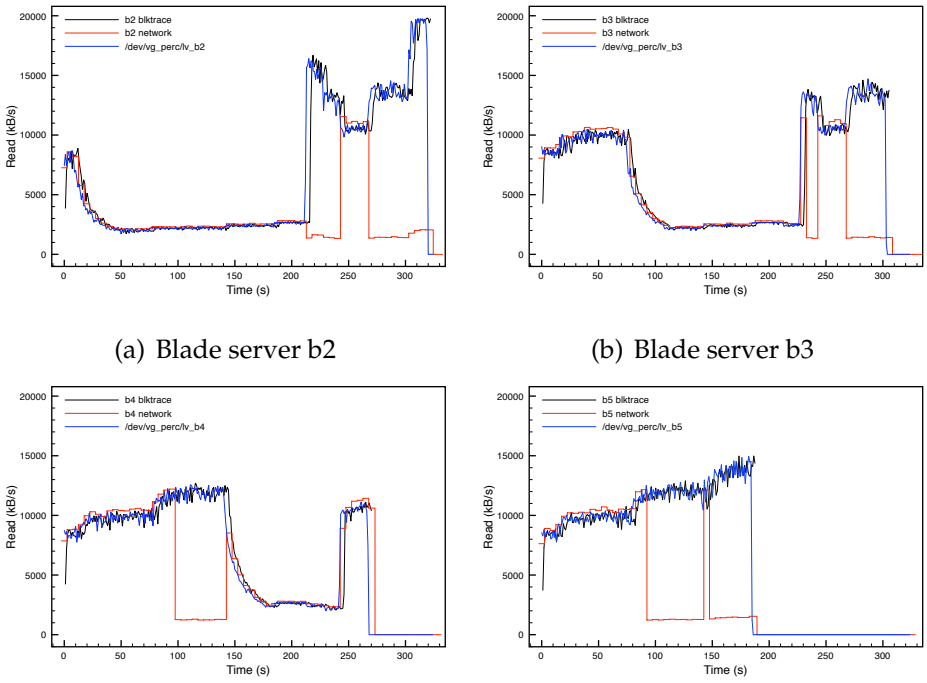
3.2.9 Argus usage

Argus captures a lot of useful information that can be queried afterwards, thus, it also support the collection strategy of the project. However, it turned out Argus suffered from packet loss. This was discovered when comparison of sender and receiver rates did not match the rate of the network in between. In Figures 3.5 and 3.6 the `blktrace` plots of the initiator devices on the blade servers (in figure 5.3 and 5.4) is split and overlaid with network traffic logged by Argus and the respective traffic from logical volumes on the iSCSI target server.

There is the expected close correlation between the read rates on the iSCSI initiator device (blktrace) and the logical volume it is tied to on the iSCSI target. What is not expected, is that Argus-logged traffic is correlating only partly. The likely cause of this is that Argus, or the mirror port in the switch, has failed to capture some packets. If the traffic did not travel safely across the network there would be differences between sender and receiver rates; however, this is not be the case.

The consequence of this packet loss is less confidence in the correctness of the test for packet loss in listing E.8. Therefore, additional steps were taken to verify the absence of packet loss during experiments. `Collectl` was run during experiments and both target and receiver TCP data from `collectl` was queried for packet loss. No packet loss was seen using this approach either (See listing E.3).

The Argus plots for Figure 3.5 is generated by the commands in listing E.4, and the logical volumes is created by the commands in listing E.5. The plots for writes were generated in the same way, but then the `plot.pl` script is picking out the `argus sload` rather than `dload` column, and write kB/s to the logical volume rather than read kB/s.



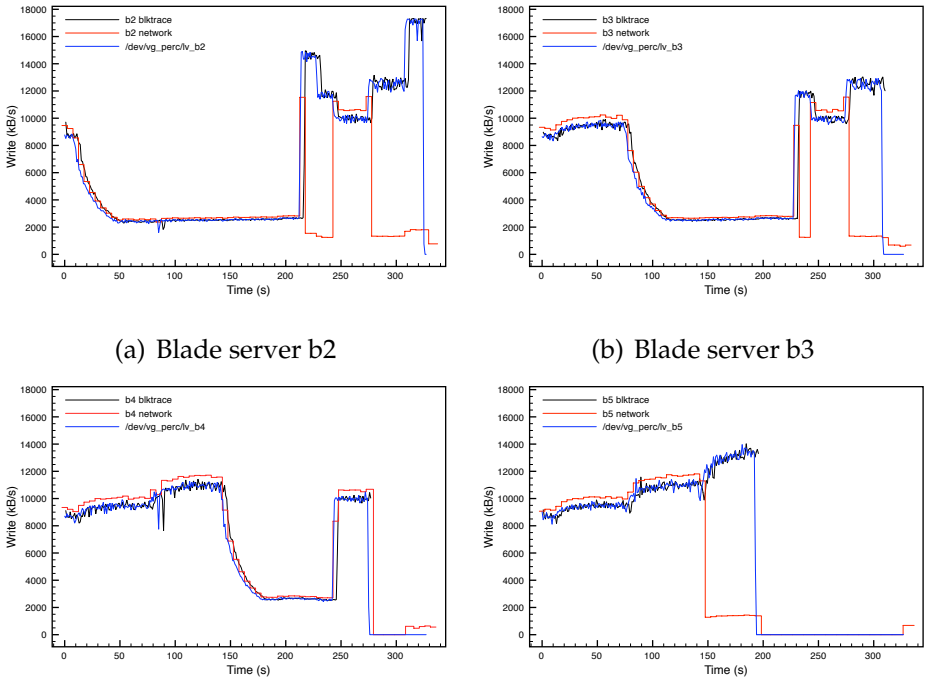
(a) Blade server b2

(b) Blade server b3

(c) Blade server b4

(d) Blade server b5

Figure 3.5: Comparison between initiator, network and target-logical-volume rates when reading



(a) Blade server b2

(b) Blade server b3

(c) Blade server b4

(d) Blade server b5

Figure 3.6: Comparison between initiator, network and target-logical-volume rates when writing

3.3 Challenges

3.3.1 Network instability

In the beginning, some instability in the network connections was experienced during heavy I/O loading over the iSCSI protocol. The Ethernet link between iSCSI initiator servers and the Dell iSCSI target server would freeze completely on random occasions. Bringing the iSCSI NIC of the iSCSI target machine down and up again would temporarily solve the problem. After upgrading switch firmware, turning off TCP segmentation offload and flow control on the switch ports and all host NICs, the problem was not seen again.

3.3.2 LVM instability

Some instability was experienced in the LVM layer. When I/O continued for a time, suddenly the LVM layer introduced delays causing the throughput to logical volumes to drop dramatically, from 30-40 MB/s aggregated throughput towards logical volumes to a rate of 512kB/s . The problem was confirmed to be in the LVM layer by testing throughput with I/O directly to logical volumes locally on the iSCSI target server when the problem exhibited itself and comparing it with direct I/O to the same underlying disks serving the logical volumes. Access to the underlying disks showed expected throughput. Access to the same disks through LVM was stuck until next reboot.

Attempts to debug the problem was done using `SystemTap` [96] and `blktrace` [85]. However none of the prerequisite kernel hooks were present in the 2.6.26 kernel of Debian Lenny. Attempts were made using `slabtop` to look at anomalies in the kernel buffer structures when problem occurred. However, the focus of the project is not debugging the block/LVM layer of the Linux kernel, but utilizing a working LVM to illustrate some points about resource sharing. For this reason it was decided to find a workaround rather than proceeding with time consuming troubleshooting. Installing CentOS 5.4 as operating system on the iSCSI target server, seemed to be the solution for a while, but the problem appeared again after some time. Since CentOS 5.4 was better equipped with tracing tools, an attempt to log data and get help from linux-lvm mailing list was made, but no responses were received.

The Dell server has a built in `aic7xxx`-based SCSI adapter in addition to the (supposedly) more powerful PERC RAID controller. To leave no option untested, the disks were hooked up to this controller, and this time there was no anomalies. Using this setup the performance anomaly was not seen again. The initial

experiments seen in figures 5.1, 5.3 5.2 and 5.4 was already done using Debian Lenny and had short enough duration to not exhibit this problem. All other experiments are done using CentOS 5 with the same disks attached to the `aic7xx` controller.

A common performance problem with such set-ups is related to block/request alignment. LVM metadata consuming space at the starting blocks of the physical drives could be causing such misalignment. However, one would expect such problem to be persistent. This one was just intermittent and unpredictable. This behavior remains unexplained, but somehow the problem must lie in the instability of the combination: PERC RAID controller accessed by LVM with striped logical volumes.

Chapter 4

System design

This chapter describes the design considerations aiming for the final goal, a working prioritization framework containing throttling, measurements and decision making. The chapter has emerged during the experimentation phase and it is influenced by the results exhibited. Thus, this chapter is tightly connected with the progress of chapter 5.

4.1 Choosing a throttling method

The main idea of this project is the utilization of common tools in novel ways in order to obtain more predictable service availability of storage devices. The objective is to demonstrate ability to mend adverse effects of interference between loads using a throttling mechanism for reducing resource contention, thereby improving service availability for important consumers. iSCSI utilizes TCP for transportation and Linux Traffic Control (`tc`) has advanced features for network traffic shaping, hence, the decision to use `tc` for the purpose of throttling was easy.

The amount of consumers that need to be throttled could become large. Also, workloads may rapidly change. Thus, a method to rapidly adapt throttling schemes is a necessary requirement. Traditionally, TCP traffic shaping with Linux Traffic Control is used with static rules targeted only at the network itself. This project should utilize feedback from resources outside of the network layer in order to adapt rules in the networking layer.

In order to have sufficient control of the consumers' resource utilization, both read and write requests must be throttled. As stated in 2.5.1, controlling in-

bound traffic is a challenge. Inbound traffic translates to iSCSI write activity. Different approaches for dealing with the shaping of inbound traffic are known. The easiest method to achieve this is ingress policing. The concept of ingress policing is to drop packets from the sender when a certain bandwidth threshold is crossed. The congestion control mechanisms of TCP will then adjust the sender rate to a level that can be maintained without packet drops (Further described in 4.2). There are clearly disadvantages to this approach. The most obvious one is packet loss, which leads to inefficient network link utilization due to packet retransmits. Another problem is the time it takes for the sender to adapt when the receiver decides to change the allowed bandwidth. During the adaptation process packet loss will occur due to the nature of the policing. This might be sufficient for a small number of senders and seldom changes in the receivers' accepted bandwidth. However, the ability to change bandwidth limitations is needed for rapid adaption to workload changes. When the number of consumers and bandwidth limits changes rapidly, this method does not scale, but adapts slowly and inefficiently. Another problem with ingress policing in Linux is the order of packet processing in the kernel; ingress policing happens before packets enter any `Iptables` chains. Hence, it is impossible to select packets to be policed using `Iptables`, and failure to do so makes it impossible to utilize the dynamic packet matching capabilities of `Iptables` described later on.

A feature called Intermediate Queueing Device (IMQ) can be added to the Linux kernel by applying a patch. The IMQ patch enables a virtual network interface which incoming traffic can be redirected to. Since IMQ is Iptables-aware, packets entering the IMQ device can be marked for later matching by `tc's` filters before packets are passed back to the incoming interface. An alternative to the IMQ device is present in the official kernel: the Intermediate Functional Block (IFB). However, IFB is not Iptables-aware because it is located before `Iptables` chains for incoming traffic. Hence, incoming packets marked with `Iptables` have already passed the IFB device, and filters attached to it are obviously unable to detect them. This behavior disables usage of `tc's` `fw` filter.

Both IFB and IMQ suffers from the following: the input buffer of the incoming interface is finite, and iSCSI traffic is typically heavy data traffic that quickly fill up even large buffers, thus, tail dropping of requests will occur. This comprises a similar situation as with ingress policing.

This project suggests a novel method of throttling designed to address the limitations just described. The method implies introducing a variable additional delay to packets sent back to initiators. Write requests are throttled by delaying outbound ACK packets, and read requests are throttled by delaying all outbound packets except ACK packets (data packets). The principle of delaying ACK packets is illustrated in Figure 4.1. The actual delay is obtained using

the `netem` module of Linux Traffic Control, and packets get different delays based on `Iptables` marks.

As previously argued, the need for a dynamic selection method for throttling packets is needed. `Iptables` provides this dynamic behavior with its many available criteria for matching packets. Combined with the `mark` target, which can be detected by the use of `tc's fw` filters, it is possible to set up a predefined set of delays that covers the needed throttling range with sufficient granularity.

The entities that consume resources in this context are the iSCSI initiators. The entity that provides the resources of interest to the initiators is the iSCSI target. Both initiators and targets have IP addresses. IP addresses can be used for throttling selections. The IP address of the iSCSI initiator will be chosen as the entity to which throttling will apply. Differing priorities for consumers will translate into different throttling schemes of those consumers' IP addresses. The underlying idea is to apply throttling to less important requests in order for important requests to have enough resources available to meet their requirements.

Packet delay throttling makes it possible to influence rates in both directions on a per initiator basis. In production environments the amount of initiators to keep track of quickly become overwhelming if throttling is based on individual consumer basis. Moreover, it is likely that the same throttling decisions should be applied to large groups of initiator IP addresses. Applying the same rules, over and over again, on lists of IP addresses is inefficient. To avoid this inefficiency the `Ipset` tool is needed [95]. It is a patch to the Linux kernel that enables creation of sets, and a companion patch to `Iptables` that makes `Iptables` able to match against those sets. This is a fast and efficient method of matching large groups of IP addresses in a single `Iptables` rule: the set of throttleable initiator IP addresses.

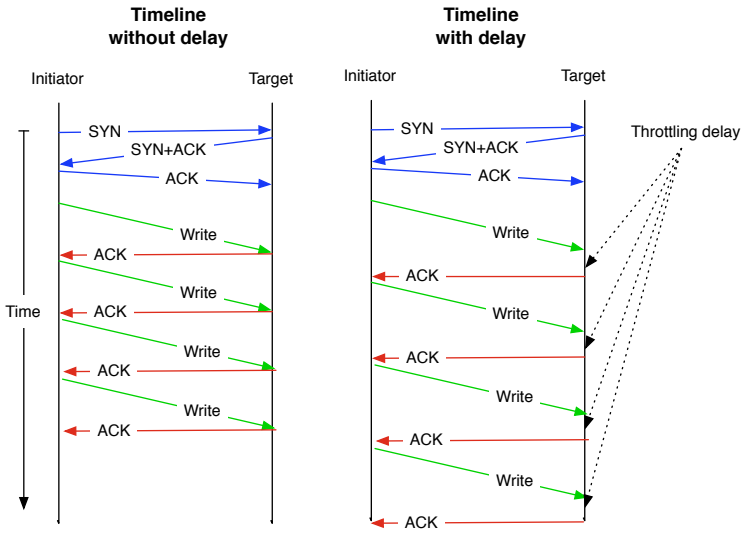


Figure 4.1: Principle of throttling by delaying packets

4.2 Discussion of the delay method

4.2.1 Risks

TCP implementations contain intelligent algorithms to avoid congestion and to be efficient in transportation of packets. One of these mechanisms is the dynamically applied retransmission timeout (RTO) which is calculated from a smoothed roundtrip time (SRTT) and its variation (RTTVAR) bounded by some fixed limits.

The RFCs defining how TCP should be implemented specify how RTO must be calculated and implemented [97]. They also specify how congestion control should be implemented [98]. Artificially manipulating TCP packets at one point in the network can affect network traffic in unexpected ways. It is reasonable to speculate that there is a limit to what extent traffic can be manipulated before congestion control and retransmit algorithms activate, causing unexpected and unwanted behavior. This is something that needs to be qualified in order to find reasonable boundaries for traffic manipulation.

It is clearly stated in [97] that RTO should not be less than one second. However, the RFC takes into consideration that future developments of network equipment might justify a lower value. Existing implementations of TCP, including the Linux Kernel, have a lower RTO minimum value than the RFC

recommendation. The default value of `TCP_RTO_MIN` (in ms) in the 2.6 Linux kernel is related to clock granularity and is defined as $200ms$ as shown in listing E.9. It is also possible to extract the active value from Linux using the method shown in listing E.6.

The results shown in Figure 5.4 have a maximum introduced delay of 10 ms, which is $<<$ $200ms$. Hence with typical transmission rates in an IP SAN environment (or faster), introducing delays of a few milliseconds has an immediate rate reducing effect without being close to affecting the `TCP_RTO_MIN` values.

When the sender decides how much data it can send before receiving an ACK packet from the receiver, there are two pieces of information to consider: the receive window which equals available buffer space at the receiving end, and the congestion window, which is influenced by events along the network path. The receive buffer is always announced by the receiver in the ACK packets sent back to the sender. The congestion window is initially low, then increased and balanced to a point where the network can cope with the traffic. The sender must always use the lowest of the two values for determining how much data to be sent before receiving an ACK packet and more data can be sent.

Congestion control is about sizing of the congestion window (cwnd). It is comprised by three phases: slow start, congestion avoidance and congestion detection. During connection establishment, the maximum segment size (MSS) is negotiated. In the slow start phase, the sender starts with a congestion window beginning at one MSS and it is increased by one MSS until the slow-start threshold (sstresh) is reached. Then the congestion avoidance phase starts. It continues increasing the rate, but with an additive rate-increase, rather than an exponential increase like the slow start phase. The increase in cwnd continues, and if the rwnd is big enough, the data rate will continue to increase until a point where there are signs of congestion in the path. Signs of congestion are detected by the sender when the need to retransmit occurs as a result of RTO expiry, or if the receiver sends three duplicate ACK packets signaling retransmit of minor chunks of data [33].

The retransmit caused by RTO expiry causes a stronger reaction than a retransmit resulting from three duplicate ACK packets. When retransmits due to RTO expiry occur, the sstresh is set to one half of the active value when the retransmit occurs, cwnd is set to the size of one segment, and the slow-start phase is initiated again.

If ingress policing was used as a means to throttle iSCSI write activity, this is the mechanism that makes the rate adapt to the bandwidth limit. The dropping of packets when bandwidth limitations are enforced causes RTO expiries on the sender side, which causes the cwnd to shrink over time in order to find

a balance where no packet drops occur. This process is harsh and introduces inefficiency by knowingly having to retransmit some packets to enforce bandwidth limitations.

As stated in chapter 3.2.4, all traffic between initiators and the target is mirrored to the port of host `b1`. On `b1`, Argus[93] captures key information about network activity during the execution of each experiment. From the captured data, the amount of packet loss and retransmits during experiments can be inspected. The command `racluster` is used to read captured binary data and aggregate metrics. Listing E.7 and E.8 shows that there is no lost or retransmitted packets during artificial delays of up to $10ms$. Since `Argus` was not able to capture a complete data set for the experiment (see section 3.2.9), packet loss were inspected by extracting TCP data collected by `collectl` (see listing E.3). This method also reported no packet loss during experiments.

4.2.2 Advantages

In addition to the obvious advantage of being able to throttle iSCSI write activity without introducing packet loss, there is another aspect: this type of throttling does not need to find out what the existing throughput is in order to have an effect. The writing process in figure 5.6 has a slower rate than the reading process (figure 5.5) when no throttling is in effect. If the underlying shared resource is the bottleneck, it means that resources is saturated, and that all consumers of that resource suffer high response times. This is one example that capacity differs depending of workload type. When throttling is started with only 0.1 ms additional delay, the effect is immediate on the data flow causing saturation. It is instantly reduced. Hence, relieving the underlying resource of pressure regardless of what the rates were before throttling started. If bandwidth shaping was used, there would be an extra step to identify what rate the consumer should be throttled to in order to achieve the same result: first a measurement of the existing rate, then a calculation of a suitable bandwidth to make the rate decrease sufficiently.

4.3 Bottleneck location

In this lab setup, the disks clearly are the main bottleneck. This is best indicated by identification of where I/O requests spend most of the time during their flight. A comparison was made between the wait-time of the local iSCSI block device and the wait time of the logical volume servicing it (on the target server). Figure 4.2 shows these wait times of the random read job while

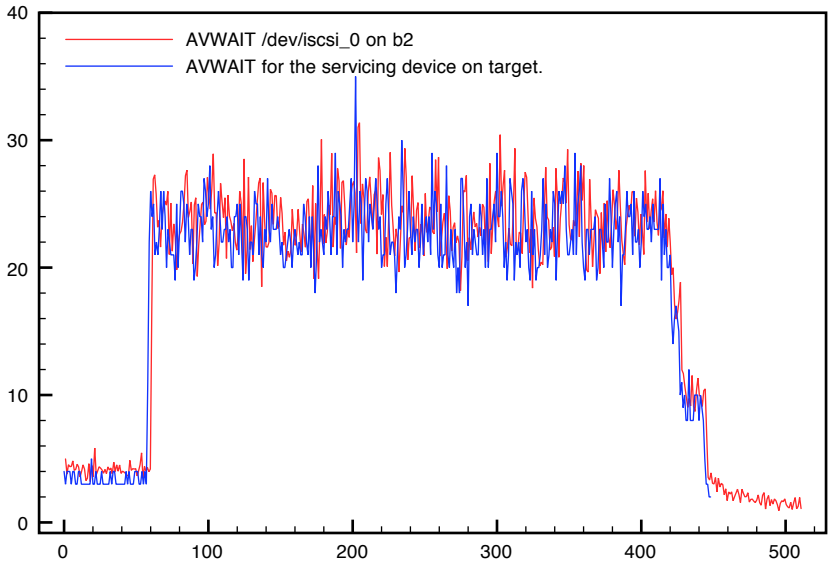


Figure 4.2: Comparison of average wait time of the iSCSI block device and the logical volume servicing it on the target server, when running 6 interfering write threads from 3 other machines

writing with six interfering threads against the shared volume-group. The difference between them is negligible, confirming the assumption that most of the total iSCSI wait time is spent waiting for disk service at the target server. In other cases the bottleneck might be in the network link or other places. It is reasonable to hypothesize that packet delay throttling will have a similar slowing effect even if the bottleneck is elsewhere, but in order to detect contention the response time probe must be moved outside of the bottleneck.

4.4 Throttling decision

4.4.1 Input signal

As pointed out by previous research, remaining capacity is not constant, it is dependent on both rate, direction and pattern of the workloads. Hence, an exact measure of remaining capacity is hard to maintain. However, it is possible to indirectly relate how close the resource is to saturation by measuring individual consumer response times without any knowledge about the cause.

Experiments in chapter 5 seek to verify the validity of this assumption, and determine to what extent this metric can be used for throttling decisions.

Previous research has successfully utilized virtual disk response time as saturation level measure [65, 67, 66]. This project will use a similar approach. In order to use the disk response time for throttling decisions, it must be smoothed to represent the general trend for the variable. Different algorithms exist for this purpose. Gulati and coworkers obtained good results using EWMA for smoothing [65]; thus, EWMA shall be a considered method. The other method considered is the moving median algorithm. Both EWMA and moving median require little computational power to maintain, and the description of their characteristics makes promises about spike resistance and close-to-trend representation. The standard moving averages will not be considered because of their susceptibility for spikes in the data, short term spikes known to exist in the average wait time. It is not desirable to trigger large throttling impacts caused by transient spikes in the average wait time. Throttling should only occur as a result of persistent problems.

In order to compare the two algorithms, plots of them were stacked on top of the actual measured wait time that they average. The actual wait time, of which the smoothing algorithms were tested, was taken from the experiment where twelve other threads were interfering with a small random read job, and timed packet-delay-throttling (using 4.6 and 9.6 ms delay) was carried out (see Figure 5.8). Mathematica was used to plot the time series of the logged wait time, an EWMA and a moving median of that data. Using dynamic variables for the α parameter of EWMA and the window-size parameter of moving median a visual best fit was found for both (see listing C.16 for the Mathematica code). For EWMA, an $\alpha = 0.15$ gave the best fit, and for the moving median, a window-size of 6 gave the best fit. Figure 4.3 shows the three plots with these values set.

It was decided to use the EWMA as input signal for throttling decision because it seems to follow the trend more closely and looks smoother than the moving median. Also, EWMA is widely adopted as a successful method in the process control field for smoothing sensor input signals. In the process control field, this filter is commonly named a time constant low pass filter. The formula used for applying the filter is shown in the following equation, where $L_{(t)}$ is the smoothed/filtered value in time t and l is the measured value in time t.

$$L_{(t)} = l_{(t)} \times \alpha + L_{(t-1)} \times (1 - \alpha)$$

The smoothing parameter effects the level of smoothing, or the bandwidth, of the low pass filter. It is defined by $\alpha \in [0, 1]$. A small α gives more smooth-

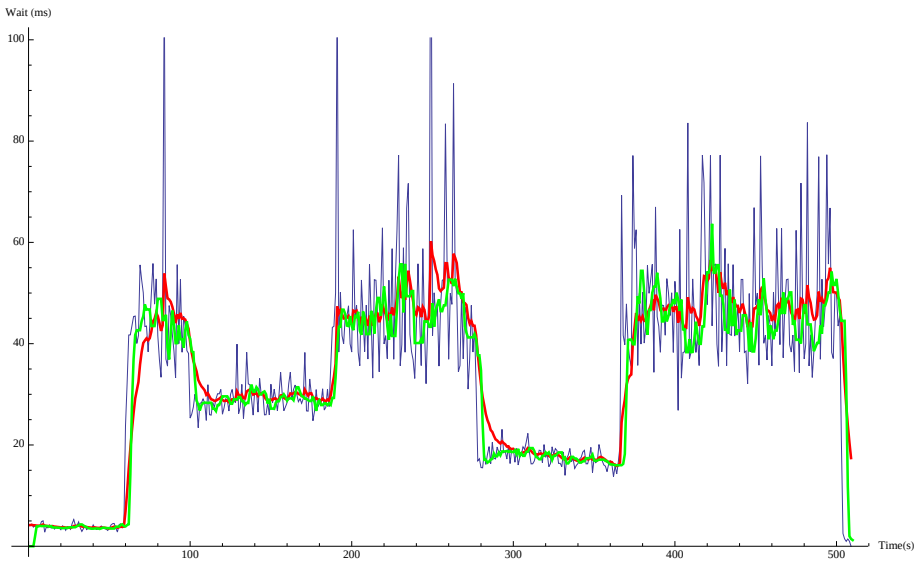


Figure 4.3: Finding a reasonable moving average. Blue is actual samples from small job. The green plot shows the moving median with wsize=6. The red plot shows the EWMA with $\alpha = 0.15$.

ing (lower filter bandwidth), and a large α gives less smoothing (higher filter bandwidth). A low value of α gives smooth output, but it also gives a high phase shift (delayed response) compared to the input trend. The best value of α is when there is an optimal balance between smoothness and phase shift. The visual inspection done in Mathematica suggests that $\alpha = 0.15$ represents such fair balance for the data used in the test (see Figure 4.3).

4.4.2 Output signal

During examination of the project's experimental results, the nature of resource saturation, load interference and throttling effects became clearer, an understanding that led the attention to cybernetics and control engineering. A commonly used concept in this field is the PID controller [99, 100]. The problem investigated in this project is similar to a process control problem solved by PID controllers. Experiments documented in section 5.6 demonstrate the instant rate reducing throttling effect freeing capacity, which again influences read response time. Section 5.4 describes a stepwise close-to-linear relationship similar to what a PID controller needs in order to work. Figure 4.4 shows the concept of a PID controller. PID controllers can be implemented in software using a numerical approximation method. This project uses a numerical implementation of the PID controller with virtual disk wait-time as input signal and packet delay as output signal.

The purpose of the PID regulator is to control throttling such that the output value stays as close as possible to a set value when the set value changes and the environment tries to change the output value. Changing the environment would be analogous to changing load interference in the case of storage QoS. The set value of maximum response time for storage resources is likely to be constant. However there is nothing that prevents implementation of dynamically adjustable thresholds. The main purpose of the controller in this project is to keep response time of important requests from violating this set threshold in spite of rapidly changing amounts of interference from less important requests.

The packet delay throttle is implemented as a range of integers representing a stepwise proportional throttling mechanism. Let this proportional throttle be named *pThrottle* from now on. Each integer step represents an increased packet delay, thus, a decreased rate. Figures 5.5 and 5.6 suggest that steps of $0.5ms$ is a suitable granularity. At $0.5ms$ granularity, the amount of steps is determined from maximum allowed artificial packet delay: i.e. zero rate reduction plus 21 increasing steps of rate reduction with a maximum delay of $20ms$ giving $pThrottle \in [0, 21]$

$$u(t) = \underbrace{K_p e(t)}_{\text{Proportional}} + \underbrace{\frac{K_p}{T_i} \int_0^t e(\tau) d\tau}_{\text{Integral}} + \underbrace{K_p T_d e'(t)}_{\text{Derivative}} \tag{4.1}$$

Equation 4.1 represents the continuous function for outputting throttling amount as a function of set-point error: the difference between the set value (threshold) and real value. Hence, the PID controller is called an error driven controller. The proportional part (P part) is the first part of the function and is parameterized by the proportional gain K_p. The second part is the integral part. It is proportional to both the error and the duration of it and is parameterized by the integral time T_i. The purpose of the integrating part is to eliminate the residual steady state error that occurs with a proportional-only controller. The third part of the equation is the differential part. It is parameterized by the derivative gain tuning parameter T_d. The purpose of the derivative part is to slow down the rate of change of the controller output, thereby reducing the magnitude of overshoot created by the integral part.

When computer based controllers replaced older analogue PID controllers, the PID function was discretized using Euler's backward method and became the basic discrete function shown in equation 4.2. The function is used as the basis for most discrete PID controllers in the industry [99, 100]. This paper implements a variation of equation 4.2 that takes the distance above preset response

time threshold as input error signal and computes an output throttling value. The modified algorithm is named a single sided PID controller because it only throttles when the error is positive: when the real value is higher than the set threshold.

The average wait time during the interval is captured by reading the accumulated wait time divided by the number of requests during the interval from the `/proc/diskstats` file, the same method as the `iostat` command uses for calculating the AVWAIT value:

$$AVWAIT = \frac{Accumulated - number - of - ms - spent - doing - I/O}{Number - of - reads + Number - of - writes}$$

Filtering of the AVWAIT value is applied using the EWMA algorithm with $\alpha = 0.25$. In order to achieve rapid response of the PID controller, the value of α had to be increased compared to the smoother signal demonstrated using Mathematica and $\alpha = 0.15$ (Figure 4.3). See also the discussion about PID tuning in section 4.4.3.

The PID control algorithm is a direct implementation of equation 4.2 below with two exceptions: the negative throttling value is capped to the maximum throttling step corresponding to the integer value of the packet delay class with the highest delay, and the positive throttling value capped to zero. This is done to prevent integral windup: the integral part accumulating too high values that takes a long time to wind down again, and to disable throttling completely when the error is negative: real value is below the threshold. The output value of the PID controller is rounded up to the next integer value, and that integer becomes the `Iptables` mark to apply to all outgoing ACK packets matching destination addresses of the iSCSI initiator IP addresses in the set of throttleable consumers. The program is what causes results the exhibited in Figures 5.9 and 5.10 and is listed in listing A.2.

$$u_k = u_{k-1} + K_p(1 + \frac{T}{T_i}) + K_p e_{k-1} + \frac{K_p T_d}{T}(e_k - 2e_{k-1} + e_{k-2}) \qquad (4.2)$$

4.4.3 Tuning of the PID controller

The PID controller must be tuned for optimal control of the process. In control engineering, the best operation of the controller is when the actual value always is stable and equal to the set point no matter how fast the set point changes or environmental forces influence the actual value. This ideal behavior is never achievable in real world applications of the PID controller: there

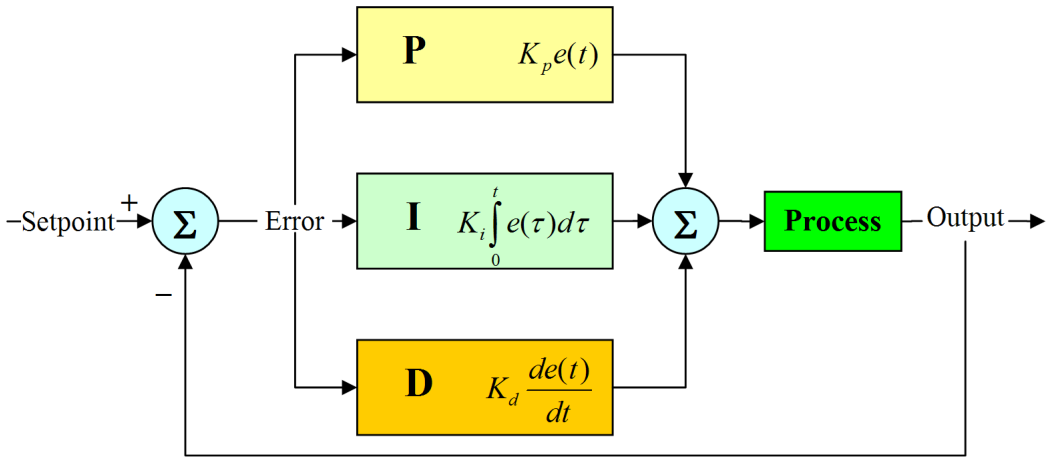


Figure 4.4: Block diagram of a PID controller. Created by [101]. Licensed under the terms of Creative Commons Attribution 2.5 Generic.

are always physical limitations that makes the ideal case a theoretical utopia. The tuning process' concern is finding the parameters to the controller that makes it behave as close to the theoretical ideal as possible. There are several known methods to tune PID controllers. The Ziegler-Nichols method, the improved Åstrøm-Hägglund method and the Skogestad method are some widely used methods in control engineering [99]. These methods have not been considered during this project since a few iterative experiments and according parameter adjustments yielded stable and good controller performance in short time. Thus, the process in this project is easy to tune compared to many industrial processes. However, thorough tuning efforts is likely to produce similar controller efficiency with less less resource usage of the controller loop.

In addition to the PID parameters, the sample interval influences loop stability and tuning. Generally, the discrete PID controller approaches the behavior of a continuous PID controller when the sample interval goes to zero. The reason to keep sample interval short is increased stability and the reason for increasing the sample interval is minimizing resources utilized by the controller. The sample interval used in this project was found by experimenting with values and observing CPU usage. A sample interval of 100*ms* yielded very stable controller behavior and CPU utilization of approximately 1%.

However, lowering the sample frequency more may be possible without sacrificing stability. Another benefit of lowering the sampling frequency is calmer operation of the throttle. It may not be necessary to move the throttled IP addresses around as agilely as in the experiments, but it must be agile enough to capture rapid workload interference changes. The interval of 100*ms* seems to

be a fair balance between controller resource consumption and agility.

4.5 Automated operation

Most I/O schedulers, and those parts of an entity responsible for servicing application I/O requests, generally have a preference for satisfaction of read requests over write requests. This is because waiting for read requests is blocking applications from continuing their work. Usually, write requests are written to cache, at several levels in the I/O path, for later de-staging to permanent storage without blocking the application from further operation. Hence, throttling write requests can be done to a certain limit without affecting application performance. Nevertheless, it has been demonstrated through earlier experimental results that write requests are able to adversely influence the more important read requests. The design goal of the final prototype is the utilization of earlier results to automatically prevent write requests from adversely impacting read requests, thus contributing to improved application service predictability without the need for user input.

The previous prototype version needed to be informed about a set of predefined important consumers to monitor average wait time for, and a predefined set of consumers to throttle in order to influence the wait time of the important consumers (see section 4.4 and 5.7). Section 2.1 points out the relation between the finite capacity of a resource and the effect of saturation on its consumers: load interference. Based on these assumptions, this section will describe the design of a prototype that completely automates the detection of saturation level and the identification of throttleable consumers, on a per resource basis. Instead of previous prototype's reliance on user determined list of important consumers, this prototype uses the read-over-write prioritization to automatically find out what to monitor and which consumers are eligible for write throttling.

In most storage devices, the disk group from which virtual disks are allocated, is bound to become the resource first saturated. This is the reason that LVM was chosen to reproduce a similar environment in the lab setup. In the lab setup, volume groups represent the shared resource that logical volumes are striped across. The objective of the prototype is to control the saturation level caused by write activity on a per-resource basis, thereby indirectly controlling the read response time of the resource. This translates to per volume group in the lab setup. In order to achieve this in the lab prototype, the following requirements will be met:

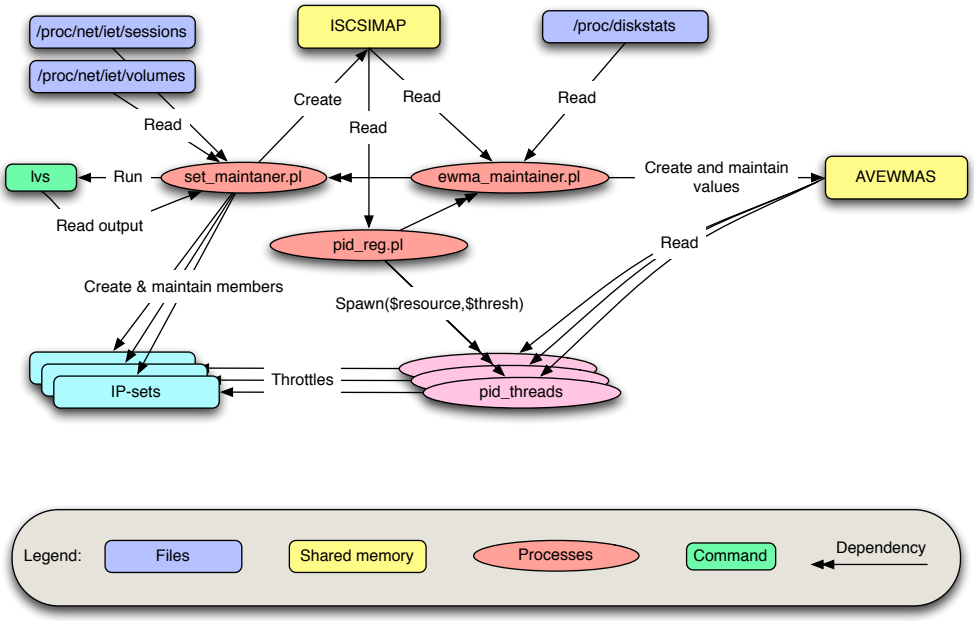


Figure 4.5: Automated controller framework overview

- An entity that maintains sets of IP addresses that are known to be doing write activity at a certain level: eligible throttlers.
  - Each set should have name of the resource of which its members are consumers.
  - Each set should be immediately throttleable by using its name.
- An entity that maintains a value representing the saturation level on a per-resource basis.
- An entity that spawns a PID controller for each resource and:
  - Uses the resource' saturation level as input .
  - Throttles the set of throttleable consumers for that particular resource so that the saturation level is kept below a set threshold.

The requirements are fulfilled by three perl programs working together with `Iptables, Ipset` and `Traffic Control`, utilizing shared memory for information exchange and perl threads for spawning parallel PID controllers. Figure 4.5 illustrates the concept of the framework implemented by the three scripts.

4.5.1 Automatic population of throttling sets

The `set_maintainer.pl` reads information about active iSCSI connections from `/proc/net/iet/*` (see listing C.2), where information about each iSCSI target id is found: the connected consumer IP and servicing device. For all active iSCSI sessions, the device-mapper (`dm`) name and consumer IP address is recorded. The `lvs` command is used to to record the logical volume name and volume group membership of each device-mapper device detected to participate in an active iSCSI session. The information found for each of the device-mapper device is recorded in a data structure and mapped into a shared memory segment with the key *ISCSIMAP*. For each of the volume groups involved in active iSCSI sessions, an empty IP-set is created with the same name as the volume group. When iSCSI device maps are exported to shared memory and the necessary IP-sets are created, the program enters maintenance mode. This is a loop that continuously monitors exponentially weighted averages (EWMAs) of the write sector rates of all `dm` devices involved in active iSCSI sessions. For each of the previously created IP-sets, it then determines the set of consumers that have a write sector rate exceeding a preset configurable threshold. The generated set is used as target for converging the previously created in-kernel IP-set used as match target by `Iptables` to match the list members. The IP-sets are converged once every second, yielding continuously updated per resource IP-sets known to contain consumers exhibiting write activity at certain level. These sets are immediately throttleable by `Iptables` matching against them.

4.5.2 Automatic determination of saturation monitors

The `ewma_maintainer.pl` program reads the shared memory information exported by the `set_maintainer.pl` program (see listing C.3), and creates resource-to-consumer mappings from it. For each resource, it continuously calculates an exponentially moving average of the read response time using information obtained from `/proc/diskstats`. Only consumers having read activity are included in the calculation. The data structure containing the resources' read response time EWMAs is tied to a shared memory segment with key *AVEWMAS* and updated every 100*ms*. The read response time EWMAs serve as per resource saturation indicators which will be used as input values to the subsequently described PID controller threads.

4.5.3 Per resource PID control

The `pid_control.pl` program attaches to the shared memory segment with the key *AVEWMAS* (see listing A.3), and reads the saturation indicators maintained by the `ewma_maintainer.pl` program. For each of the resources found in the *AVEWMAS* shared memory segment, a PID controller thread is created with the resource name and its accepted read response time threshold as parameters. Each PID control thread monitors the saturation level of its designated resource and directly controls the delay throttle of the set containing current consumers exhibiting write activity towards that resource. The `pid_control.pl` then detaches from the worker threads and enters an infinite sleep loop, letting the workers control resource saturation levels in parallel until a `SIGINT` signal is received.

Chapter 5

Results

This chapter describes the experiments and their results. To make a clear separation between results and the incremental experiment design, the design considerations were put in the separate system design chapter: chapter 4. Results are chronologically ordered, and they influence the progress of subsequent experiments, the system design chapter and ultimately the direction of the project.

The expected basic effect of throttling down one or more initiators is to free resources for the remaining initiators in order to improve their resource availability. It is expected that the improved resource availability will improve the remaining initiators' response time and/or throughput depending on the nature of the load running on them. Furthermore it is expected that request wait-times of individual virtual disks (logical volumes) can be used as indirect saturation level metric of the underlying shared resource. Last, it is expected to be possible to create a closed-loop regulator which is able to keep request response times and data rates of important consumers within certain boundaries by the use of the described throttling methods.

5.1 Without throttling

When there is no throttling mechanism in place, there is free competition for available resources. Figure 5.1 shows how four equal read loads, run on each of the equally powerful blade servers, share the total bandwidth of the disk resources, serving each of the logical volumes to which the blade servers' iSCSI block devices are attached. The plotted read rates show what each of the consuming blade servers achieve individually.

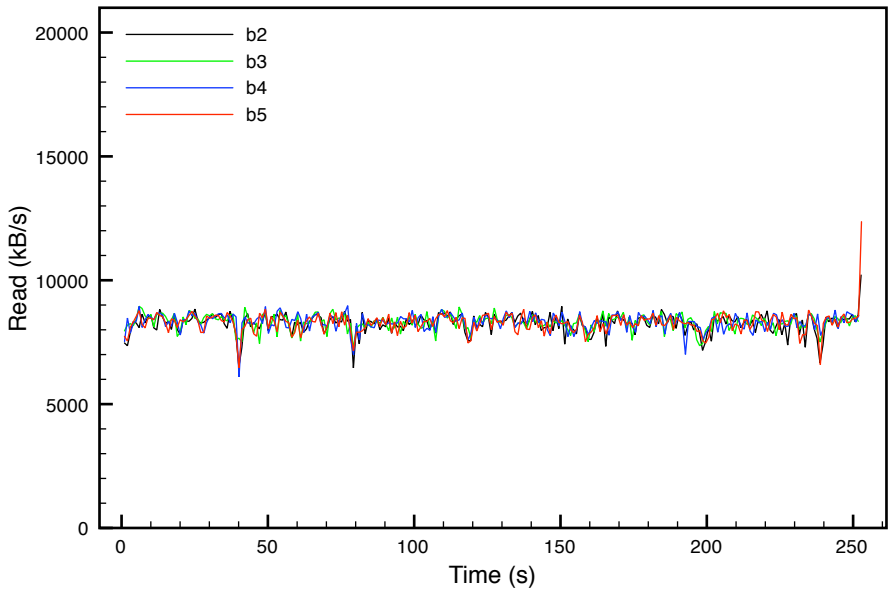


Figure 5.1: Equal sequential read load from four identically equipped blade servers without throttling

5.2 Throttling by bandwidth limitation

Linux Traffic Control is be used to make bandwidth prioritization between the I/O-consuming blade servers seen in Figure 5.1. The job that generates workload in this experiment is identical to the one used in Figure 5.1. iSCSI read requests on blade servers translate to outgoing TCP packets on the target server. These can be shaped using the Hierarchical Token Bucket (HTB) filter in Linux Traffic Control. The setup of HTB in Linux Traffic Control for this experiment is described in section 3.2.6. Figure 5.2 shows the effect by using HTB to enforce outbound rate prioritization. Traffic is throttled by moving the blade servers between predefined HTB bandwidth classes using packet marking in `Iptables`.

In this experiment, a shaping script on the target server is throttling down blade servers b2, b3 and b4 at predefined time offsets from the start time of the experiment and releasing them at later points in time. When blade server b2 gets throttled down, the remaining blade servers increase their throughput as a result of the bandwidth freed. When b3 and b4 are throttled down the procedure repeats and available resources to remaining consumers increase. As more resource become available to the remaining servers, they automatically

utilize these resources to increase their own throughput. When b2 is freed from its bandwidth limitations, b5 once again must share resources with b2, and both consumers stabilize at a rate of approximately 13 MB/s. Then b3 is freed from its bandwidth limitations, and b2, b3 and b5 must share the remaining bandwidth. They stabilize at approximately 10 MB/s each, 30 MB/s in total. b4 is freed and all 4 blade servers equally share bandwidth for a short period until b5 finishes its job. When b5 is finished, there are only three consumers left to share the total resources and they all get a bit more throughput. When b4 finishes the job, there are two servers left to share, and when b3 finishes b2, will receive all available resources and achieve a throughput of approximately 19 MB/s towards the end.

There is a drop in bandwidth of all consumers, including the unthrottled blade server b2, at the start time of the throttling phase of each blade server. The reason for this could be processing overhead introduced by `Iptables` during rapid modifications of its chains. Another possible explanation is that parallel read jobs experience some synergy benefits from each other when running equally fast and started at the same time, thus accessing areas on the disk with closer locations, and that this benefit is reduced when some jobs get throttled down.

To suggest that the plots are not pure coincidence, the job was run twice, and the results from the second run were stacked on top of the plots from the first run.

Section 3.2.6 describes the division of the interface into different bandwidth classes in detail. Section 3.2.8 describes how Iptables is used to dynamically move blades between bandwidth classes.

The idea of using traffic policing as bandwidth control for iSCSI writes was abandoned due to inefficient operation and lack of `Iptables` support. Detailed arguments for this decision are found in section 4.1.

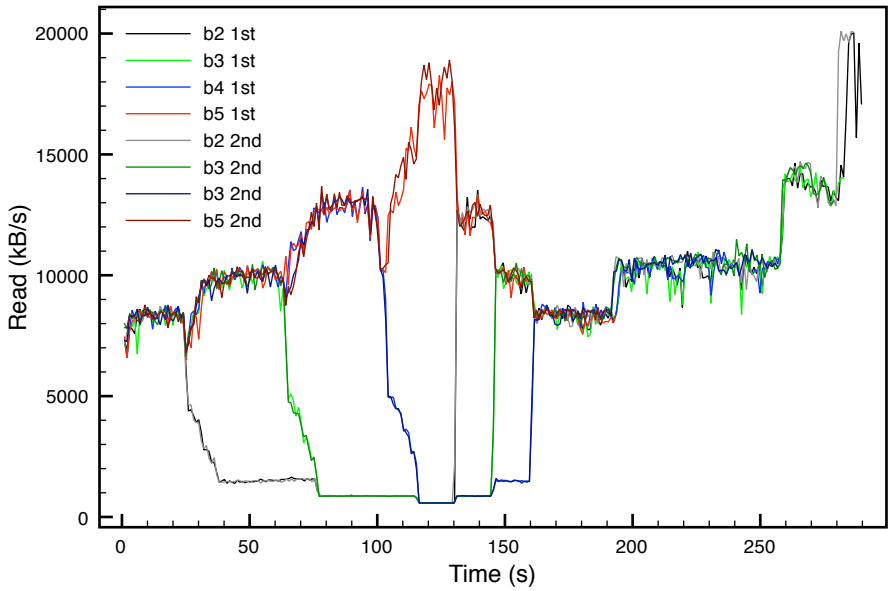


Figure 5.2: Throttling of initiator's sequential read activity using Hierarchical Token Bucket bandwidth (HTB) limitation in tc(1). Two independent runs are stacked on top of each other for verification of result repeatability.

5.3 Throttling by packet delay

Both iSCSI read requests and write requests can be throttled using artificial packet delay. This experiment shows that it is possible to achieve similar results as with bandwidth throttling by introducing minor additional packet delays to individual consumers. The concept of packet delay is illustrated in Figure 4.1 and explained in section 4.1. The experiment shows that it is possible to throttle write and read activity using the same set of delay queueing disciplines (qdiscs) in Linux Traffic Control (`tc`). For writes, the ACK packets to the consumers are delayed, and for reads all packets except ACK packets are delayed.

Figure 5.3 shows the effect of packet delay based throttling on the same workload as in figures 3.3 and 5.1, and figure 5.4 shows the effect when writing the same load that was previously read.

The shaping is done in a similar manner as in section 5.2, using `Iptables'` packet marking abilities to place packets from individual consumers in different predefined delay qdiscs at different points in time. Throttling of blade server b2 frees up resources to the remaining consumers. Next, throttling of b3 and b4 gives increased resources to the remaining consumers. When b2 is freed, b5 is already done with its job, and most resources are available to b2 which increases its throughput dramatically. When b3 is freed, b2 and b3 share the resources again and stabilize at approximately 14 MB/s each. Finally b4 is freed, and b2, b3 and b4 share the resources, each having a throughput of ca. 10 MB/s. When b4 finishes its job, there are two machines left to share the resources, and when b3 finishes, only b2 is left to consume all resources.

The drop in throughput for un-throttled consumers, when throttling starts, is present also with the delay shaping method, but the effect seems to be somewhat smaller. Additional research is necessary to identify if there are significant differences and to identify the cause of the drop.

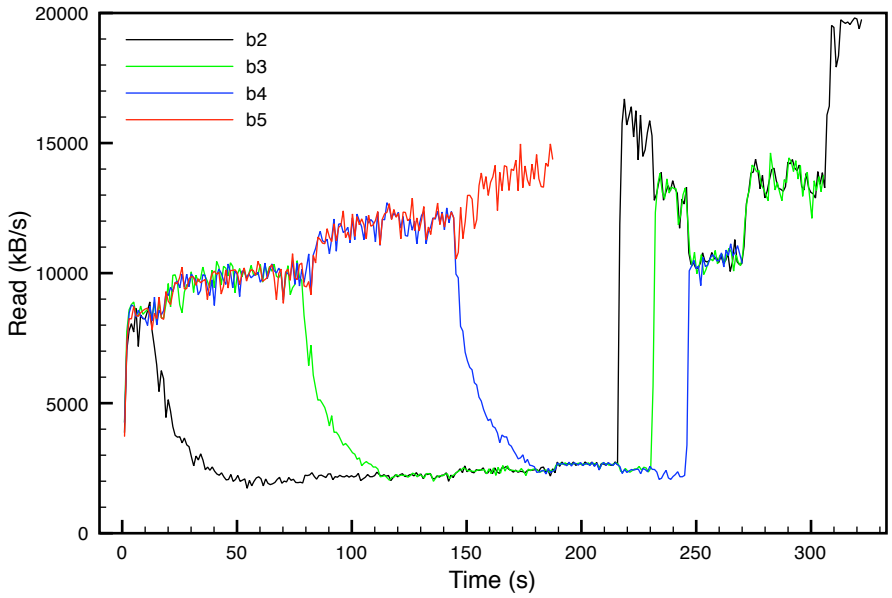


Figure 5.3: Throttling of initiator's sequential read activity using delayed ACK packets in tc(1) (See Figure 3.2.7).

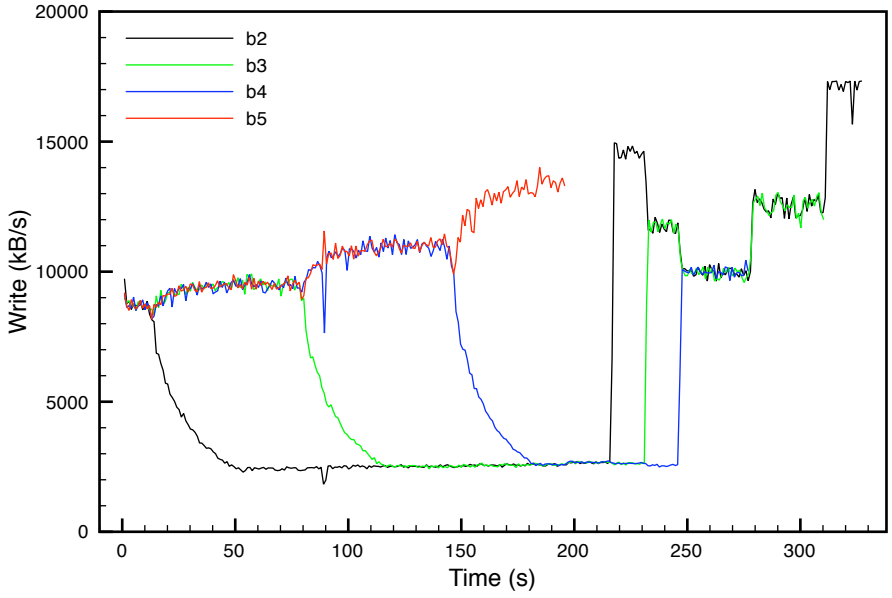


Figure 5.4: Throttling of initiator's sequential write activity using delayed ACK packets in tc(1) (See Figure 3.2.7).

5.4 Introduced delay vs throughput

Previous results suggest that the method of introducing artificial delay to outgoing packets could be an efficient way of throttling iSCSI initiators in order to decrease the pressure on shared resources like disk groups. To find out the predictability of throttling as an effect of artificial delay, 200 MB of data was repeatedly read and written from the iSCSI initiator device of one blade server, measuring the time it took to complete each job. Each job were repeated 20 times for each value of artificial delay. Figures 5.6 and 5.5 show the results with error indicators, representing the standard error, on top of the bars. The precision of the means is so high that it is hard to see the error indicators at all.

The plots show that variation of artificial delay between 0 and 9.6 ms is consistently able to throttle reads between 22 MB/s and 5 MB/s and writes between 15 MB/s and 2.5 MB/s. There is no absolute relationship between artificial delay and throughput. Rather, the introduced delay has an immediate rate reducing effect regardless of what the throughput was when throttling started. Figures 5.6 and 5.5 suggests that there is a close-to-linear functional relationship between introduced delay, the start rate and the resulting rate after throttling. It is also reasonable to suggest that NIC buffer size and usage of jumbo frames in the network are variables in the equation. This is because they control the packet frequency hence indirectly how often the artificial delay is applied during a particular amount of transferred data. However, further research would be necessary to establish a model for such a relationship, and as demonstrated later, such a model is not necessary in order to utilize the method in a closed loop controller.

See listings E.1, C.1 in appendix D for details about data and plot generation.

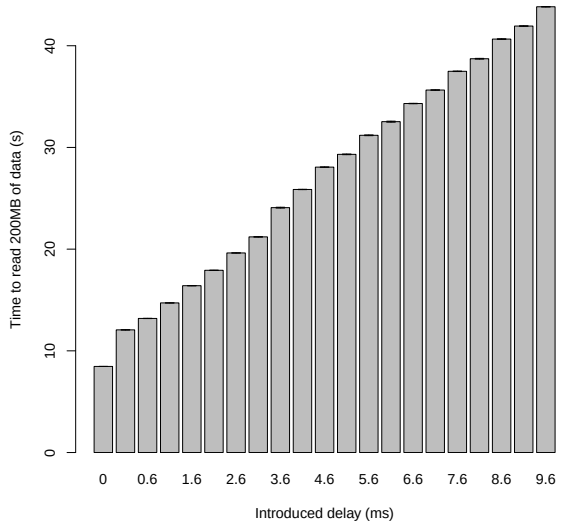


Figure 5.5: Repeated measurements of the time used to read 200 MB with stepwise increase in artificial delay of outgoing packets from target server.

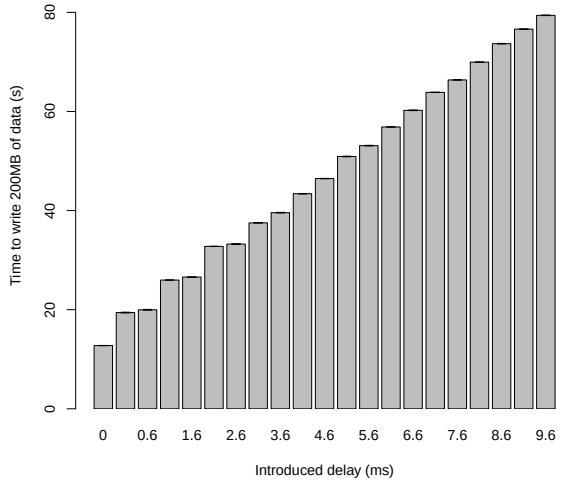


Figure 5.6: Repeated measurements of the time used to write 200 MB with stepwise increase in artificial delay of outgoing packets (ACK packets) from target server.

5.5 Interference between loads demonstrated

This experiment was set up to demonstrate how loads sharing the same underlying resource affect each other. A job named *smalljob* was run on b2, performing random read of 8kB request size with one thread and a total data size of 128 MB. The purpose of *smalljob* was to mimic an interactive workload that has demand for low response times and requests I/O in a relaxed manner. Thus, it was rate limited to 256kB/s. Figure 5.7 shows how the average wait time of *smalljob* gets influenced by an increasing amount of interference from other hosts writing to their own virtual disks. The plots are from four different runs, each having a different amount of interference started 60 seconds after *smalljob* is started. The black line depicts *smalljob's* average wait time when no other activity occurs. The green line shows the next run stacked on top, and depicts how *smalljob's* response time is more than doubled at 60 seconds, when an interfering single threaded write job executes unlimited sequential writes toward its own virtual disk. At approximately 125 seconds, the interfering thread stops and the response time of *smalljob* drops to the same value it was before interference started. The blue and red plots are subsequent runs of the same jobs, but with three and twelve threads interfering write threads respectively. Clearly the average wait time of *smalljob* increases with an increasing amount of interfering threads that operate on their own virtual disks. With twelve interfering threads, spread across three hosts, the average wait time of *smalljob* varies between 30*ms* and 120*ms*. The cause of *smalljob's* increased response time lies not in the activity of *smalljob*, but in the activity of other consumers saturating the capacity of the underlying resource. If the *smalljob* was an application highly dependent on response time it would have been five to six times slower when write interference occurs. In reality, a single machine with multiple CPU's, and an application capable of parallelizing a lot of I/O, can easily saturate the request queues of a storage device, thus adversely affecting response time of all consumers sharing that resource.

Jobs with increasing amounts of threads take longer due to the increased total amount of data to write (the same amount of data for each thread). The job definition of *smalljob* is shown in listing D.2 and the job definition of each interfering thread in listing D.3.

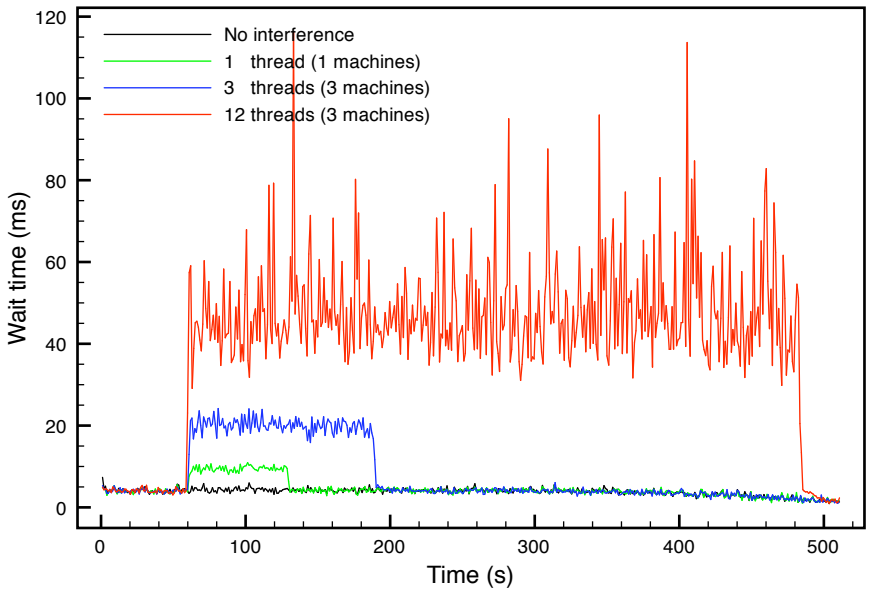


Figure 5.7: The effect on average wait time for smalljob on b2 with interfering write activity from 1 and 3 other machines respectively.

5.6 Effect of throttling on wait time

In the previous experiment, the effect on consumer response time, caused by other consumers' activity was examined. In this experiment, the effect on consumer response time by throttling the interfering consumers' activity is examined. Expected behavior is that the throttling of demanding consumers will free up capacity for the unthrottled important consumers, thus improving their perceived performance. Figure 5.7 shows that writing activity of other machines increases the average wait time of a *smalljob* doing random reads. The objective is to ameliorate this situation by throttling the activity of the interfering loads.

Figure 5.8 shows the effect on the *smalljob's* average wait time when throttling the 12 interfering sequential writers. Packet delay throttling is done in the periods $100ms - 190s$ and $280s - 370s$, using $4.6ms$ and $9.6ms$ packet delay respectively. Clearly the throttling of interference contributes to wait time improvement. The magnitude of improvement is higher if the wait time is high before throttling (i.e. level of saturation is high). It means that the throttling cost for improving response time from terrible to acceptable can be very very low, but the cost of throttling increases as the response time improves

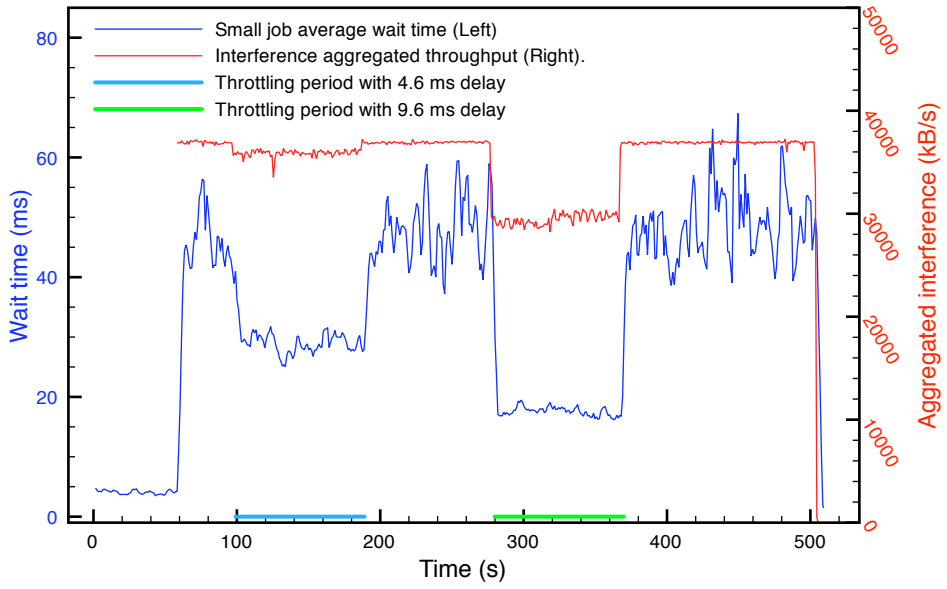


Figure 5.8: The effect on small job's wait time when throttling interfering loads with delays of 4.6 ms and 9.6 ms respectively.

(decreases).

5.7 PID control of response time

Previous experiments demonstrated that the packet-delay throttling method works well for instantly slowing the rate of less important consumers, and doing so improves important consumers' response time. The rate-reduction is achieved by adding a variable packet delay, typically $0.5 - 20ms$, that instantaneously reduces the current rate of the consumer it is applied to. The next step is to automate the throttling decision: the decision about which delay should be put on which packets. The ideas and design of this automation involves the usage of a proportional integrating derivate (PID) controller. Detailed arguments for this design decision is found in section 4.4.

Experimental results from testing the controller's adaptability to rapidly changing workloads is shown in Figures 5.9 and 5.10. The black plot in Figure 5.10 shows the aggregated throughput of 12 sequential write threads spread across 3 blade servers, and Figure 5.9 shows the effect they cause on a rate-limited random read job running on a different machine when no regulation occurs.

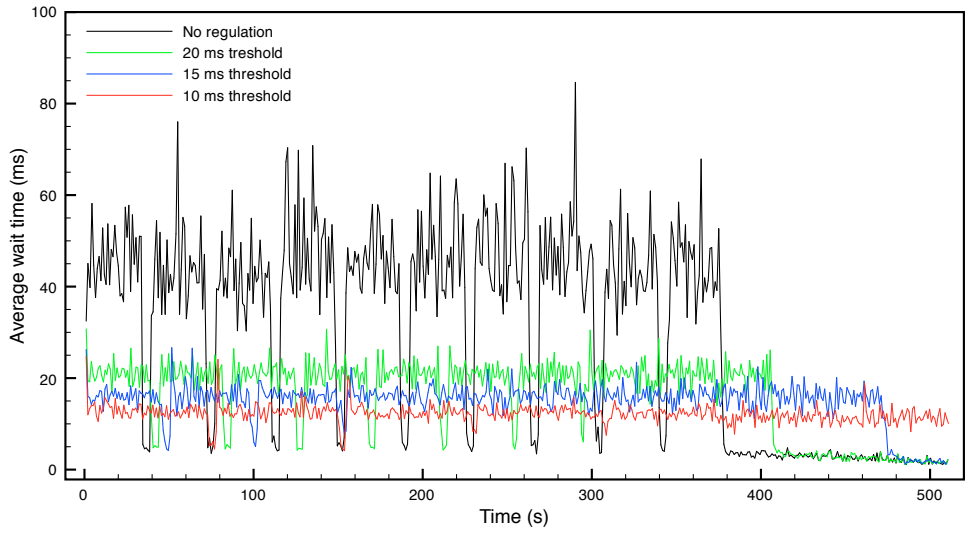


Figure 5.9: The average wait time of a rate limited (256kB/s) random read job interfered by 12 write threads started simultaneously and repeated with 5 seconds pause in between. The black plot shows the effect with free resource competition. The colored plots show how the PID regulator keeps different response time thresholds by regulating interfering workloads.

All write threads are turned on synchronously and repeated with five second sleep in between, thus creating relatively large and rapid impacts on the random read job's response time. The colored plots show the effect of the same interfering workloads with the PID regulator enabled having thresholds set to 20, 15 and 10 ms respectively. Figure 5.10 shows the throttling effect on the corresponding interfering workloads (aggregated throughput). Notable is the relatively higher response time improvement for the random read job by throttling aggregate write throughput from its maximum of $39MB/s$ down to $33MB/s$, yielding an improvement of 25 ms lower response time. Taking the response time down another five milliseconds costs another $7MB/s$ of throttling to achieve. Clearly the throttling cost for each step of improved response time increases as response time improves. Looking at it another way, if the set threshold is close to the saturation point, the cost of avoiding saturation is minimal.

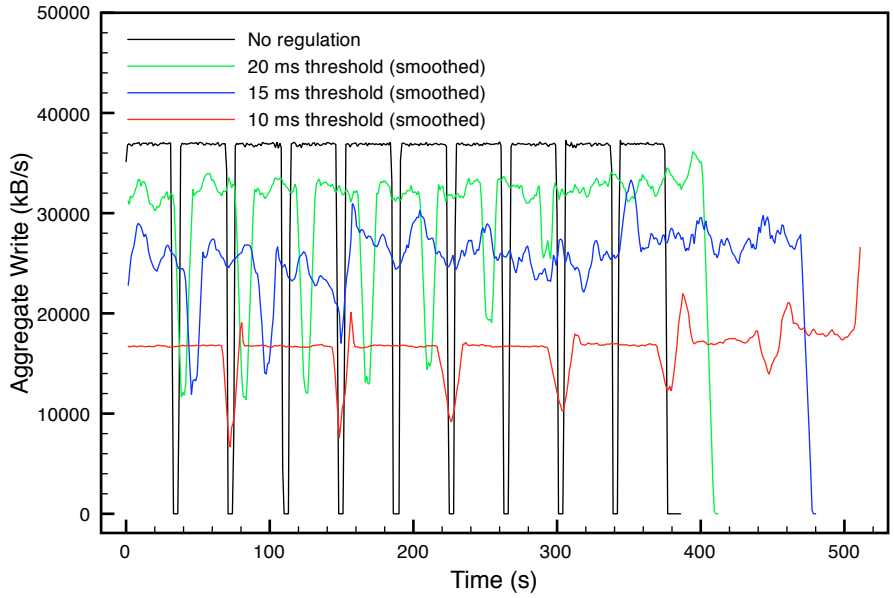


Figure 5.10: The aggregated throughput caused by throttling to keep latencies at the set thresholds in Figure 5.9.

5.8 Measuring overhead

By adding the throttling feature there is a risk of adding extra overhead compared to the same setup with no throttling. Experiments done so far indicate little or no overhead, but this shall be further examined in the following experiment.

Overhead when no throttling occurs is unwanted. Since no `Iptables` rules are active when no throttling occurs, there is no overhead introduced by `Iptables`. The only possible source of overhead in this situation is the static `tc` queueing disciplines (qdiscs) and/or the static filters attached to the root qdisc. All outgoing packets are checked for marks by the static filters and there is a risk that this checking introduce overhead. To investigate if the existence of static delay queues and their filters add overhead, the difference in throughput was measured with static qdiscs present and absent. Also, to maximize any impact caused by `tc` packet checking, the logical volume servicing the iSCSI initiator was interchanged with a RAM-disk. The fast speed of the RAM-disk ensures that any overhead introduced by packet checking in the network layer becomes visible. The test was carried out by reading/writing 512MB from/to the RAM-disk based iSCSI target from one of the blade servers (b2), first with-

out any `tc` qdiscs and filters enabled and then with 20 delay classes with filters attached. Each job were repeated 20 times, yielding four vectors of twenty numbers. The two pairs of vectors, with and without qdiscs/filters, were compared using student's t-tests in `R`.

The following command were used, on host b2, for capturing the times (seconds) of each read and write operation:

```
/usr/bin/time -f %e /usr/local/bin/fio --minimal \
--output /dev/null $fio-jobdef
```

The `$fio-jobdef` file defined a 64Kb request size, a total data amount 512MB and direct I/O using the synchronous I/O engine. The target for the job was the `/dev/iscsi_0` device bound to the RAM-disk on the target server, and the `rw` parameter were varied to create read and write direction of the job respectively.

The 99% confidence interval of the t-test difference between the two read jobs is $CI_{read} = 0.011s < \bar{t} < 0.035s$, and mean difference is $0.023s$. The 99% confidence interval of the t.test difference between the two write jobs is $CI_{write} = 0.069s < \bar{t} < 0.155s$, and mean difference is $0.112s$. Hence, the worst case overhead, with 99% confidence is $0.035s/0.155s$ for reads/writes respectively.

The average read rate with no qdiscs is $\frac{512MB}{7.188s} = 71.2MB/s$, and the average write rate with no qdiscs is $\frac{512MB}{8.731} = 58.6MB/s$. The read rate with worst case overhead is $\frac{512MB}{7.188s+0.035s} = 70.9MB/s$, yielding a read rate difference of 0.3 MB/s, a worst case overhead of 0.42% relative to the rate without qdiscs. The average write rate with worst case overhead is $\frac{512MB}{8.731s+0.155s} = 57.6MB/s$, yielding a write rate difference of 1MB/s, a worst case overhead of 1.7% relative to the rate without qdiscs.

5.9 Automated PID control approach

The design of a fully automated per-resource read-response-time-controller is described in section 4.5. This section describes experimental results when the automated framework is exposed to the same loads as in section 5.7. In this experiment, information about resources and per resource throttleable consumers are automatically inferred by the framework.

Figure 5.11 shows that the results with per resource saturation level autodetection, and dynamically maintained throttleable consumer sets, is close to the results in section 5.7 when defining throttleable consumers and response

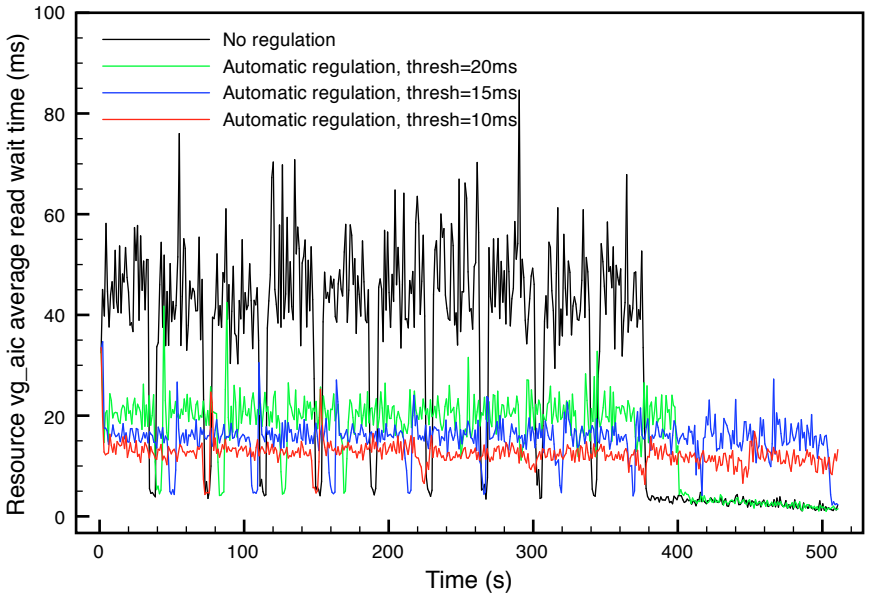


Figure 5.11: The average wait time of a rate limited (256kB/s) random read job interfered by 12 write threads started simultaneously and repeated with 5 seconds pause in between. The black plot shows the effect with free resource competition. The colored plots show how the PID regulator keeps different response time thresholds by regulating interfering workloads. In this plot, the resource saturation indicator and the set of throttleable host are maintained automatically.

time monitors manually. Figure 5.12 shows the resulting aggregated write rates as a consequence of the automated throttling carried out to keep read response time below the set thresholds in 5.11. Again, the black plot depicts response-time/write-rate without regulation, and the colored ones depicts the same but with regulation at different threshold values.

The results shows that the automated per resource PID control framework is able to closely reproduce the results in section 5.7 where throttleable consumer sets and resource saturation indicators were manually given as parameters to the PID regulators.

There is a slight delay in the throttle response compared to section 5.7, giving a slightly larger magnitude and duration of the overshoot created by the simultaneous starting of 12 interfering threads. It is reasonable to speculate that this is caused by the additional time required to populate the sets of throttleable consumers.

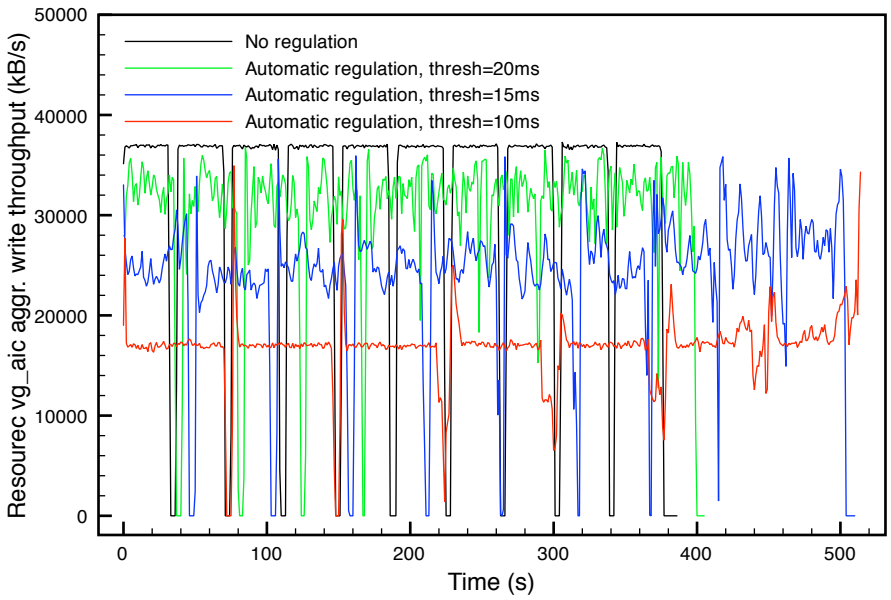


Figure 5.12: The aggregated throughput caused by throttling to keep latencies at the set thresholds in Figure 5.11

During experiment execution, the OUTPUT chain of the Netfilter mangle table was monitored with the command `watch iptables -L OUTPUT -t mangle`. As expected, the rule that marks the outbound ACK packets of all consumers in the set of throttleable consumers appeared as soon as the response time threshold was violated. Further observation revealed rapid increase of the `mark` value as the write interference increased in magnitude, thus directly inhibiting write activity to a level that does not cause threshold violation. The command `watch ipset -L` was used to observe that an empty set with the same name as the active resources (the vg_aic volumgroup) were created upon startup of the `set_maintainer.pl` program. Furthermore, the set was populated with the correct IP addresses as the write activity of consumers violated the set threshold, and the IP addresses were removed from the set when consumers ceased/reduced write activity.

Before creating the workload used in this experiment, various smaller workloads were tested while plotting average wait time in realtime during experiments. By applying various increasing and decreasing write interference, the PID controller's behavior was observed in real time. The controller exhibited remarkable stability when gradually increasing interference. Hence, it was decided to produce the most extreme workload variation possible for the plotted results by turning on and off 12 writer threads (powered by three machines)

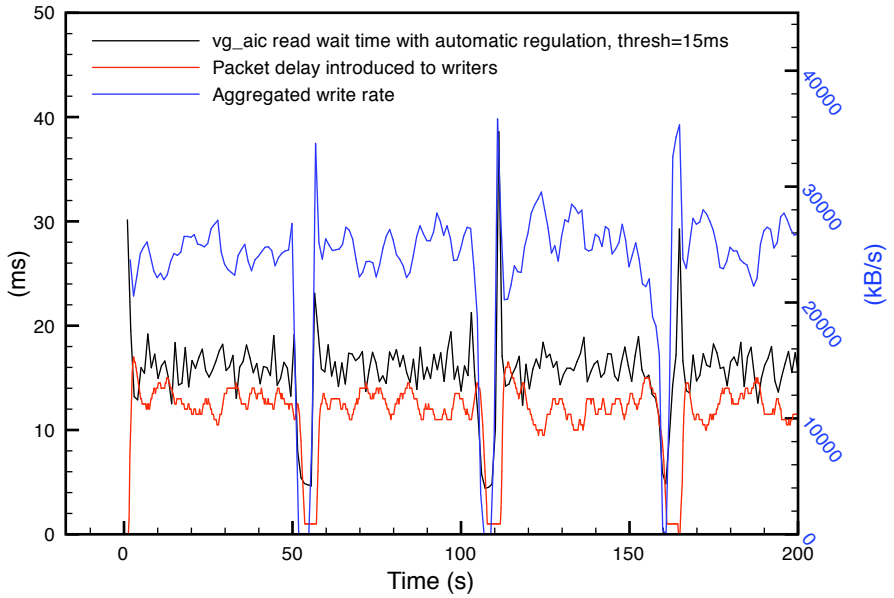


Figure 5.13: The resource average wait time, the throttling delay and the aggregated write rate with a set resource-wait-time-threshold of 15ms

simultaneously.

It is interesting to examine how the throttle-produced packet delay changes as the the PID controller decides throttle values. Thus, the experiment used in 5.9 and 5.7 were run again, capturing the packet delay applied to the set of throttleable hosts along the duration of the experiment. Figure 5.13 shows the monitored resource's (vg_aic) actual wait time, the throttle value (packet delay) produced by the PID controller and the actual resource's aggregated write rate. The 12 writer threads want as much I/O bandwidth as they can get (37 MB/s without regulation), however, they get throttled by introducing the packet delay seen in the red plot. The decreased write rate caused by packet delay prevents resource saturation, which again prevents read response time of the resource from exceeding the set threshold of 15 ms.

Chapter 6

Discussion and conclusion

This chapter discusses the methods and design used, the choices made during the process and the results exhibited together with their implications.

6.1 Approach review

Approaches of previous work vary from pure model design to thorough experiments based on simple assumptions. The difficulty of modeling the dynamic and complex behavior of disc arrays' performance, in the cases where resource-sharing is used extensively, has been pointed out by a large part of the previous research. Those works which relied on extensive model design were either tested using simulations only, or failed to capture the complexity when tested in realistic experiments. Approaches using simple assumptions and close-to-real-world experiments seemed to get the most applicable results. Thus, a similar approach was used in this project. Given the results exhibited, that seems to be have been a fruitful decision.

The approach of this project is highly influenced by real-world problems experienced by the author, introduced by the resource sharing mechanisms seen in many networked storage devices. These challenges would have been reduced, or completely avoided, by having a simple two level prioritization mechanism: important and less-important. Hence, a major motivation of this project has been to address this incompleteness within the available scope of the chosen technology, namely iSCSI based disk arrays. This approach requires a manual value decision about what virtual disks are important and response time sensitive and what virtual disks can tolerate being rate-reduced in order to

avoid resource saturation. An initial prototype was created with this specific problem in mind.

The subsequent prototype tries to make more general assumptions about what operations are important, and automatically makes prioritization decisions based on them. This prototype exchanges fine grained manual control with automatic decisions based the general assumption that read requests are more important than write requests (see section 4.5 for assumption discussion). The prototypes demonstrate how the basic elements studied in this project can be utilized for various kinds of prioritization systems with differing properties.

Of course, none of the prototypes offer a magic method to increase the amount of total resources. If a virtual disk consumer deemed important by policy (automated or not) decides to saturate all resources, it will be allowed to do so. This is the intended behavior though, since the objective of the project is to design methods preventing less-important activity from adversely affecting important activity. As seen in the two prototypes, what is considered important is not a universal truth. If activity deemed important by policy saturates all resources, either the policy is flawed or the total capacity of the resources is insufficient.

This project is characterized by a broad approach, a thorough evaluation of existing research, and cross-disciplinary and practically oriented thinking in the application of solutions. By combining ideas from the networking and control engineering fields it was possible to create two working prototypes by utilizing the ideas in novel ways.

6.2 Tools used

Choice of tools is important in order to build confidence in the results exhibited. Tools are used to measure behavior and create workload. It is essential that measuring tools are well known and accurate, and that the tool used for workload generation is producing exactly what it is instructed to in a reproducible way.

This project utilizes scripts extensively, together with ntp, at and ssh, to synchronize events between several hosts. The scripts make sure that the timing, order of execution, data collection and post processing are identical for job setups that compare similar aspects. The scripts call well known tools like `blktrace`, `collectl`, `argus`, `collectd`, `dstat`, `gnu-time` and `fio` that monitor the execution of the experiments and generate the desired workloads

at predetermined points in time. Using the same tools and scripts for executing them, the results in this project can easily be reproduced.

6.3 Identification of resource utilization

The assumptions stated in section 2.1, section 1.1 and previous work [65] suggested a reliable relation between average consumer response times and saturation level of their underlying resource. The resource saturation level, or conversely the remaining capacity, is determined by the aggregate workload utilizing the resource. Magnitude, direction, randomness, and request sizes of the aggregate workload are only some of the variables determining remaining capacity. The other part of this equation is comprised by RAID level, stripe sizes, stripe lengths, disk access times, bus speeds, head position of disks, controller CPU capacity, speed and amount of cache in various levels of the data path, internal algorithms for cache management, dynamic redistribution of data and the like. Attempts to modeling the remaining capacity as a function of all these parameters remains a difficult outstanding problem. Therefore, this project chose to use the best means now available as an indirect measure of remaining resources capacity: the response time of currently active resource consumers. Measuring this value is simple and the measurement consumes a negligible amount of resources. The usability of average consumer response time as a saturation level measure is underlined by all response time related experiments carried out in this project, and further confirmed by the successful operation of the two PID controller prototypes described in sections 4.4 and 4.5.

6.4 Effect of interference

Interference between loads sharing a common resource causes consumers to experience varying performance which is not caused by their own activity. It is caused by the previously mentioned remaining capacity, which varies in a highly unpredictable manner, and is a consequence of the resource's aggregate workload and its hardware setup. The ultimate goal of this project is to increase individual consumers' predictability with respect to the performance they perceive. The latter is directly related to the previously mentioned consumer average response time. In order to make this performance more predictable, it was necessary to study the effects of load interference. Section 5.5 demonstrates clearly how varying amounts of write activity influence the read

response time of a consumer that produces little workload by itself. While this is not the only aspect of load interference, it is an important one. Generally read request response times are most critical for application operation. For these particular experiments the effect of writing activity on other consumers read response time were chosen to illustrate the problem of load interference, but clearly any kind of consumer workload is able influence all consumers' available capacity by executing any kind of workload towards its own virtual disks. It is just a matter of how much power is driving the resource hogging workloads.

6.5 Effects of throttling

Throttling of workloads has been utilized as a means to influence remaining capacity by many previous works, and it is normally carried out by some kind of rate limitation applied to the workloads. Utilization of the iSCSI protocol comes with the additional benefit of utilizing TCP traffic shaping tools to enforce rate limitation. In order to examine the effects on consumers by throttling taking place in the TCP layer, a number of experiments were executed. The first throttling approach involved bandwidth limitations by using hierarchical token bucket filters (HTB). The expected effect of throttling individual consumers was achieved, but the pure bandwidth throttler had a few practical limitations: the need for constantly calculating the bandwidth to be applied and, more important, the inefficient way of controlling write requests. Controlling write rates was not possible without packet loss, resulting in slow and inefficient convergence towards bandwidth target. This is thoroughly discussed in section 4.1.

The shortcomings of the bandwidth shaping method inspired the idea of using packet delay for throttling. The `netem` module of Linux Traffic control was used to add delay to packets in a dynamic way using `Iptables` packet marks. The concept is to add a small wait time to outgoing ACK packets, thus slowing down the packet rate of the sender: the iSCSI writer. This concept, with its pros and cons, is thoroughly discussed in sections 4.2 and 4.1. The main outcome of the design and subsequent experiments is an efficient way of throttling individual iSCSI consumers' traffic in both directions, with close-to-linear rate reduction and without packet loss (see section 5.4). To our knowledge, this approach has not been used to apply throttling in this way before.

The packet delay throttle is a tool by itself with its capabilities to throttle traffic in both directions. This tool is ready to be used as a means to execute the throttling part in any kind of iSCSI/TCP based automated framework for pri-

oritization. In the experiments, writing activity was chosen as interference because it yielded the most violent interference. Therefore it served the purpose of demonstrating the concept of load interference in the best possible way for this setup. Other situations may call for the need to throttle read interference too, and there is nothing preventing the packet delay throttle to be used in this scenario. It is has been demonstrated to work equally well as for write interference (see section 5.4).

The usefulness of the packet delay throttle is also demonstrated by its efficient means to execute PID controller throttling decisions in the two prototypes subsequently developed.

6.6 Throttling decision

Design and experiments up to this point yielded an efficient method of manually specifying a rate-limiting throttle value on a per consumer and per direction (read/write) basis: the packet delay throttle. However, having to manually control groups of individual consumers is clearly not sufficient in order to make keepable promises about individual consumers' performance. Statically set rate limitations quickly become invalid as the aggregated workload of the resource is changing. The blackbox approach taken in this project necessarily implies no prediction of workload changes, but relies on measuring the effect of them. Having just a manual knob to control throttling is clearly not sufficient when interfering workloads rapidly change. Previous experiments shows that the response time of a resource is a sufficient measure of remaining capacity regardless of workload pattern. The decision to use this response time as input to the throttling decision engine should therefore not be particularly controversial.

The purpose of the decision engine is to throttle loads deemed less important in order to keep more important loads to be adversely affected. What is deemed important will vary between different situations. It can be read over write prioritization, fair sharing with weights, manually defined sets of important consumers or any combination of these. The first approach of this project is manually defined sets of important and less important consumers. Due to the choice of workloads this approach implies read over write prioritization, however, if the workloads changed the set of prioritized consumers would still be the same and whatever workload they would run would be throttled accordingly.

The idea of using a PID controller as decision engine emerged from the observations of the relation between interfering workloads, the interference by other

consumers and the efficient operation of the packet delay throttle. This behavior is similar to the control organs used to control industrial processes operated by PID controllers in the field of control engineering. Preliminary experiments using the PID controller algorithm exhibited promising behavior with respect to the problem: keeping consumer response time below a certain threshold in spite of massive interference. Thus, more extensive and synchronized experiments were designed to further confirm the PID controller's suitability for the purpose.

The experiments in section 5.7 shows the results when the PID controller operates on predefined sets of important and less important consumers. They clearly verify the suitability of the PID controller for this purpose. The PID controller exhibits remarkable ability to keep response time at the predefined thresholds, in spite of violently changing workload interference. If the response time threshold is reasonably set, the rate reduction needed for interfering workloads is small. For lower thresholds the controller loop also keeps a stable value, but at a much cost in the form of further rate reduction of interfering workloads.

6.7 An automated framework

In order to take one step further with respect to autonomous operation, an approach using read over write prioritization was designed 4.5. While this approach does not cover all possible needs for various prioritization schemes, it further emphasizes the suitability of the packet delay throttle and the PID controller as basic building blocks of an example scheme. Furthermore, additional techniques are demonstrated to automate resource/consumer mappings, per resource saturation monitors and autonomic maintenance of throttleable consumers. Using these basic building blocks, it should be easy to build any kind of prioritization scheme or combinations of such.

The approach for automatically deciding what to include in the calculation of resource saturation level, and the means to influence it, has demonstrated equally good results compared with experiments where this information explicitly was given. Hence, the automated per resource PID regulation is a step forward with respect to generalization of the framework into per resource individually maintained controller loops.

The results of the autonomous framework shows a slight increase in magnitude and duration of the read response time threshold-overshoot compared to the controller loop utilizing predefined consumers sets. It is reasonable to

speculate that this is caused by the additional time to populate the set of throttleable consumers before throttling influences the rate. Increasing the current one second convergence rate of the throttleable sets will probably make this overshoot less. This is a value decision considering how much CPU resources is spent checking for potential set members, compared to the acceptable overshoot. However, the magnitude and duration of the overshoot is considered to be within acceptable limits, given the nature of the interference workload.

The workloads are designed to create maximum variation in interference by simultaneously switching on and off 12 threads spread across three machines. The impact of this interference, when there is no control loop active, is clearly shown by the black plots in Figures 5.11 and 5.9. Wait time of the impacted random read workload peaks at > 80 ms when there is no control loop. Applying the control loop stabilizes the wait time of the random read job at the set threshold with remarkable stability. This is managed by the framework in an autonomous way on a per resource basis, comprising a solution to problem stated in section 1.2.

The modular design of the programs comprising the two prototypes makes it trivial to reimplement the framework in similar environments. Moreover, they are easily used as building blocks to achieve different prioritization schemes than those demonstrated in this project or they can be used as components in a bridged packet throttle.

6.8 Throttling overhead

When examining alternatives, the overhead term is commonly related to the difference in overhead between alternatives. This project introduces new features to prioritize workloads sharing a common resource. It is timely to ask if this new feature comes with an added overhead. Experiments in section 5.8 indicates a worst case overhead of 1.7% for writes and 0.3% for reads when accessing an iSCSI target device serviced by a RAM disk. Clearly, having the static filters ready to be used for delay throttling adds some overhead. While the the overall overhead is small, it is still much larger for writes than reads. The reason for this is not clear, but some of the difference can be explained by the worst case calculation being impacted by a larger confidence interval (more variation) for the writes. If the difference in means were used for the calculation, the write jobs would have a difference of $0.7MB/s$ or 1.2%. For reads, it would have been $0.2MB/s$ or 0.28%. One hypothesis suggested was that writes generated more outbound packets than reads. Hence, the number of packets to check per data amount would be higher for writes. However, this

hypothesis was refuted by looking at the actual outgoing packet rates from the target server during the experiment. Reads generated higher outbound packet rates than writes. This was also expected behavior, since the most of the outbound packets was the ACK packets back to the initiator. Hence, this behavior remains unexplained.

Experiments in section 5.8 suggest that the introduced overhead is related to the amount of static `tc` filters attached to the root qdisc of the iSCSI interface. This is reasonable since all packets must be checked for a particular mark by each filter. This could be greatly improved by having one filter checking if packets are marked or not, and then send packets that are marked for further checking by subsequent filters. Packets that are not marked would not need further checking. It is expected that implementation of this method will nearly remove the no-throttling-overhead, while the additional delay introduced by subsequent packet inspection for packets with marks is negligible compared to the added delay they will end up with.

The concept of throttling implies inducing overhead to a set of consumers on purpose. Thus, this kind of overhead is not considered harmful or unwanted. However, if throttling of some consumers induces overhead to other unthrottled consumers it is unwanted behavior. This behavior observed in Figures 5.2, 5.4 and 5.3, when the rate of the unthrottled consumer is affected by the throttling of other consumers. However, the effect is not necessarily caused by throttling overhead. When all consumers read or write sequentially from striped logical volumes, it is possible that there is some synergy effect between jobs due to read-ahead or consolidated operations in the block layer. When some consumers get throttled down, this synergy effect is reduced, and it could explain the temporary throughput reduction seen by the unthrottled consumers.

6.9 Future work and suggested improvements

This project opens several interesting paths for further research and applications. By using the fundamental ideas explored, it should be possible to create QoS modules to be used as external bridges in front of iSCSI appliances or integrated into Linux based iSCSI appliances similar to the lab prototype. By utilizing the ideas from this project, system administrators and vendors can offer QoS for iSCSI storage. Hence, they can offer differentiated SLAs to storage consumers with a confidence previously very difficult to achieve and contribute their share to overall application SLAs.

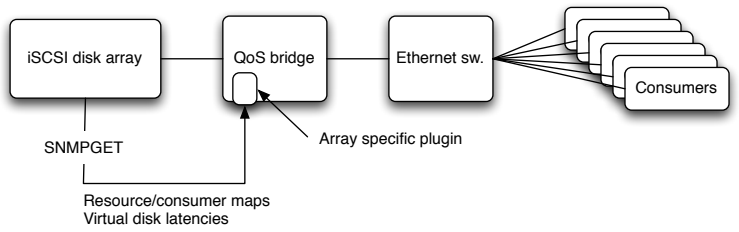


Figure 6.1: Illustration of how the framework could be utilized as an independent black box with limited array knowledge.

Figure 6.1 illustrates an approach for moving the controller to an external bridge. Information about consumer/resource mapping and virtual disk read latencies would be necessary in order to directly utilize the techniques demonstrated here. In the figure, usage of SNMP GET requests towards the array is suggested as an easy method for this purpose. However, the ultimate black box approach would be to infer this information from packet inspection. If achievable, this approach could serve as a self contained, non-intrusive, iSCSI QoS machine applicable to all iSCSI solutions regardless of their make and the feedback loop to the storage device would not be necessary. But it is unlikely that the actual consumer/resource mapping can be detected by packet inspection since this is internal storage device knowledge. However, it could be indirectly inferred by using a predefined initiator naming convention that contain resource membership.

Even with high sampling rate, and convergence rate of throttleable consumer sets, the PID controller framework consumes little resources. Small resource consumption and overhead are important attributes to enable high scalability. The small resource consumption and overhead seen in the lab prototype, makes it reasonable to project high scalability in a production environment with large amounts of resources and consumers per resource. Combined with the suggested PID controller tuning and rearrangement of `tc` filters an even smaller footprint can be achieved.

Like mentioned in section 4.3, the measuring point where virtual disk response time is measured must be moved in order to detect bottlenecks that occur before the local disks of the target server. An approach using agents on iSCSI initiators would be the best way of considering all bottlenecks along the data path by providing the initiator-experienced wait time to the throttling bridge. The advantage of this approach is its simplicity, and how efficiently it will capture all bottlenecks along the iSCSI data path. The disadvantage is its reliance on initiator host modifications. A viable approach could be to use the attribute

has_agent_installed to infer relative higher importance to the set of initiator that has agents, and automatically use the set of consumers not having agents as a first attempt of throttling before resorting to prioritization between initiators with agents installed. Using this approach, the action of installing an agent serves both the purpose of making performance metrics available to the controller and telling about the membership in the set of important hosts.

Previously developed algorithms other than the PID algorithm can be combined with the throttling techniques from this project to create even more efficient and/or general purpose QoS mechanisms for iSCSI or even other IP/Ethernet based storage technologies. Furthermore, the PID control algorithm could be evaluated as a means to create stability and predictability in other infrastructure components than just iSCSI devices. It is likely that the problem of controlling iSCSI consumers is not the only one where a PID controller can contribute.

There is always a persistent and large interest in workload classification/modeling techniques in various research areas, not only in the storage field. Together with the ever-evolving efforts to model storage devices, this research can be combined with the ideas and results in this thesis in order to add improved and even more generalized frameworks. Response time measurements can still serve as a fallback when model generation fails or is too inaccurate, while improved operation is achieved in the cases where workload prediction works.

6.10 Conclusion

Resource sharing is widely used in storage devices for the purpose of flexibility and maximum utilization of the underlying hardware. Sharing resources like this introduces a considerable risk of violating application service level agreements caused by the unpredictable amount of I/O capacity available to individual storage consumers. The difficulties experienced by system administrators in making keepable promise about storage performance and the amount of previous research in the storage QoS field clearly emphasizes the need for practical and real-world-usable QoS mechanisms for storage systems.

iSCSI based storage solutions are capturing increased market share from FC based storage solutions due to increased performance and low cost. Thus, iSCSI is an interesting target technology for devolpment of QoS mechanisms for wide industry and system administrator adoption. The fact that iSCSI utilizes TCP for transportation makes it possible, and very interesting, to adapt

well known network traffic shaping tools for the purpose of QoS in iSCSI environments.

This project reproduces and demonstrates the nature of resource sharing, the effect of resource saturation on throughput and consumer response time, and the resulting interference caused by load interaction. Using a Linux based iSCSI storage appliance, experiments reproduce the varying performance of individual consumers caused by other consumers' activity. The lab environment, verified to exhibit similar properties to problematic real-world storage solutions, is then used to design methods to solve some relevant aspects of load interference. The methods involve using a network packet delay method, available in the `netem` module of Linux Traffic Control, in novel ways and a modified proportional integral derivative (PID) controller. By combining the features of the `netem` module with Iptables' ability to dynamically mark packets, an efficient bidirectional mechanism for throttling individual iSCSI initiators consumers is created. The created packet delay throttle is utilized by a modified PID controller implemented in software. The PID controller utilizes the packet delay throttle as a means to influence its input value: the average wait time of the resource being controlled. The resource being controlled in the lab setup is LVM volume groups, but the methods are generally adaptable to any kind of resource exhibiting similar attributes.

The effect of packet delay throttling and the PID controllers' suitability as decision engine is thoroughly examined through experimental results. Finally, all previously designed and tested elements used in single aspect experiments are tied together in a prototype for a autonomous resource control framework that is able to keep resource read response time below a configurable threshold by throttling write activity to the resource automatically. In spite of rapidly varying write workloads, the framework is able to keep a resource read response time below the set threshold. The set of throttleable write consumers is automatically maintained and ready to be used by the PID controller monitoring read response time. The framework spawns a PID controller per resource, using per resource sets of throttleable consumers and per resource response time measurements.

Throttling only occurs when response time of a resource violates the preset threshold. When no throttling occurs, there is a negligible worst case overhead of 0.4% for reads and 1.7% for writes caused by the static traffic control filters which are always present and ready to detect packet marks.

This project opens several interesting paths for further research and applications. By using the fundamental ideas explored, it is possible to create QoS modules to be used as an external bridge in front of iSCSI appliances or integrated into Linux based iSCSI appliances similar to the lab environment.

Previously developed algorithms can be combined with the throttling techniques from this paper to create even more efficient and/or general purpose QoS mechanisms for iSCSI or even other IP/Ethernet based storage technologies. Furthermore, the PID control algorithm could be evaluated as a means to create stability and predictability in other infrastructure components than just iSCSI devices.

By using the basic building blocks of this project it is possible to create a vast amount of prioritization schemes. The few examples demonstrated serves as a demonstration of the inherent opportunities. With the modular design of the different programs it should be trivial to reimplement the framework in similar set ups with minor adjustments only.

With the small resource consumption footprint of the prototype, and room for further improvement of it, this concept should scale to enterprise level production environments with large amounts of resources and storage consumers.

By utilizing the ideas from this project, system administrators and vendors can offer QoS for iSCSI storage, thereby making it possible to offer differentiated SLAs to storage consumers supporting application SLAs with a confidence previously very difficult to achieve.

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Appendix A

I/O Throttlers

Listing A.1: Script for throttling individual IP address

```
#!/usr/bin/perl -w

# name: throttle_iscsi_initiator.pl

# This script classify packets for further treatment
# by traffic control. Classification is done using the
   mark
# target of iptables.

if ( ! exists($ARGV[1])) {
  &usage;
}

my $lasthandle = 20; # Needs to be adapted to number of
    tc classes.
my $step;
if ( exists $ARGV[2] ) { $step = $ARGV[2] } else {
   $step = 1 };
my $initiator_ip = $ARGV[0];
my $action = $ARGV[1];
my $myip = '10.0.0.253';
my $rv = 0;
my $rulenum = -1;
my $mark = 0 ;
my $iptables = "/sbin/iptables ";
my $starthandle = 1 ;
my $tc = "/sbin/tc";
```

```
my $iscsi_dev = "eth1";

if ( $initiator_ip =~ /^([\d]+)\.([\d]+)\.([\d]+)\.([\d
   ]+)$/ ) {
  if ( $action eq 'slower') {
    ( $rulenum, $mark ) = &get_rule("up");
    if ( $rulenum == -1 ) {
      if ( $step > $lasthandle ) { $step = $lasthandle
         };
      $rv = `$iptables -A OUTPUT -o $iscsi_dev -s $myip
          -d $initiator_ip -j MARK --set-mark $step`;
    } else {
      $rv = `$iptables -A OUTPUT -o $iscsi_dev -s $myip
          -d $initiator_ip -j MARK --set-mark $mark`;
      $rv = `$iptables -D OUTPUT $rulenum`;
    }
  } elsif (  $action eq 'faster') {
    ( $rulenum, $mark ) = &get_rule("down");
    if ( $rulenum != -1 ) {
      if ( ($mark + 1 ) == $starthandle ) {
        $rv = `$iptables -D OUTPUT $rulenum`;
      } else {
        $rv = `$iptables -A OUTPUT -o $iscsi_dev -s
           $myip -d $initiator_ip -j MARK --set-mark
           $mark`;
        $rv = `$iptables -D OUTPUT $rulenum`;
      }
    }
  } elsif (  $action eq 'free') {
     ( $rulenum, $mark ) = &get_rule("up");
     $rv = `$iptables -D OUTPUT $rulenum`;
  } else {
    &usage
  }
} else {
  &usage
}

# ------- Functions ----------

sub usage {
  print "Usage: $0 initator_ipaddr faster|slower|free [
     step] \n";
```

```
  exit 1;
}

sub get_rule {
# Check if $initator_ip is classified and get its
   existing handle.
# Increment or decremnent returned new mark based on
   given argument
  my $direction = shift;
  my $newmark = 0 ;
  if ( $direction eq "down" ) {
   $step = $step * -1 ;
  }
  my @ret=[];
  foreach (`$iptables --line-numbers -n -L OUTPUT `) {
    chomp;
    if ( /^\d+.+/) {
      my @rule = split(" ",$_);
      if ( $rule[4] eq $myip && $rule[5] eq
         $initiator_ip ) {
        $rulenum = $rule[0] ;
        $rule[8] =~ /^0x(.+)\/.+/;
        $mark = sprintf('%d',hex($1));
        if ( $mark + $step < 0 ) {
         $newmark = 0;
        } elsif ( $mark + $step > $lasthandle ) {
         $newmark = $lasthandle ;
        } else {
         $newmark = $mark + $step;
        }
      }
    }
  }
  @ret = ($rulenum,$newmark);
  return @ret;
}
```

Listing A.2: The PID controller script used in 5.9 and 5.10

```
#!/usr/bin/perl -w
# name: reg.pl

use POSIX;;
```

```
use Time::HiRes qw( usleep );

$SIG{INT} = "cleanup";
my $ipt_mark = 0;
my $lastmark = 0;
my $ds = "/proc/diskstats";
my $countermem;
my $lastewma = 0;
my $ewma_alpha = 0.25;
my $setpoint = 10;
my $max_throttle = -40;
my @prev_devs = (0,0,0);
my @prev_uks = (0,0,0);
my $Kp = 0.3;
my $Ti = 500;
my $Td = 1;
my $T = 16;
my $iptables = "/usr/local/sbin/iptables -t mangle";
$|=1;

my $mondev = "dm-0";

STDOUT->autoflush;
create_sets();

while ( 1 ) {
  open(DISKSTATS,"<",$ds)  or die "open $ds, $!";
  while (<DISKSTATS>) {
    chomp;
    s/\s+/ /g;
    my ($major, $minor, $dev, @fields ) = split(' ',$_)
       ;
    if ( $dev eq $mondev ) {
      my $weitime = counter("dm-0","weitime",$fields
         [10]);
      my $req = counter("dm-0","r",$fields[0]) +
         counter("dm-0","w",$fields[4]);
      my $wait;
      if ($req > 0 ) { $wait = $weitime / $req } else {
          $wait = 0 } ;
      my $cur_ewma =  $lastewma + $ewma_alpha*($wait -
         $lastewma);
      unshift(@prev_devs,$setpoint - $cur_ewma);
```

```
      pid_reg();
      $lastewma = $cur_ewma;
    }
  }
  close(DISKSTATS);
  usleep 100000;
}

# functions

sub pid_reg {
  my $uk = $prev_uks[0]  + $Kp*(1-($T/$Ti)) +  $Kp*
     $prev_devs[0] + (($Kp*$Td)/$T)*($prev_devs[0] - 2*
     $prev_devs[1] + $prev_devs[2]);
  if ( $uk > 0 ) {
    $uk = 0;
  } elsif ($uk <  $max_throttle ) {
    $uk = $max_throttle;
  }
  if ( $uk < 0 ) {
    $ipt_mark = -1*ceil($uk);
  }
  if ( $ipt_mark != $lastmark ) {
    throttle("throttlers",$ipt_mark);
    if ( $ipt_mark > $lastmark ) {
     for (my $bar=1;$bar <= $ipt_mark - $lastmark; $bar
        ++) {
       print "#";
     }
    } elsif ( $ipt_mark < $lastmark ) {
      for (my $bar=1;$bar <= $lastmark - $ipt_mark;
         $bar++) {
       print  "\x08";
      }
    }
  }
  unshift(@prev_uks,$uk);pop(@prev_uks);
  pop(@prev_devs);
  $lastmark = $ipt_mark;
}

sub counter  {
  my $obj = shift;
```

```
  my $field = shift;
  my $current_value = shift;
  my $cm;
  my $ret = 0 ;
  if (exists($countermem->{$obj}->{$field})) {
    $cm = $countermem->{$obj}->{$field};
    if ( $cm > $current_value ) {
      $ret = ( 4294967296 - $cm) + $current_value;
    } else {
      $ret = $current_value - $cm;
    }
  }
  $countermem->{$obj}->{$field} =  $current_value;
  return $ret;
}

sub create_sets {
  `ipset -N throttlers ipmap --network 10.0.0.0/24`;
  `ipset -A throttlers 10.0.0.243`;
  `ipset -A throttlers 10.0.0.244`;
  `ipset -A throttlers 10.0.0.245`;
}

sub cleanup {
  `iptables -F -t mangle `;
  `ipset -X throttlers`;
  die "Ouch !\n";
}

sub throttle {
  my $set_name = shift;
  my $tv = shift;
  my $myip = '10.0.0.253';
  my $mark = 0 ;
  my $iscsi_dev = "eth1";
  my @ipsets;

  foreach (`ipset -L `) {
    chomp;
    if ( /^Name.*/) {
      my @l = split;
      push(@ipsets,$l[1]);
    }
```

```
  }

  if ( grep /^$set_name$/,@ipsets ) {
    unless ( $tv == 0  ) {
    `$iptables -A OUTPUT -o $iscsi_dev -s $myip -m set
       --match-set $set_name dst  -j MARK --set-mark
       $tv`;
    }
    delete_other($set_name,$tv,$myip);
  }
}

sub delete_other {
  my $set_name = shift;
  my $tv = shift;
  my $myip = shift;
  foreach (`$iptables --line-numbers -n -L OUTPUT `) {
    print if $debug;
    chomp;
    if ( /^\d+.+/) {
      my @rule = split(" ",$_);
      print join(",",@rule)."\n" if $debug;
      $rule[11] =~ /^0x(.+)/;
      $mark = sprintf('%d',hex($1));
      if ( $rule[4] eq $myip && $rule[7] eq $set_name
         && $mark != $tv ) {
        `$iptables -D  OUTPUT $rule[0]` ;
      }
    }
  }
}
```

Listing A.3: The PID controller script used in FIXME

```
#!/usr/bin/perl -w

use Config;
$Config{useithreads} or die('Recompile Perl with
   threads to run this program.');
use IPC::Shareable;
use Data::Dumper;
use POSIX;;
use Time::HiRes qw( usleep );
```

```
use threads;
$SIG{INT} = "cleanup";
my @prev_devs = (0,0,0);
my @prev_uks = (0,0,0);

my $ewmas;
tie $ewmas, 'IPC::Shareable', 'AVEWMAS', {create => 0,
   destroy => 0};

my $Kp = 0.3;
my $Ti = 500;
my $Td = 1;
my $T = 16;
my $max_throttle = -40;
my $lat_thresh = 10;
my $iptables = "/usr/local/sbin/iptables -t mangle";
my $controller_mem;
my $threads;


foreach my $resource (keys %{$ewmas}) {
  print "Creating PID controller for $resource \n";
  $controller_mem->{$resource}->{'prev_uk'} = 0;
  $controller_mem->{$resource}->{'lastmark'} = 0;
  @{$controller_mem->{$resource}->{'prev_devs'}} =
     (0,0,0);
  $threads->{$resource} = threads->create(\&pid_reg,
     $resource,$lat_thresh);
  $threads->{$resource}->detach();
}

while (1) {
  sleep 10;
}
# Functions


sub pid_reg {
  my $resource = shift;
  my $thresh = shift;
  my $ipt_mark = 0;
  while (1) {
    unshift(@{$controller_mem->{$resource}->{'prev_devs
```

```
        '}},$thresh - $ewmas->{$resource});
    my $prev_uk = $controller_mem->{$resource}->{'
        prev_uk'};
    my @prev_devs =  @{$controller_mem->{$resource}->{'
        prev_devs'}};
#print "$prev_uk" .join("-", @prev_devs)."\n";
#print Dumper($controller_mem);
#print "$prev_uk --  $Kp -- $T -- $Ti -- $prev_devs[0]
   -- $Td -- $prev_devs[1]  --  $prev_devs[2] \n";
    my $uk = $prev_uk  + $Kp*(1-($T/$Ti)) +  $Kp*
        $prev_devs[0] + (($Kp*$Td)/$T)*($prev_devs[0] -
        2*$prev_devs[1] + $prev_devs[2]);
#print "$uk -- $prev_uk --  $Kp -- $T -- $Ti --
   $prev_devs[0] -- $Td -- $prev_devs[1]  --
   $prev_devs[2] \n";
    if ( $uk > 0 ) {
      $uk = 0;
    } elsif ($uk <  $max_throttle ) {
      $uk = $max_throttle;
    }
    if ( $uk < 0 ) {
      $ipt_mark = -1*ceil($uk);
    }
    if ( $ipt_mark !=  $controller_mem->{$resource}->{'
        lastmark'} ) {
      throttle($resource,$ipt_mark);
    }
    $controller_mem->{$resource}->{'prev_uk'} = $uk;
    pop(@{$controller_mem->{$resource}->{'prev_devs'}})
        ;
    $controller_mem->{$resource}->{'lastmark'} =
        $ipt_mark;
    usleep 200000;
  }
}

sub throttle {
  my $set_name = shift;
  my $tv = shift;
  my $myip = '10.0.0.253';
  my $mark = 0 ;
  my $iscsi_dev = "eth1";
  my @ipsets;
```

```
  foreach (`ipset -L `) {
    chomp;
    if ( /^Name.*/) {
      my @l = split;
      push(@ipsets,$l[1]);
    }
  }

  if ( grep /^$set_name$/,@ipsets ) {
    unless ( $tv == 0  ) {
     `$iptables -A OUTPUT -o $iscsi_dev  -p tcp --tcp-
        flags ACK ACK -s $myip -m set --match-set
        $set_name dst  -j MARK --set-mark $tv`;
    }

    delete_other($set_name,$tv,$myip);
  }
}

sub delete_other {
  my $set_name = shift;
  my $tv = shift;
  my $myip = shift;
  foreach (`$iptables --line-numbers -n -L OUTPUT `) {
    print if $debug;
    chomp;
    if ( /^\d+.+/) {
      my @rule = split(" ",$_);
      print join(",",@rule)."\n" if $debug;
      $rule[13] =~ /^0x(.+)/;
      $mark = sprintf('%d',hex($1));
      if ( $rule[4] eq $myip && $rule[9] eq $set_name
         && $mark != $tv ) {
      my $ret = `$iptables -D  OUTPUT $rule[0]` ;
      }
    }
  }
}

sub cleanup {
  `iptables -F -t mangle `;
  die "Ouch !\n";
```

```
}
```

Listing A.4: Shaping script for bandwidth Used in figure

```
#!/bin/bash

# name bw-shaping.sh

# script for doing timed throttling of
# individual iscsi initiators.

stm=`date +%s`
scriptdir="/root/scripts"
resultdir="/root/results"
iscsi_dev="eth1"
firsthandle=10
lasthandle=19
sleep_period="10"
b2=10.0.0.242
b3=10.0.0.243
b4=10.0.0.244
b5=10.0.0.245

# Go to a starting point where throttling has an effect
   .
for i in $b2 $b3 $b4
do
 ${scriptdir}/throttle_iscsi_initiator.pl $i slower 10
done

for i in `seq 11 23`
do
 ${scriptdir}/throttle_iscsi_initiator.pl $b2 slower
 sleep 3
done

for i in `seq 11 23`
do
 ${scriptdir}/throttle_iscsi_initiator.pl $b3 slower
 sleep 3
done

for i in `seq 11 23`
```

```
do
 ${scriptdir}/throttle_iscsi_initiator.pl $b4 slower
 sleep 3
done

sleep 12
${scriptdir}/throttle_iscsi_initiator.pl $b2 free
sleep 15
${scriptdir}/throttle_iscsi_initiator.pl $b3 free
sleep 15
${scriptdir}/throttle_iscsi_initiator.pl $b4 free
```

Listing A.5: Shaping script for packet delay (Used in figures 5.3 and 5.4)

```
#!/bin/bash

stm=‘date +%s‘
scriptdir="/root/scripts"
resultdir="/root/results"
iscsi_dev="eth1"
firsthandle=10
lasthandle=19
sleep_period="10"
> ${resultdir}/runlog
b2=10.0.0.242
b3=10.0.0.243
b4=10.0.0.244
b5=10.0.0.245

sleep 10

for i in ‘seq 1 30‘
do
 ${scriptdir}/throttle_iscsi_initiator.pl $b2 slower
 sleep 2
done
sleep 5
for i in ‘seq 1 30‘
do
 ${scriptdir}/throttle_iscsi_initiator.pl $b3 slower
 sleep 2
done
sleep 5
```

```
for i in ‘seq 1 30‘
do
 ${scriptdir}/throttle_iscsi_initiator.pl $b4 slower
 sleep 2
done

sleep 12
${scriptdir}/throttle_iscsi_initiator.pl $b2 free
sleep 15
${scriptdir}/throttle_iscsi_initiator.pl $b3 free
sleep 15
${scriptdir}/throttle_iscsi_initiator.pl $b4 free
```

Appendix B

Interface queueing setup

Listing B.1: Scripts which creates egress bandwidth queues (Creates figure 3.3)

```
#!/bin/bash

# name: class_chop_nic_bw.sh

# This script attach a number of bandwidth queues to
   the iscsi
# interface. Traffic is classified by marks assigned by
# iptables mark target

tc="/sbin/tc"
iscsi_nic="eth1"

case $1 in
 "start")
 typeset -i class=2
 ${tc} qdisc add dev ${iscsi_nic} root handle 1: htb
    default 1
 ${tc} class add dev ${iscsi_nic} parent 1:0 classid
    1:1 htb rate 1gbit burst 1mbit ceil 1gbit cburst 1
    mbit

for limit in `seq  50 50 950|sort -n -r`
do
 ${tc} class add dev ${iscsi_nic} parent 1:1 classid 1:
    ${class} htb rate ${limit}mbit
 class=${class}+1
done
```

```
for limit in `seq  5 10 45|sort -n -r`
do
 ${tc} class add dev ${iscsi_nic} parent 1:1 classid 1:
    ${class} htb rate ${limit}mbit
 class=${class}+1
done

for filter in `seq 1 $((${class}-2))`
do
 ${tc} filter add dev ${iscsi_nic} protocol ip parent
    1: prio 1 handle ${filter} fw classid 1:$((${filter
    }+1))
done

;;
"stop")
  ${tc} qdisc del dev ${iscsi_nic} root
;;
 "show" )
  echo "----- Show qdisc of  ${iscsi_nic} -----"
  ${tc} qdisc show dev   ${iscsi_nic}
  echo "----- Show classes of  ${iscsi_nic}  -----"
  ${tc} class show dev   ${iscsi_nic}
  echo "----- Show filters of  ${iscsi_nic} -----"
  ${tc} filter show dev  ${iscsi_nic}
 ;;
 * )
 echo "Usage $0 start|stop|show"
 ;;
esac
```

Listing B.2: Scripts which creates egress packet delay queues (Creates figure 3.2.7

```
#!/bin/bash

# name: class_chop_nic_delay.sh

# This script attach a number of delay queues to the
   iscsi
# interface. Traffic is classified by marks assigned by
# iptables mark target
```

```
tc="/sbin/tc"
iscsi_nic="eth1"

case $1 in
 "start")
 typeset -i class=1
 ${tc} qdisc add dev ${iscsi_nic} root handle 1: htb
    default 1
 class=${class}+1

for delay in `seq 0.1 0.5 10`
do
 tc class add dev ${iscsi_nic}  parent 1:0 classid 1:${
    class}  htb rate 1Gbps
 tc qdisc add dev eth1 parent 1:${class} handle 1${
    class}: netem delay ${delay}ms
 class=${class}+1
done

for filter in `seq 1 $((${class}-2))`
do
 ${tc} filter add dev ${iscsi_nic} protocol ip parent
    1: prio 1 handle ${filter} fw classid 1:$((${filter
    }+1))
done

;;
"stop")
  ${tc} qdisc del dev ${iscsi_nic} root
;;
 "show" )
  echo "----- Show qdisc of  ${iscsi_nic} -----"
  ${tc} qdisc show dev   ${iscsi_nic}
  echo "----- Show classes of  ${iscsi_nic}  -----"
  ${tc} class show dev   ${iscsi_nic}
  echo "----- Show filters of  ${iscsi_nic} -----"
  ${tc} filter show dev  ${iscsi_nic}
 ;;
 * )
 echo "Usage $0 start|stop|show"
 ;;
esac
```

Appendix C

Other scripts

Listing C.1: Script for finding stable relation between delay and throughput (It produces data for figures 5.5 and 5.5)

```
#!/bin/bash

jobdefs="/root/scripts/jobdefs/"
job=‘basename $0 .sh‘
delay=0

function loop {
  for i in ‘seq 1 20‘
    do
      echo "‘date +%H:%M:%S‘ ${delay} ‘/usr/bin/time -f
          %e /usr/local/bin/fio --minimal --output /dev
         /null ${jobdefs}${job}_$(hostname) 2>&1‘ "
    done
}

loop
sleep 2
for delay in ‘seq 0.1 0.5 10‘
do
ssh -p 5432 bm ’/root/scripts/throttle_iscsi_initiator.
   pl 10.0.0.242 slower’
loop
sleep 2
done
```

Listing C.2: Script used for dynamically maintaining sets of throttle-able IP addresses

```
#!/usr/bin/perl -w

use Set::Scalar;
use Time::HiRes qw(time sleep);
use Data::Dumper;
use IPC::Shareable;
$SIG{'INT'} = 'inthandler';
$SIG{'TERM'} = 'inthandler';
my $countermem;
my $ewmas;
my @ipsets = ();
my $write_thresh = 1000;
my %fm =  (     r => 0,
    rrqm => 1,
    rsec => 2,
    rtime => 3,
    w => 4,
    wsec => 6,
    wtime => 7,
    inflight => 8,
    time => 9,
    weitime => 10,
    );

my $iscsi_sessions;
tie $iscsi_sessions, 'IPC::Shareable', 'ISCSIMAP', {
   create => 1, mode => 664, destroy => 1};
$iscsi_sessions = get_iscsi_session_map();


while (1) {
  update_metrics();
  foreach my $s (@ipsets) {
    my $target_population = populate_target_set($s);
    converge_ipset($s,$target_population)
  }
  sleep 1;
}
```

```
# Functions

sub populate_target_set {
 $setname = shift;
 my @ips = ();
 foreach my $dm ( keys %{$ewmas} ) {
   if (  $iscsi_sessions->{$dm}->{'vg'} eq $setname ) {
    if ( $ewmas->{$dm}->{'wsec'} > $write_thresh ) {
      push(@ips, $iscsi_sessions->{$dm}->{'ip'}); # Add
          the ip of this abuser
     }
   }
 }
 my $ret;
 if ( $#ips >= 0 ) {
   $ret = new Set::Scalar(@ips);
 } else {
   $ret =  new Set::Scalar->null;
 }
 return $ret;
}

sub converge_ipset {
 my $setname = shift;
 my $target = shift;
 my @ips = ();
 foreach  (`ipset -L $setname`) {
  chomp;
  if ( /^(\d{1,3}\.\d{1,3}\.\d{1,3}\.\d{1,3})$/) {;
   push(@ips,$1);
  }
 }
 my $ipset;
 if ($#ips >= 0 ) {
  $ipset = new Set::Scalar(@ips);
 } else {
  $ipset = new Set::Scalar->null;
 }
 my $remove =  $ipset - $target ;
 my $add = $target - $ipset ;
 unless ($remove->is_null) {
   for my $i ($remove->members) {
     `ipset -D $setname $i`;
```

```
    }
  }
  unless ($add->is_null) {
    for my $i ($add->members) {
      `ipset -A $setname $i`;
    }
  }
}

sub get_iscsi_session_map {
  my $lvs;
  my $raw;
  my $active_dms;
  my %iet_sessions;
  my $stats;
  my $vgs;
  my $lvs_cmd = '/sbin/lvs -v';
  if ( -f "/etc/redhat-release" ) { $lvs_cmd = "/usr/
     sbin/lvs -v";}

  foreach (`$lvs_cmd 2> /dev/null`) {
    next if  /.+UUID.+/ ;
    s/\s+/ /g;
    chomp;
    my @l = split;
# Map dm vg-lv to dm-nn
    $lvs->{$l[1]}->{$l[0]}->{'dm'} = 'dm-'.$l[8];
  }
# Map tids to volumes
  $raw = `cat /proc/net/iet/volume`;
  my %iet_volumes = $raw =~ /tid:(\d{1,3})\sname:.+?\n
     .+?path:(.+?)\n/smg;
# Map tids to sessions
# Only populate tids with an initator attached
  my @tids;
  foreach my $l (`cat /proc/net/iet/session`) {
    if ($l =~ /^tid:(\d{1,3})\sname.+/) {
      push(@tids,$1);
    } elsif ( $l =~ /^\s+cid:.+ip:(.+)\sstate.+/) {
# Only populate if it seems like an lv-name
      $iet_sessions{$tids[$#tids]} = $1;
      shift(@tids);
    }
```

```
  }


# Know various info about dm- devices that is involved
   in
# active iscsi sessions
  foreach my $tid (keys %iet_sessions) {
    if ( $iet_volumes{$tid} && $iet_volumes{$tid} =~
       /^\/.+?\/.+?\/.+$/ ) {
      my @a = split('/',$iet_volumes{$tid});
      my $vg = $a[2];
      my $lv = $a[3];
      my $dm = $lvs->{$vg}->{$lv}->{'dm'};
      my $stat = $lvs->{$vg}->{$lv}->{'stat'};
      my $ip = $iet_sessions{$tid};
      $active_dms->{$dm}->{'vg'} = $vg;
      $active_dms->{$dm}->{'lv'} = $lv;
#     $active_dms->{$dm}->{'statfile'} = $stat;
      $active_dms->{$dm}->{'ip'} = $ip;
      push (@{$vgs->{$vg}},$dm);
    }
  }
  foreach my $vg (keys %{$vgs}) {
    `ipset -N $vg ipmap --network 10.0.0.0/24`;
    push(@ipsets,$vg);
   }
  return $active_dms;
}

sub counter  {
  my $obj = shift;
  my $field = shift;
  my $current_value = shift;
  my $cm;
  my $ret = "nan" ;
  if (exists($countermem->{$obj}->{$field})) {
    $cm = $countermem->{$obj}->{$field};
    if ( $cm > $current_value ) {
      $ret = ( 4294967296 - $cm) + $current_value;
    } else {
      $ret = $current_value - $cm;
    }
  }
```

```
  $countermem->{$obj}->{$field} =  $current_value;
  return $ret;
}

sub update_metrics {
  my $active_dms = shift;
  my $interval = shift;
  my $alpha = 0.25;
  my $ds = "/proc/diskstats";
# Snapshot disstats with a minimum of time usage
  open(DISKSTATS,"<",$ds)  or die "open $ds, $!";
  my $time = time;
  while (<DISKSTATS>) {
    chomp;
    s/\s+/ /g;
    my ($major, $minor, $dev, @fields ) = split(' ',$_)
       ;
    if ( $dev =~ /dm-\d+/) {
      my $cur_rate = counter($dev,'wsec',$fields[$fm{'
         wsec'}]); #Sector->Kb
      if ( $cur_rate eq "nan" ) {
       $ewmas->{$dev}->{'wsec'} = 0;
      } else {
       $ewmas->{$dev}->{'wsec'} = $ewmas->{$dev}->{'
          wsec'} + $alpha*($cur_rate - $ewmas->{$dev
          }->{'wsec'});
      }
      #print "$dev -> $cur_rate $ewmas->{$dev}->{'wsec
         '} \n";
    }
  }
  close(DISKSTATS);
  #print "----------\n";
}

sub inthandler {
 (tied $iscsi_sessions)->remove;
  `ipset -X`;
   exit;
 }
```

Listing C.3: Script used for dynamically maintaining a resource saturation in-

dicator in shared memory. The information is used as input to A.3

```
#!/usr/bin/perl -w

use IPC::Shareable;
use Time::HiRes qw(time usleep);
use Data::Dumper;
#use Statistics::Descriptive;
$SIG{'INT'} = 'inthandler';
$SIG{'TERM'} = 'inthandler';

my $alpha = 0.25;
my $iscsi_sessions;
tie $iscsi_sessions, 'IPC::Shareable', 'ISCSIMAP', {
   create => 0, destroy => 0};
my $avwait_ewmas ;
tie $avwait_ewmas, 'IPC::Shareable', 'AVEWMAS', {create
    => 1, mode => 664, destroy => 1};

my $resource_map = map_resource_consumers();


while (1) {
  my $cur_wait = grab_current_avwait();
  foreach my $resource (keys %{$resource_map}) {
    my $touched = 0;
    foreach my $dm (@{$resource_map->{$resource}} ) {
      if ($cur_wait->{$dm} ne "nan" ) {
        my $w = $cur_wait->{$dm} ;
        my $e = $avwait_ewmas->{$resource};
        my $n = $e + $alpha*($w - $e);
        $avwait_ewmas->{$resource} = $n;
        $touched = 1
      }
    }
    if ( $touched == 0 ) {
       my $e = $avwait_ewmas->{$resource};
       $avwait_ewmas->{$resource} =  $e - $alpha * $e;
          # Drop ewma when no activity
    }
    usleep 100000;
  }
}
```

```
# Functions

sub map_resource_consumers {
  my $map;
  foreach my $dm (keys %{$iscsi_sessions}) {
    push(@{$map->{$iscsi_sessions->{$dm}->{'vg'}}},$dm)
       ;
  }
  return $map;
}

sub grab_current_avwait {
  my $ds = "/proc/diskstats";
  open(DISKSTATS,"<",$ds)  or die "open $ds, $!";
  while (<DISKSTATS>) {
    chomp;
    s/\s+/ /g;
    my ($major, $minor, $dev, @fields ) = split(' ',$_)
       ;
    if ( $dev =~ /^dm-.+/  ) {
      my $weitime = counter($dev,"weitime",$fields[10])
         ;
      my $req = counter($dev,"r",$fields[0]) ;#+
         counter($dev,"w",$fields[4]);
      my $wait;
      if ($req > 0 ) { $wait = $weitime / $req } else {
          $wait = "nan" } ;
      $cur_wait->{$dev} = $wait;
    }
  }
  close(DISKSTATS);
  return $cur_wait;
}

sub inthandler {
  (tied $avwait_ewmas)->remove;
  exit;
}

sub counter  {
  my $obj = shift;
```

```
  my $field = shift;
  my $current_value = shift;
  my $cm;
  my $ret = "nan" ;
  if (exists($countermem->{$obj}->{$field})) {
    $cm = $countermem->{$obj}->{$field};
    if ( $cm > $current_value ) {
      $ret = ( 4294967296 - $cm) + $current_value;
    } else {
      $ret = $current_value - $cm;
    }
  }
  $countermem->{$obj}->{$field} =  $current_value;
  return $ret;
}
```

Listing C.4: Script for collecting test results

```
#!/usr/bin/perl -w
# name: get_results.pl

my @hosts = ( "b1","bm","b2","b3","b4","b5" );
my $rresultdir = "/root/results";

if ( ! exists($ARGV[0])) {
 print "Usage: $0 job-script\n";
 exit 1;
}
my $job = $ARGV[0];

my $jobdir = "/Users/jarleb/Documents/masterprog/thesis
   /results/$job";

if ( -d $jobdir ) {
 `rm -rf $jobdir ` ;
}
`mkdir -p $jobdir`;

foreach my $host (@hosts) {
 print "--- Fetching from $host ---- \n";
  `mkdir "$jobdir/$host"`;
  `scp -r "$host:$rresultdir/$job/*" "$jobdir/$host/"`;
}
```

Listing C.5: Script for distributing scripts and job definitions

```
#!/usr/bin/perl -w
# name: dist.pl

my @dist_hosts = ( "b1","b2","b3","b4","b5","bm" );
my $scriptdir = "/root/scripts";

foreach my $host (@dist_hosts) {
 print "--- Dist to $host ---- \n";
 `ssh $host mkdir -p $scriptdir`;
 `rsync --delete -avz -e ssh * "$host:$scriptdir"`;
 `ssh $host chmod +x $scriptdir/*`;
 }
```

Listing C.6: Script for scheduling jobs

```
#!/usr/bin/perl -w
# name: schedule.pl

`./dist.pl`;

my @hosts = ( "b2","b3","b4","b5" );
my $scriptdir = "/root/scripts/";

if ( ! exists($ARGV[1])  ) {
 print "Usage: $0 time[hh:mm] script\n";
 exit 1;
}

my $tm = $ARGV[0];
my $script = $ARGV[1];
$script=~/^(.+)\.sh/;
my $job=$1;
my $resultdir = "/root/results/$job";
my $runlog = "$resultdir/runlog";

print "Scheduling monitoring on b1 tcpdump\n";
`echo "$scriptdir/b1-mon.sh $job >/dev/null  2>&1" |ssh
    b1 'cat |at $tm '`;

foreach my $host (@hosts) {
 print "--- Scheduling on $host ---- \n";
 `echo "$scriptdir/$script "|ssh $host 'cat |at $tm'`;
```

```
 }

print "Scheduling monitoring on bm \n";
`echo "$scriptdir/bm-mon.sh $job " |ssh bm 'cat |at $tm
    '`;

print "scheduling shaping on bm\n" ;
`echo "$scriptdir/shaping.sh > /var/tmp/shaping_log
   2>&1" |ssh bm 'cat |at $tm'`;
```

Listing C.7: Script for binding iSCSI initiators

```
#!/usr/bin/perl -w
# name iscsi_bind.pl

if ( ! exists($ARGV[0])) {
 print "Usage: $0 start|stop\n";
 exit 1;
}

my @initiator_hosts = ( "b2","b3","b4","b5" );
my $cmd = $ARGV[0];
my $bind_script = "/root/scripts/blade_iscsi_bind.sh";
my $target_script = "/root/scripts/iscsi-target.sh";

if ($cmd eq 'start' ) {
 #&target;
 #sleep 5;
 &initators;
 exit 0;
}

if ($cmd eq 'stop' ) {
 &initators;
 #&target;
 exit 0;
}

sub initators {
 foreach my $host (@initiator_hosts) {
  print "--- Running $cmd on $host ---- \n";
  `ssh $host  'iscsiadm --mode discovery --type
     sendtargets --portal bm'`;
```

```
  `ssh $host $bind_script $cmd`;
  }
}

sub target {
 `ssh bm  $target_script $cmd`;
}
```

Listing C.8: Script for picking out the relevant data from collectd files

```
#!/usr/bin/perl -w
# tc_extract.pl

use File::Find;
use POSIX;

my @files = () ;
my %items;
my $start ;
my $end;
my @searchdirs = ( "/var/lib/collectd/csv/blademon.vlab
   .iu.hio.no/netlink-eth1/" );
my $date=`date +%Y-%m-%d`;
chomp($date);

if ( $ARGV[0] eq "showfiles" ) {
 find(\&wanted,  @searchdirs);
 foreach (keys %items) {print "$_\t-> $items{$_}\n";}
 exit 0;
}

if ( ! $ARGV[2] ) {
 usage();
 exit 1;
} elsif ( $ARGV[0] eq "showfiles" ) {
 find(\&wanted,  @searchdirs);
 foreach (keys %items) {print "$_\t-> $items{$_}\n";}
 exit 0;
}

if ( $ARGV[0] =~ m/\d{1,2}:\d{1,2}:\d{1,2}/ &&  $ARGV
   [1] =~ m/\d+/ ) {
 my $job = $ARGV[2];
```

```
 my $runlength = $ARGV[1];
 my $outdir = "/root/results/$job/tc-vectors";
`mkdir -p $outdir`;
`rm $outdir/*`;
 $start = `date +%s --date $ARGV[0]`; chomp($start);
 #$end = `date +%s --date $ARGV[0]`; chomp($end);
 $end = $start + $runlength;

 find(\&wanted,  @searchdirs);
 print localtime($start)." -> ".localtime( $end)." \n";
 foreach my $item ( keys %items  ) {
   print "Generating $item  \n";
   open F, "$items{$item}" or die "Cannot open $items{
      $item} for read: $!";
   open O, ">$outdir/$item" or die "Cannot open $outdir
      /$item for write :$!";
   my $lastval = 0;
   my $cval = 0;
   while (<F>) {
    chomp;
    next if ( ! /^\d/ );
    my @l = split(",",$_);
    if ( $l[0] >= $start && $l[0] <= $end ) {
      $cval = $l[1];
      $val = $cval - $lastval;
      if (  $val != $cval || $cval == 0 ) {
      my $plot_time = $l[0] - 978307200;
      print O "$plot_time,$val\n";
     }
     $lastval = $cval;
    }
   }
   close O;
   close F;
 }
} else { usage(); }

sub usage {
 print "Usage: $0 showfiles| HH:MM:SS runlength(s)
    jobname\n";
}

sub wanted {
```

```
 if ($File::Find::name =~ /.*\/(ipt_.+-.+:.+)-$date/) {
  $items{$1} = $File::Find::name;
 }
}
```

Listing C.9: Script for picking out iostat columns based on header names

```
#!/usr/bin/perl
# name: fix_iostat.pl

my $f = $ARGV[0];

open F, "$f" or die "Cannot open $f for read: $!";
my $header = readline(*F);
my @metrics = split(" ",$header);
shift(@metrics);
my $c = 0;
my %metrics;
my @pmetrics;

foreach (@metrics) {
 $metrics{$_} = $c;
 $c++;
}

if ( ! exists($ARGV[1]) ) {
 print "Usage: $0 blktrace_iostat_file metric.\n";
 print "Available metrics:\n";
 foreach my $metric (keys %metrics) {
  print "$metric \n";
  #print "$metric ($metrics{$metric})\n";
 }
 close F;
 exit 1;
}

$pmetrics[0] = 'Stamp';
push(@pmetrics,$ARGV[1]);

while (<F>) {
 if ( /^\(.*/ && ! /.*TOTAL.*/ ) {
  chomp;
  s/\(.+\)//;
```

```
  my @line = split(" ",$_);
  foreach my $pm (@pmetrics) {
   print "$line[$metrics{$pm}] ";
  }
  print "\n";
 }
}
close F;
```

Listing C.10: Script for binding iSCSI locally on blade server

```
#!/bin/bash
# name: blade_iscsi_bind.sh

case $1 in
 "start")
   iscsiadm --mode node --targetname iqn.iscsilab:perc_
      `hostname` bm:3260 --login
   iscsiadm --mode node --targetname iqn.iscsilab:aic_`
      hostname` bm:3260 --login
 ;;
 "stop")
   iscsiadm --mode node --targetname iqn.iscsilab:perc_
      `hostname` bm:3260 --logout
   iscsiadm --mode node --targetname iqn.iscsilab:aic_`
      hostname` bm:3260 --logout
 ;;
 *)
  echo "Usage $0 start|stop"
 ;;
esac
```

Listing C.11: Script for generating separate files for Plot

```
#!/bin/bash
# name: generate_plotdata.sh

metrics=( wkB/s rkB/s r/s w/s await svctm %util avgrq-
   sz wrqm/s rrqm/s wsec/s avgqu-sz rsec/s )
resultdir="/Users/jarleb/Documents/masterprog/thesis/
   results/";
iostatfile="blkt_iostat";
plotdatadir="/Users/jarleb/Documents/masterprog/thesis/
   plotdata";
```

```
mkdir -p ${plotdatadir}

for jobdir in `ls ${resultdir}`
do
 if [[ -d ${plotdatadir}/${jobdir} ]]
 then
  rm -rf  ${plotdatadir}/${jobdir}
 fi
 mkdir -p  ${plotdatadir}/${jobdir}
 for bladedir in `ls "${resultdir}/${jobdir}"`
 do
  if [[ -f ${resultdir}/${jobdir}/${bladedir}/${
     iostatfile} ]]
  then
    if [[ -d ${plotdatadir}/${jobdir}/${bladedir} ]]
    then
     rm -rf  ${plotdatadir}/${jobdir}/${bladedir}
    fi
    mkdir -p  ${plotdatadir}/${jobdir}/${bladedir}
    for metric in  ${metrics[*]}
    do
      outmetric=`echo $metric|sed 's|/|_pr_|g'`
     `pwd`/fix_iostat.pl ${resultdir}/${jobdir}/${
       bladedir}/${iostatfile} ${metric} > ${
       plotdatadir}/${jobdir}/${bladedir}/${outmetric}
    done
  fi
 done
done
echo "remember dstat and tc data in results dir"
```

Listing C.12: Post processing script for target server

```
#!/bin/bash
# name: postproc.sh


if [[ -z $1 ]]
then
 echo "Usage: $0 jobname"
 exit 1
fi
```

```
exec &> /root/results/$1/pp-log
echo "-----`date`-----"
echo "Killing dstat and collectl"
pkill -f "dstat --noheaders"
pkill collectl

echo "Copying script versions for this run"
cp -r /root/scripts /root/results/$1

/root/scripts/tc-graph.pl >  /root/results/$1/tc-graph.
   dot

jobstart=$(grep 'Monitoring started' /root/results/job2
   /runlog |awk '{print $6}')
jobstart_epoch=`date -d ${jobstart} +%s`
period=$((`date +%s`-${jobstart_epoch}))
/root/scripts/tc_extract.pl ${jobstart} ${period} $1
sync
sleep 3
cat  /root/results/$1/runlog  /root/results/$1/pp-log|/
   root/scripts/sendmail.pl  $1
```

Listing C.13: Monitor script for target server

```
#!/bin/bash
# bm-mon.sh


if [[ -z $1 ]]
then
echo "Usage: $0 jobname"
exit 1
fi
rm  /var/lib/collectd/csv/blademon.vlab.iu.hio.no/
   netlink-eth1/*
/etc/init.d/collectd restart

dir="/root/results/$1"
if [[ -d $dir ]]
then
rm -rf $dir
fi
mkdir -p ${dir}
```

```
exec &> ${dir}/runlog
echo "Monitoring started `date `------"
echo "starting collectl "
collectl -s nNdDtTcCmyjJ -f$dir &
echo "Starting dstat with output to $dir/dstat.csv"

dstat --noheaders -tdnmc -D total,dm-0,dm-1,dm-2,dm-3,
   sdb,sdc,sdd,sde,sdf,sdg,sdh,sdj,sdi,sdk -N eth1 --
   sys -s -T --output ${dir}/dstat.csv > /dev/null 2>&1
     &
```

Listing C.14: Monitor script to b1 (argus)

```
#!/bin/bash
# name: b1-mon.sh

results="/root/results/"
job=$1
tcpdump_file="${results}/${job}/argus.bin"


if [[ -d ${results}/${job} ]]
then
 rm -rf ${results}/${job}
fi
mkdir -p "${results}/${job}"
exec &> /root/results/${job}/runlog
argus -S 1 -i eth1 -w ${tcpdump_file}
```

Listing C.15: Job template script

```
#!/bin/bash


starttime=`date`
#date=`/bin/date +%Y%m%d-%H%M-%S`;
jobdefs="/root/scripts/jobdefs/"
job=`basename $0 .sh`
results="/root/results/"
blktrace_prefix="iscsi_0.trace"
blkparse_binfile="iscsi_0.bin"
blktrace_devices="/dev/iscsi_0"
blktrace_iostat_file="blkt_iostat"
blktrace_q2c_lat_prefix="blkt_q2c"
```

```
blktrace_qd_prefix="blkt_qdepth"
runlog="runlog"

if [[ -d ${results}/${job} ]]
then
 rm -rf ${results}/${job}
fi
mkdir -p "${results}/${job}"
exec &> "${results}/${job}/${runlog}"
cd ${results}/${job}
echo "Started job1 on ${starttime}"
if [[ -f ${jobdefs}${job}_$(hostname) ]]
then
echo "Running blktrace on ${blktrace_devices}"
blktrace -o ${blktrace_prefix} ${blktrace_devices} &
blkpid=$!

echo "Copying fio config file"
cp ${jobdefs}/${job}_`hostname` ${results}/${job}/
   fio_jobdef
echo "Starting collectl"
collectl -s nNdDtTcCmyjJ -f${results}/${job}/ &
echo "Running /usr/bin/time -f %e /usr/local/bin/fio --
   minimal --output ${results}/${job}/fio.out ${jobdefs
   }${job}_`hostname`"

echo "Elapsed: `/usr/bin/time -f %e /usr/local/bin/fio
   --minimal --output ${results}/${job}/fio.out ${
   jobdefs}${job}_$(hostname) 2>&1` "
kill $blkpid
if [[ $? -eq 0 ]]
then
 echo "Successfully killed blktrace pid: ${blkpid}"
else
 echo "Failed to kill blktrace pid: ${blkpid}"
fi

echo "Running /usr/bin/blkparse -i ${results}/${job}/${
   blktrace_prefix} -d ${blkparse_binfile} --no-text"
/usr/bin/blkparse -i ${results}/${job}/${
   blktrace_prefix} -d ${blkparse_binfile} --no-text
echo "Running btt -i ${blkparse_binfile} -S 1 -I ${
   blktrace_iostat_file}"
```

```
btt -i ${blkparse_binfile} -S 1 -I ${
   blktrace_iostat_file} > /dev/null
echo "Running btt -i ${blkparse_binfile} -q ${
   blktrace_q2c_lat_prefix}"
btt -i ${blkparse_binfile} -q ${blktrace_q2c_lat_prefix
   }  > /dev/null
echo "Running btt -i ${blkparse_binfile} -Q ${
   blktrace_qd_prefix}"
btt -i ${blkparse_binfile} -Q ${blktrace_qd_prefix} > /
   dev/null
echo "Creating btrecord files"
mkdir btrecord
btrecord  -D btrecord  ${blktrace_prefix}
echo "Deleting blktrace and blkparse files for space
   conservation"
rm ${blkparse_binfile}
rm ${blktrace_prefix}*
pkill collectl
echo "Ended job1 on `date`"
else
 echo "No jobfile, not running any fio job"
fi

if [[ `hostname` == "b2" ]]
then
 while true
 do
 f=""
 for b in b3 b4 b5
  do
   f=${f}`ssh $b pgrep $job`
  done
  echo "-- `date` contents of f=$f"
  if [[ -z ${f} ]]
  then
   break
  fi
  sleep 5
 done
 echo "-- `date` running postproc on bm"
 ssh -p 5432 bm  "/root/scripts/postproc.sh ${job} "
 ssh b1 "pkill argus;gzip /root/results/${job}/argus.
    bin"
```

```
fi
```

Listing C.16: Mathematica code for finding the best moving average algorithm in Figure 4.3

```
(* Import the vector representing the real AVWAIT
   logged during experiment*)
(* This is the raw data that will be tested for the
   best sliding average algoritmh. *)

v = Flatten[Import["/Users/jarleb/Documents/masterprog/
   thesis/results/jb-AVWAIT-comp/bm/v_wait", "Table"]];

(* Generate a plot of the raw data and store it in a
   variable*)

a = ListPlot[v, PlotJoined -> True];

(* Function for prepending the vector with the same
   amount of elements as the moving median reduces it
   with when window size increases.*)
(* This is done to avoid time shifting of the moving
   median graph when stacked on top of the real data
   and the EWMA*)

tr[{elem_, num_}] := Table[elem, {num}]

(* A slider for moving median window size (integers) *)

Slider[Dynamic[r], {2, 20, 1}]

(* Slider for ewma alpha parameter*)

Slider[Dynamic[alpha], {0.0001, 1}]

(* Dynamic plot with the three grahs stacked on top of
   each other *)

Dynamic[Show[a,ListPlot[ExponentialMovingAverage[v,
   alpha], PlotJoined -> True,PlotStyle -> {RGBColor[1,
    0, 0], Thick}],ListPlot[MovingMedian[Join[tr[{0, av
   }], v], av], PlotJoined -> True,PlotStyle -> {
   RGBColor[0, 2, 0], Thick}]]]
```

Appendix D

Collection of fio job definitions

Listing D.1: Fio job definition run from script 5.4

```
[global]
rw=read
#rw=write
size=200m

blocksize=64k
direct=1
ioengine=sync
write_lat_log
write_bw_log
[job1-1]
filename=/dev/iscsi_1
;
```

Listing D.2: Fio job definition for the small job described in 5.5

```
[global]
rw=randread
size=128m

blocksize=8k
ioengine=sync
rate=256k
write_lat_log
direct=1
[job1-1]
filename=/dev/iscsi_0
```

```
;
```

Listing D.3: Fio job definition for the interference job described in 5.5

```
[global]
size=2048m
rw=write

blocksize=64k
ioengine=sync
direct=1
[job1]
filename=/dev/iscsi_0
;
```

Listing D.4: `fio` job definition for load generated in figures 5.1 and 5.2

```
[global]
rw=read
size=2048m

blocksize=32k
direct=1
ioengine=sync
write_lat_log
write_bw_log
[job1-1]
filename=/dev/iscsi_0
;
```

Listing D.5: `fio` job definition for load generated in figures 5.4 and 5.3

```
[global]
size=2048m
rw=write

blocksize=64k
ioengine=sync
direct=1
write_lat_log
write_bw_log
[job1-1]
filename=/dev/iscsi_0
;
```

Appendix E

Collection of commands

Listing E.1: R commands used to create figures 5.5 and 5.6

```
library(sciplot)
t=read.table(r)
bargraph.CI(V1,V2,data=t,xlab="Introduced delay (ms)",
   ylab="Time to read 200MB of data (s)",err.width
   =0.05)
```

Listing E.2: R commands used to identify overhead introduced by tc packet checking

```
> no_tc_r=read.table("no_tc_read.out")
> w_tc_r=read.table("with_tc_read.out")
> w_tc_w=read.table("with_tc_write.out")
> no_tc_w=read.table("no_tc_write.out")

> read=t.test(w_tc_r,no_tc_r,conf.level=0.99)
> write=t.test(w_tc_w,no_tc_w,conf.level=0.99)
> round(c(read$conf.int[1],read$estimate[1]-
   read$estimate[2],read$conf.int[2],read$estimate[1],
   read$estimate[2]),3)
          mean of x           mean of x mean of y
    0.011     0.023     0.035     7.210     7.188
> round(c(write$conf.int[1],write$estimate[1]-
   write$estimate[2],write$conf.int[2],write$estimate
   [1],write$estimate[2]),3)
          mean of x           mean of x mean of y
    0.069     0.112     0.155     8.843     8.731
>
```

```
>
```

Listing E.3: Commands used to check for packet loss logged on the host side in experiment 5.5 and 5.6

```
jarleb@rubeus b2 $ pwd
/Users/jarleb/Documents/masterprog/thesis/results/dfunc
   -write/b2
jarleb@rubeus b2 $ cat lossfish.pl
#!/usr/bin/perl -w

while (<> ) {
 next if /^#/;
 chomp;
 s/\s+/ /g;
 my @l = split;
 print "$l[0] $l[1] $l[4] \n" if $l[4] != 0;
}
jarleb@rubeus b2 $
jarleb@rubeus b2 $ collectl -p collectl-b2
   -20100413-211521.raw -s t -oT --thru 20100414:03:00
   --plot|./lossfish.pl
jarleb@rubeus bm $ cd ../bm
jarleb@rubeus bm $ collectl -p collectl-blademon
   -20100413-211329.raw.gz -s t -oT --thru
   20100414:03:00 --plot|../b2/lossfish.pl
jarleb@rubeus b2 $ cd ../../dfunc-read/b2
jarleb@rubeus b2 $ collectl -p collectl-b2
   -20100412-162129.raw.gz -s t -oT --thru
   20100412:19:40:00 --plot|../../dfunc-write/b2/
   lossfish.pl
jarleb@rubeus b2 $
jarleb@rubeus bm $ collectl -p collectl-blademon
   -20100412-162357.raw.gz -s t -oT --thru
   20100412:19:40:00 --plot |../../dfunc-write/b2/
   lossfish.pl
jarleb@rubeus bm $
```

Listing E.4: Commands used to generate argus plots in figure 3.5

```
jarleb@rubeus b1 $ra -r argus.bin.gz -u -n -s stime,
   ltime,saddr,sport,daddr,dport,spkts,dpkts,sload,
   dload - dst port 3260 and src 10.0.0.242 and  src
   port 36966|./plot.pl > plots/b2
```

```
jarleb@rubeus b1 $ra -r argus.bin.gz -u -n -s stime,
   ltime,saddr,sport,daddr,dport,spkts,dpkts,sload,
   dload - dst port 3260 and src 10.0.0.243 and src
   port 52209|./plot.pl > plots/b3
jarleb@rubeus b1 $ra -r argus.bin.gz -u -n -s stime,
   ltime,saddr,sport,daddr,dport,spkts,dpkts,sload,
   dload - dst port 3260 and src 10.0.0.244  and src
   port 46645|./plot.pl > plots/b4
jarleb@rubeus b1 $ra -r argus.bin.gz -u -n -s stime,
   ltime,saddr,sport,daddr,dport,spkts,dpkts,sload,
   dload - dst port 3260 and src 10.0.0.245  and src
   port 51901|./plot.pl > plots/b5
jarleb@rubeus b1 $
jarleb@rubeus b1 $ pwd
/Users/jarleb/Documents/masterprog/thesis/results/
   seqread-delay-shape/b1
jarleb@rubeus b1 $
jarleb@rubeus b1 $ cat plot.pl
#!/usr/bin/perl -w

my $divisor = ( 1024*8 );
my $column = 7 ;
my $starttime;

while (<>) {
 chomp;
 s/\s+/ /g;
 my @l = split ;
 if ( $. == 1 ) { $starttime = $l[0]; }
 my $reltime = $l[0] - $starttime;
 my $v = $l[$column] / $divisor ;
 print "$reltime $v\n";
}
jarleb@rubeus b1 $
```

Listing E.5: Commands used to generate logical volume plots in figure 3.5

```
jarleb@rubeus bm $ collectl -p blademon
   -20100324-194803.raw.gz -s D -oT -oD |grep dm-0 |./
   plot.pl > plots/b2
jarleb@rubeus bm $ collectl -p blademon
   -20100324-194803.raw.gz -s D -oT -oD |grep dm-1 |./
   plot.pl > plots/b3
```

```
jarleb@rubeus bm $ collectl -p blademon
   -20100324-194803.raw.gz -s D -oT -oD |grep dm-2 |./
   plot.pl > plots/b4
jarleb@rubeus bm $ collectl -p blademon
   -20100324-194803.raw.gz -s D -oT -oD |grep dm-3 |./
   plot.pl > plots/b5
jarleb@rubeus bm $
jarleb@rubeus bm $ pwd
/Users/jarleb/Documents/masterprog/thesis/results/
   seqread-delay-shape/bm
jarleb@rubeus bm $
jarleb@rubeus bm $ cat plot.pl
#!/usr/bin/perl

use Date::Parse;
my $starttime;

while (<>) {
 chomp;
 s/\s+/ /g;
 @l = split;
 my $timestr = "$l[0] $l[1]";
 my $time = str2time($timestr);
 if ($. == 1 ) { $starttime = $time ; }
 my $reltime = $time - $starttime;
 print $reltime." $l[3]\n";
}
jarleb@rubeus bm $
```

Listing E.6: RTO min value from /proc/net/snmp

```
[root@blademon scripts]# cat /proc/net/snmp|grep ^Tcp |
   awk '{print $3}'
RtoMin
200
[root@blademon scripts]#
```

Listing E.7: Aggregated amount of lost or retransmitted packets during traffic shaping using artificial delay of ACK packets as shown in figure 5.4

```
jarleb@rubeus b1 $ pwd
/Users/jarleb/Documents/masterprog/thesis/results/
   seqwrite-delay-shape/b1
```

```
jarleb@rubeus b1 $ racluster -m saddr -r argus.bin.gz -
   s saddr  loss
                10.0.0.242          0
                10.0.0.243          0
                10.0.0.244          0
                10.0.0.245          0
                10.0.0.253          0
                10.0.0.254          0
                10.0.0.200          0
                10.0.0.242          0
                10.0.0.253          0
jarleb@rubeus b1 $
```

Listing E.8: Aggregated amount of lost or retransmitted packets during traffic shaping using artificial delay of ACK data packets as shown in figure 5.3

```
jarleb@rubeus b1 $ pwd
/Users/jarleb/Documents/masterprog/thesis/results/
   seqread-delay-shape/b1
jarleb@rubeus b1 $ racluster -m saddr -r argus.bin.gz -
   s saddr  loss
        10.0.0.242          0
        10.0.0.243          0
        10.0.0.244          0
        10.0.0.245          0
        10.0.0.253          0
        10.0.0.200          0
        10.0.0.242          0
        10.0.0.253          0
jarleb@rubeus b1 $
```

Listing E.9: Implementation of RTO_MIN in Linux 2.6

```
<snip  of linux/include/net/tcp.h>
#define TCP_RTO_MIN     ((unsigned)(HZ/5))
</snip>

<snip of linux/include/asm-x86/param.h>
# define HZ             CONFIG_HZ
</snip>

And since CONFIG_HZ is 1000 by default in 2.6,
   TCP_RTO_MIN is 200 ms
```