Are Disks the Dominant Contributor for Storage Failures? A Comprehensive Study of Storage Subsystem Failure Characteristics

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Building reliable storage systems becomes increasingly challenging as the complexity of modern storage systems continues to grow. Understanding storage failure characteristics is crucially important for designing and building a reliable storage system. While several recent studies have been conducted on understanding storage failures, almost all of them focus on the failure characteristics of one component—disks—and do not study other storage component failures.

This article analyzes the failure characteristics of storage subsystems. More specifically, we analyzed the storage logs collected from about 39,000 storage systems commercially deployed at various customer sites. The dataset covers a period of 44 months and includes about 1,800,000 disks hosted in about 155,000 storage-shelf enclosures. Our study reveals many interesting findings, providing useful guidelines for designing reliable storage systems. Some of our major findings include: (1) In addition to disk failures that contribute to 20–55% of storage subsystem failures, other components such as physical interconnects and protocol stacks also account for a significant percentage of storage subsystem failures. (2) Each individual storage subsystem failure type, and storage subsystem failure as a whole, exhibits strong self-correlations. In addition, these failures exhibit "bursty" patterns. (3) Storage subsystems configured with redundant interconnects experience 30–40% lower failure rates than those with a single interconnect. (4) Spanning disks of a RAID group across multiple shelves provides a more resilient solution for storage subsystems than within a single shelf.

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1. INTRODUCTION

1.1 Motivation

Reliability is a critically important issue for storage systems because storage failures can not only cause service downtime, but also lead to data loss. Building reliable storage systems becomes increasingly challenging as the complexity of modern storage systems grows into an unprecedented level. For example, the EMC™ Symmetrix DMX-4 can be configured with up to 2400 disks [EMC 2007], the Google™ File System cluster is composed of 1000 storage nodes [Ghemawat et al. 2003], and the NetApp® FAS6000 series can support more than 1000 disks per node, with up to 24 nodes in a system [NetApp 2008].

To make things even worse, disks are not the only component in storage systems. To connect and access disks, modern storage systems also contain many other components, including shelf enclosures, cables, and host adapters, as well as complex software protocol stacks. Failures in these components can lead to downtime and/or data loss of the storage system. Hence, in complex storage systems, component failures are very common and critical to storage system reliability.

To design and build a reliable storage system, it is crucially important to understand the storage failure characteristics. First, accurate estimation of storage failure rate can help system designers decide how many resources should be used to tolerate failures and to meet certain service-level agreement (SLA) metrics (e.g., data availability). Second, knowledge about factors that greatly impact the storage system reliability can guide designers to select more reliable components or build redundancy into unreliable components. Third, understanding the statistical properties such as failure distribution over time of modern storage systems is necessary to build right testbed and fault injection models to evaluate existing resiliency mechanisms and to develop better fault-tolerant mechanisms.

While several recent studies have been conducted on understanding storage failures, almost all have focused on the failure characteristics of one storage component: disks. For example, disk vendors have studied the disk failure characteristics through running accelerated life tests and collecting statistics from their return unit databases [Cole 2000; Yang and Sun 1999]. Based on such tests, they calculate the *mean-time-to-failure (MTTF)* and record it in a disk specification. For most of the disks, the specified MTTF is typically more than one million hours, equivalent to a lower than 1% *annualized failure rate (AFR)*. But such low AFR is usually not what has been experienced by users. Motivated from this observation, recently some researchers have studied *disk failures* from a user's perspective by analyzing disk replacement logs collected in the field [Pinheiro et al. 2007; Schroeder and Gibson 2007]. Interestingly, they found disks are replaced much more frequently (2–4 times) than vendor-specified AFRs. But as this study indicates, there are other storage subsystem failures besides disk failures that are treated as disk faults and lead to unnecessary disk replacements. Additionally, some researchers analyzed the characteristics of disk sector errors, which can potentially lead to complete disk failures [Bairavasundaram et al. 2007], and they found that sector errors exhibit strong temporal locality (i.e., bursty patterns).

While previous works provide very good understanding of disk failures and an inspiring starting point, it is not enough since, besides disks, there are many other components that may contribute to storage failures. Without a good understanding of these components' failure rates, failure distributions, and other characteristics, as well as the impact of these component failures on the storage system, our estimation of the storage failure rate/distribution may be inaccurate. For example, as we will show in our study from real-world field data, having a lower disk failure rate does not necessarily mean that the corresponding storage system is more reliable because some other components may not be as reliable.

More importantly, if we only focus on disk failures and ignore other component failures, we may fail to build a highly reliable storage system. For example, RAID is usually the only resiliency mechanism built into most modern storage systems (various forms of checksumming are considered as part of RAID). As RAID is mainly designed to tolerate disk failures, it is insufficient to handle other component failures such as failures in shelf enclosures, interconnects, and software protocol layers.

While we are interested in failures of a whole storage system, this study is concentrated on the core part of it: *the storage subsystem*, which contains disks and all components providing connectivity and usage of disks to the entire storage system.

We conducted a study using real-world field data from Network Appliance™ AutoSupport Database, to answer the following questions.

— How much do disk failures contribute to storage subsystem failures? What are other major factors that can lead to storage subsystem failures?
— What are the failure rates of other types of storage subsystem components such as physical interconnects and protocol stacks? What are the failure characteristics such as failure distribution and failure correlation for these components?
— Typically, some resiliency mechanisms, such as RAID, and redundancy mechanisms, such as multipathing, are used in practice to achieve high reliability

and availability [Corbett et al. 2004; Ghemawat et al. 2003]. How effective are these mechanisms in handling storage subsystem failures?

Data from the same AutoSupport Database was first analyzed in Bairavasundaram et al. [2007] on latent sector errors and was further analyzed in Bairavasundaram et al. [2008] on data corruptions.

There are other redundancy and resiliency mechanisms in storage system layers higher than the storage subsystem and RAID-based resiliency mechanism studied in this article. These mechanisms handle some of the storage subsystem failures. Studying the impacts of these resiliency and redundancy mechanisms on storage failures, including storage subsystem failures, is part of the future work.

1.2 Our Contributions

This article analyzes the failure characteristics of storage subsystems, including disks and other system components, based on a significant amount of field data collected from customers. Specifically, we analyzed the storage logs collected from about 39,000 storage systems commercially deployed at various customer sites. The dataset covers a period of 44 months and includes about 1,800,000 disks hosted in about 155,000 storage-shelf enclosures. Furthermore, our data covers a wide range of storage system classes, including *near-line (backup)*, *low-end*, *mid-range*, and *high-end* systems.

This article studies failure characteristics from several angles. First, we classify storage subsystem failures into four failure types based on their symptoms and root causes and examine the relative frequency of each failure type. Second, we study the effect of several factors on storage subsystem reliability. These factors include disk models, shelf enclosure models, and network redundancy mechanisms. Finally, we analyze the statistical properties of storage subsystem failures, including the correlation between failures and their time distribution.

Our study reveals many interesting findings, providing a useful guideline for designing reliable storage systems. Following is a summary of our major findings and the corresponding implications.

— In addition to disk failures that contribute to 20–55% of storage subsystem failures, other components such as physical interconnects (including shelf enclosures) and protocol stacks also account for significant percentages (27–68% and 5–10%, respectively) of failures. Due to these component failures, even though storage systems of certain types (e.g., low-end primary systems) use more reliable disks than some other types (e.g., near-line backup systems), their storage subsystems exhibit higher failure rates. These results indicate that, to build highly reliable and available storage systems, only using resiliency mechanisms targeting disk failures (e.g., RAID) is not enough. We also need to build resiliency mechanisms, such as redundant physical interconnects and self-checking protocol stacks, to tolerate failures in these storage components.
— Each individual storage subsystem failure type, and storage subsystem failure as a whole, exhibit, strong correlations (i.e. after one failure, the

probability of additional failures of the same type is higher). In addition, failures also exhibit bursty patterns in time distribution (i.e. multiple failures of the same type tend to happen relatively close together). These results motivate a revisiting of current resiliency mechanisms such as RAID that assume independent failures. These results also motivate development of better resiliency mechanisms that can tolerate multiple correlated failures and bursty failure behaviors.

—Storage subsystems configured with two independent interconnects experienced much (30–40%) lower AFRs than those with a single interconnect. This result indicates the importance of interconnect redundancy in the design of reliable storage systems.

—RAID groups built with disks spanning multiple shelf enclosures show much less bursty failure patterns than those built with disks from the same shelf enclosure. This indicates that the former is a more resilient solution for large storage systems.

The rest of the article is organized as follows. Section 2 provides the background and describes our methodology. Section 3 presents the contribution of disk failures to storage subsystem failures and frequency of other types of storage subsystem failures. Section 4 quantitatively analyzes the effects of several factors on storage subsystem reliability, while Section 5 analyzes the statistical properties of storage subsystem failures. Section 6 discusses the related work, and Section 7 concludes the article and provides directions for future work.

2. BACKGROUND AND METHODOLOGY

In this section, we detail the typical architecture of storage systems, the definition and terminology used in this article, and the source of the data studied in this work.

2.1 Storage System Architecture

Figure 1 shows the typical architecture of a modern storage system.

From the customers' perspective, a storage system is a virtual device that is attached to customers' systems and provides customers with the desired storage capacity with high reliability, good performance, and flexible management.

Looking from inside, a storage system is composed of storage subsystems, resiliency mechanisms, a storage head/controller, and other higher-level system layers. The storage subsystem is the core part of a storage system and provides connectivity and usage of disks to the entire storage system. It contains various components, including disks, shelf enclosures, cables, and host adapters, and complex software protocol stacks. Shelf enclosures provide power supply, cooling service, and prewired backplane for the disks mounted in them. Cables initiated from host adapters connect one or multiple shelf enclosures to the network. Each shelf enclosure can be optionally connected to a secondary network for redundancy. In Section 4.3 we will show the impact of this redundancy mechanism on failures of the storage subsystem.

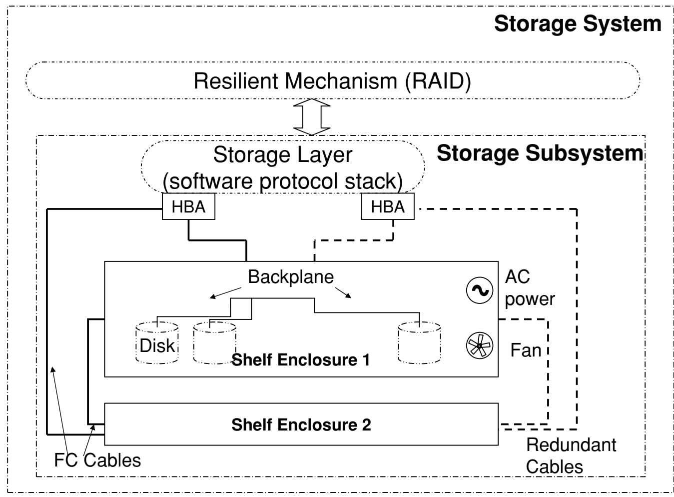


Fig. 1. Storage system architecture.

Usually, on top of the storage subsystem, resiliency mechanisms, such as RAID, are used to tolerate failures in storage subsystems.

2.2 Terminology

We use the followings terms in this article.

—*Disk family*: a particular disk product. The same product may be offered in different capacities. For example, “Seagate Cheetah 10k.7” is a disk family.

—*Disk model* the combination of a disk family and a particular disk capacity. For example, “Seagate Cheetah 10k.7 300GB” is a disk model. For disk family and disk model, we use the same naming convention as in Bairavasundaram et al. [2008, 2007].

—*Failure types*: refers to the four types of storage subsystem failure: disk failure, physical interconnect failure, protocol failure, and performance failure.

—*Shelf enclosure model* a particular shelf enclosure product. All shelf enclosure models studied in this article can host at most 14 disks.

—*Storage subsystem failure*: refers to failures that prevent the storage subsystem from providing storage service to the whole storage system. However, not all storage subsystem failures are experienced by customers, since some of the failures can be handled by resiliency mechanisms on top of storage subsystems (e.g. RAID) and other mechanisms at higher layers.

—*Storage system class*: refers to the capability and usage of storage systems. There are four storage system classes studied in this article: near-line systems (mainly used as secondary storage), low-end, mid-range, and high-end (mainly used as primary storage).

—Other terms in the article are used as defined by SNIA [2008].

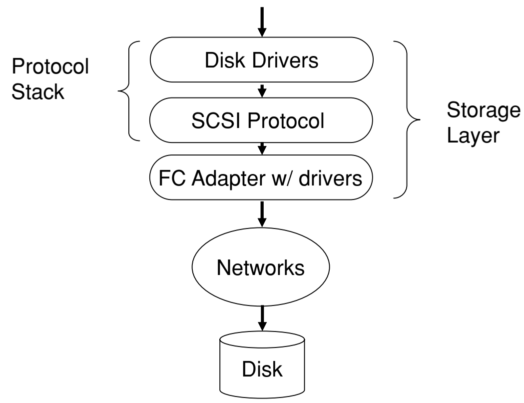


Fig. 2. I/O request path in storage subsystem.

2.3 Definition and Classification of Storage Subsystem Failures

Figure 2 shows the steps and components that are involved in fulfilling an I/O request in a storage subsystem. As shown in Figure 2, for the storage layer to fulfill an I/O request, the I/O request will first be processed and transformed by protocols and then delivered to disks through networks initiated by host adapters. *Storage subsystem failures* are the failures that break the I/O request path, and can be caused by hardware failures, software bugs, and protocol incompatibilities along the path.

To better understand storage subsystem failures, we partition them into four categories along the I/O request path. These are next described.

—*Disk Failure*. This type of failure is triggered by failure mechanisms of disks. Imperfect media, media scratches caused by loose particles, rotational vibration, and many other factors internal to a disk can lead to this type of failure. Sometimes, the storage layer proactively fails disks based on statistics collected by on-disk health monitoring mechanisms (e.g., a disk has experienced too many sector errors [Allen 2004]; such incidences are also counted as *disk failures*).

—*Physical Interconnect Failure*. This type of failure is triggered by errors in the networks connecting disks and storage heads. It can be caused by host adapter failures, broken cables, shelf-enclosure power outage, shelf backplanes errors, and/or errors in shelf FC drivers. When *physical interconnect failures* happen, affected disks appear to be missing from the system.

—*Protocol Failure*. This type of failure is caused by incompatibility between protocols in disk drivers or shelf enclosures and storage heads and software bugs in the disk drivers. When this type of failure happens, disks are visible to the storage layer but I/O requests are not correctly responded by disks.

—*Performance Failure*. This type of failure happens when the storage layer detects that a disk cannot serve I/O requests in a timely manner while none of previous three types of failure is detected. It is mainly caused by partial failures, such as unstable connectivity or when disks are heavily loaded with disk-level recovery (e.g., broken sector remapping).

The occurrences of these four types of failures are recorded in logs collected by Network Appliance.

2.4 Data Sources

Table I provides an overview of the data used in this study. Support logs from about 39,000 commercially deployed storage systems in four system classes are used for the results presented in this article. There are in total about 1,800,000 disks mounted in 155,000 shelf enclosures. The disks are a combination of SATA and FC disks. The population of disks contains at least 9 disk families and 15 disk models. The storage logs used for this study were collected between January 2004 and August 2007.

In the following we describe each storage system class.

Near-line systems are deployed as cost-efficient archival or backup storage systems. Less expensive SATA disks are used in near-line systems. In near-line systems, one storage subsystem on average contains about 7 shelf enclosures and 98 disks. Both RAID4 and RAID6 are supported as resiliency mechanisms in near-line systems.

Primary storage systems, including low-, mid-, and high-end systems, are mainly used in mission- or business-critical environments and primarily use FC disks. Low-end storage systems have embedded storage heads with shelf enclosures, but external shelf enclosures can be added. Mid-range and high-end systems use external shelves and are usually configured with more shelf enclosures and disks than are low-end systems. Each mid-range system has about 7 shelf enclosures and 80 disks (not every shelf is fully utilized and configured with 14 disks), and high-end systems are in similar scale. Going from low- to high-end systems, more reliable components and more redundancy mechanisms are used. For example, both mid-range and high-end systems support dual paths for redundant connectivity.

2.5 Support Logs and Analysis

The storage systems studied in this article have a low-overhead logging mechanism that automatically records informational and error events on each layer (software and hardware) and each subsystem during operation. Several recent works such as Bairavasundaram et al. [2007, 2008] also studied the same set of storage logs from different aspects.

Figure 3 shows a log example that reports a physical interconnect failure. As can be seen in the figure, when a failure happens, multiple events are generated as the failure propagates from lower layers to higher layers (fiber channel to SCSI to RAID). By keeping track of events generated by lower layers, higher layers can identify the cause of events and tag these events with corresponding failure types. In this example, the RAID layer, which is right above the storage subsystem, generates a disk missing event, indicating a physical interconnect failure. In this article, we look at four types of events generated by the RAID layer, corresponding to four categories of storage subsystem failures.

Table I. Overview of Studied Storage Systems

System Classes	Duration	# Systems	# Shelves	Multipathing	# Disks	Disk Types	# RAID Groups	RAID Types	# Failure Types	# Failure Events
Near-line (Backup)	1/04 - 8/07	4,927	33,681	single path	520,776	SATA	67,227	RAID4	Disk Failure	10,105
									Physical Inter. Failure	4,888
									Protocol Failure	1,819
									Performance Failure	1,080
Low-end	1/04 - 8/07	22,031	37,260	single-path	264,983	FC	44,252	RAID4	Disk Failure	3,230
								RAID6	Physical Inter. Failure	4,338
									Protocol Failure	1,021
									Performance Failure	1,235
Mid-range	1/04 - 8/07	7,154	52,621	single-path	578,980	FC	77,831	RAID4	Disk Failure	8,989
				dual-path				RAID6	Physical Inter. Failure	7,949
									Protocol Failure	2,298
									Performance Failure	2,060
High-end	1/04 - 8/07	5,003	33,428	single-path	454,684	FC	49,555	RAID4	Disk Failure	8,240
				dual-path				RAID6	Physical Inter. Failure	7,395
									Protocol Failure	1,576
									Performance Failure	153

Note that the “# Disks” column given in the table is the number of disks that have ever been installed in the system during the 44 months. For some systems, disks have been replaced during the period, and we account for this in our analysis by calculating the lifetime of each individual disk. The “# Failure Events” column is the number of the four types of storage subsystem failures (disk failure, physical interconnect failure, protocol failure, and performance failure) that happened during the period.

- Sun Jul 23 05:43:36 PDT [fci.device.timeout:error]: Adapter 8 encountered a device timeout on device 8.24
- Sun Jul 23 05:43:50 PDT [fci.adapter.reset:info]: Resetting Fibre Channel adapter 8.
- Sun Jul 23 05:43:50 PDT [scsi.cmd.abortedByHost:error]: Device 8.24: Command aborted by host adapter:
- Sun Jul 23 05:44:12 PDT [scsi.cmd.selectionTimeout:error]: Device 8.24: Adapter/target error: Targeted device did not respond to requested I/O. I/O will be retried.
- Sun Jul 23 05:44:22 PDT [scsi.cmd.noMorePaths:error]: Device 8.24: No more paths to device. All retries have failed.
- Sun Jul 23 05:46:22 PDT [raid.config.filesystem.disk.missing:info]: File system Disk 8.24 S/N [3EL03PAV00007111LR8W] is missing.

Fig. 3. Example of a piece of log reporting a physical interconnect failure.

Besides the events shown in the example, there are many other events recorded in the logs. For example, standard error reports from the SCSI protocol layer tell us what failure mechanisms happen inside disks [Shah and Elerath 2005]. Disk medium error messages from disk drivers provide information about broken sectors [Bairavasundaram et al. 2007]. Similarly, messages from FC protocol and FC host adapter drivers report errors that occur in FC networks and FC adapters.

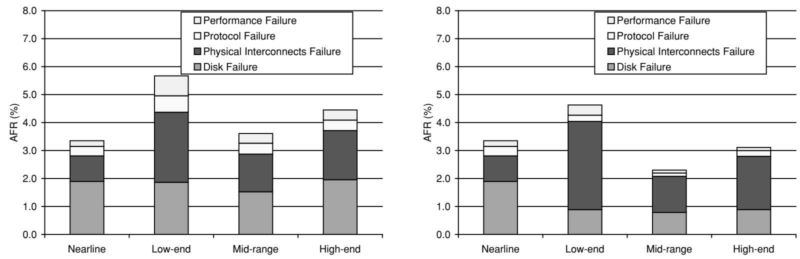
It is important to notice that not all failures propagate to the RAID layer, as some failures are recovered or tolerated by storage subsystems. For example, an interconnect failure can be recovered through retries at SCSI layer or may be tolerated through multipathing. Therefore, storage failures characterized as storage subsystem failure as a whole are those errors exposed by storage subsystems to the rest of the system.

As Figure 3 shows, each event is tagged with the timestamps when the failure is detected and with the ID of the disk affected by the failure. Since all the storage systems studied in this work periodically send data verification requests to all disks as a proactive method to detect failures, the lag between occurrence and detection of the failure is usually shorter than an hour.

System information is also copied with snapshots and recorded in storage logs on a weekly basis. This information is particularly important for understanding storage subsystem reliability, since it provides insight into the system parameters of storage subsystems. More specifically, storage logs contain information about hardware components used in storage subsystems, such as disk models and shelf enclosure models, and they also contain the information about the layout of disks, such as which are mounted in the same shelf enclosures, and which are in the same RAID group. This information is used for analyzing statistical properties of storage subsystem failures in Section 5.

3. FREQUENCY OF STORAGE SUBSYSTEM FAILURES

As we categorize storage subsystem failures into four failure types based on their root causes, a natural question is therefore what the relative frequency of each failure type is. To answer this question, we study the storage logs collected from 39,000 storage systems.



(a) including storage subsystems using Disk H (b) excluding storagesub systems using Disk H

Fig. 4. AFR for storage subsystems in four system classes and the breakdown based on failure types.

Figure 4(a) presents the breakdown of AFR for storage subsystems based on failure types, for all four system classes studied in this article. Since one problematic disk family, denoted as Disk H, has already been reported in Bairavasundaram et al. [2007], for Figure 4(b) we exclude data from storage subsystems using Disk H, so that we can analyze the trend without being skewed by one problematic disk family. The discussion on Disk H is presented in Section 4.1.

Finding (1): In addition to disk failures (20–55%), physical interconnect failures make up a significant part (27–68%) of storage subsystem failures. Protocol failures and performance failures both make up noticeable fractions.
Implications: Disk failures do not always comprise a dominant factor of storage subsystem failures, and a reliability study for storage subsystems cannot only focus on *disk failures*. Resilient mechanisms should target all failure types.

As Figure 4(b) shows, across all system classes, disk failures do not always dominate storage subsystem failures. For example, in low-end storage systems, the AFR for storage subsystems is about 4.6%, while the AFR for *disks* is only 0.9%, about 20% of overall AFR. On the other hand, physical interconnect failures account for a significant fraction of storage subsystem failures, ranging from 27–68%. The other two failure types, protocol failures and performance failures, contribute to 5–10% and 4–8% of storage subsystem failures, respectively.

Finding (2): For disks, near-line storage systems show higher (1.9%) AFR than low-end storage systems (0.9%). But for the whole *storage subsystem*, near-line storage systems show lower (3.4%) AFR than low-end storage systems (4.6%).
Implications: Disk failure rate is not indicative of the storage subsystem failure rate.

Figure 4(b) also shows that near-line systems, which mostly use SATA disks, experience about 1.9% AFR for disks, while for low-end, mid-range, and high-end systems, which mostly use FC disks, the AFR for disks is under 0.9%. This observation is consistent with the common belief that enterprise disks (FC) are more reliable than near-line disks (SATA).

However, the AFR for storage subsystems does not follow the same trend. Storage subsystem AFR of near-line systems is about 3.4%, lower than that of low-end systems (4.6%). This indicates that other factors, such as the shelf enclosure model and network configurations, strongly affect storage subsystem reliability. The impact of these factors are examined in the next section.

Another interesting observation that can be seen in Figure 4(b) is that for FC drives, the disk failure rate is consistently below 1%, as published by disk drive manufacturers, while some previous works claim that the AFR for disks is much higher [Pinheiro et al. 2007; Schroeder and Gibson 2007]. We believe that the main reason for this discrepancy is that these studies look at disk failures from different angles. Our study is from a system's perspective, as we extract disk failure events from system logs, similar to disk drive manufacturers' studies. On the other hand, Pinheiro et al. [2007], and Schroeder and Gibson [2007], look at disk failures from a user's perspective. Since their studies are based on disk replacement logs, they cannot identify the reasons for disk replacement. As system administrators often replace disks when they observe unavailability of disks, the disk replacement rates reported in these studies are actually close to the storage subsystem failure rate of this article.

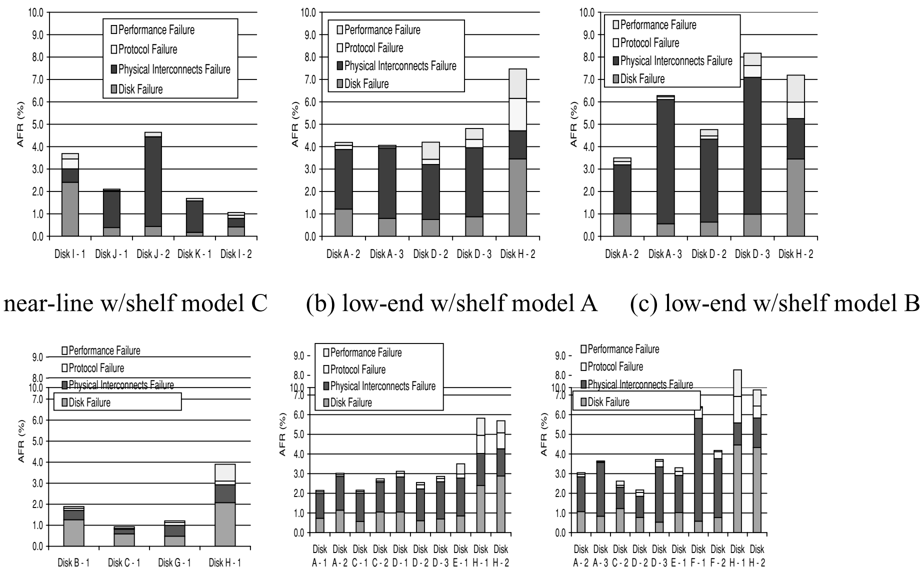
4. IMPACT OF SYSTEM PARAMETERS ON STORAGE SUBSYSTEM FAILURES

As we have earlier shown, storage subsystems of different system classes show different AFRs. While these storage subsystems are architecturally similar, the characteristics of their components, like disks and shelves, and their redundancy mechanisms, like multipathing, differ. We now explore the impact of these factors on storage subsystem failures.

4.1 Disk Model

The disk is the key component of a storage subsystem; therefore, it is important to understand how disk models affect storage subsystem failures. To understand the impact of the disk model, we study data collected from near-line, low-end, mid-range, and high-end systems.

Figure 5 shows the AFRs for storage subsystems from four system classes configured with three shelf enclosure models, for six combinations in total (not every shelf enclosure model works with all system classes). Since we find that the enclosure model also has a strong impact on storage subsystem failures, we group data based on system class, shelf enclosure model, and disk model so that we can separately study the effects of these factors. In this section, we mainly focus on disk model; the shelf enclosure model will be discussed in Section 4.2.



(a) near-line w/shelf model C (b) low-end w/shelf model A (c) low-end w/shelf model B

(d) mid-range w/shelf model C (e) mid-range w/shelf model B (f) high-end w/shelf model B

Fig. 5. AFR for storage subsystems by disk model.

There are a total of 20 disk models used in these systems, and each disk model is denoted as *family-type*, with the same convention as in Bairavasundaram et al. [2007]. For anonymization purposes, a single letter is used to represent a disk family (e.g., Seagate Cheetah 10k.7), and type is a single number indicating the disk's capacity. The relative capacity within a family is ordered by the number. For example, Disk A-2 is larger than A-1 and B-2 is larger than B-1.

Finding (3): Storage subsystems using disks from a problematic disk family show much higher (2 times) AFR than other storage subsystems.

Implications: Disk model is a critical factor to consider for designing reliable storage subsystems.

We can see from Figure 5(a)–(f) that for most storage subsystems, AFR is about 2%–4%. However, storage subsystems using Disk H-1 and Disk H-2 show 3.9%–8.3% AFR, higher than the average AFR by a factor of two.

We know that Disk H-1 and Disk H-2 are problematic. It is interesting to observe that not only disk failures, but also protocol failures and performance failures are negatively affected by the problematic disks. The possible reason is that as disks experience failures, corner-case bugs in the protocol stacks are more likely to be triggered, leading to more occurrences of protocol failures. At the same time, some I/O requests cannot be served in time, causing more performance failures.

Finding (4): Storage subsystems using disks from the same disk models exhibit similar disk failure rates across different system environments (different system class or shelf enclosure models), but they show very different storage subsystem failure rates.

Implications: Factors other than disk model also heavily affect storage subsystem failures, while they are not revealed by disk failures.

As Figure 5 shows, some disk models are used by storage subsystems of multiple system classes, together with various shelf enclosure models. For example, Disk A-2 and Disk D-2 are used in low-end systems with different shelf models and by mid-range and high-end systems with the same shelf model.

As we can see from Figure 5, for those storage subsystems using the same disk models, disk failure rates do not change much. For example, disk AFR of Disk D-2 varies from 0.6%–0.77%, with a standard deviation of 8%. For all storage subsystems sharing the same disk models, the average standard deviation of disk AFR is less than 11%.

On the other hand, the storage subsystem AFR exhibits strong variation. For example, AFR for storage subsystems using Disk D-2 varies from 2.2%–4.9%, with a standard deviation of 127%. For all such storage subsystems, the average standard deviation of storage subsystem AFR is as high as 98%. This observation indicates that storage subsystem AFR is strongly affected by factors other than disk model, while these factors do not affect disk failures much.

Finding (5): The AFR for disks and storage subsystems does not increase with disk size.

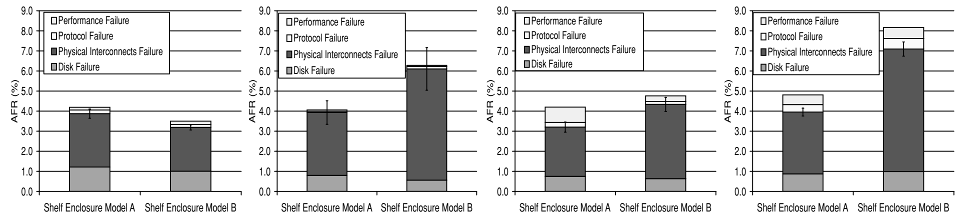
Implications: As disk capacity rapidly increases, storage subsystems will not necessarily experience more disk failures or storage subsystem failures.

We do not observe increasing disk failure rate or storage subsystem failure rate with increasing disk capacity. For example, as Figure 5(e) shows, storage subsystems using Disk D-2 show lower disk and storage subsystem AFR than those using Disk D-1.

4.2 Shelf Enclosure Model

Shelf enclosures contain power supplies, cooling devices, and prewired backplanes that carry power and I/O bus signals to the disks mounted in them. Different shelf enclosure models vary in design and have different mechanisms for providing these services; therefore, it is interesting to see how shelf enclosure model affects storage subsystem failures.

In order to study the impact of the shelf enclosure model, we look at the data collected from low-end storage systems, since low-end systems use the same disk models with different shelf enclosure models, so that we can study the effect of shelf enclosure models without inference from disk models.



(a) Disk-A2 (b) Disk-A3 (c) Disk-D2 (d) Disk-D3

Fig. 6. AFR for storage subsystems of low-end storage systems by shelf enclosure models using the same disk models (a subset of data from Figure 5). The error bars show 99.5%+ confidence intervals for physical interconnect failures.

Finding (6): The shelf enclosure model has a strong impact on storage subsystem failures, and different shelf enclosure models work better with different disk models.

Implications: To build a reliable storage subsystem, hardware components other than disks (e.g., shelf enclosure) should also be carefully selected. And due to component interoperability issues, there might be a different "best choice" for one component, depending on the choice of other components.

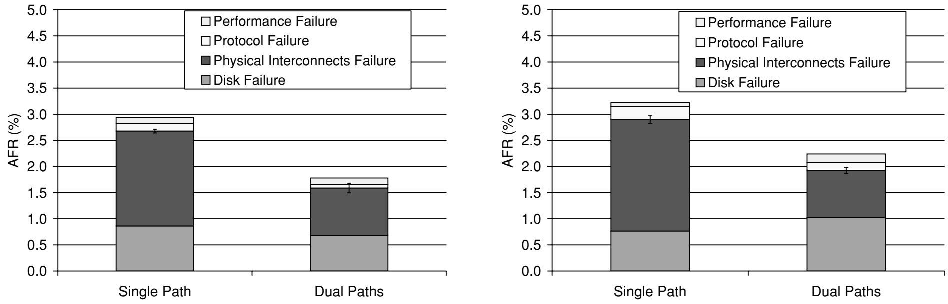
Figure 6 (a)–(d) shows AFR for storage subsystems when configured with different shelf enclosure models but the same disk models. As expected, shelf enclosure model primarily impacts physical interconnect failures, with little impact on other failure types. This is different from disk model, which impacts all failure types.

To confirm this observation, we tested the statistical significance using a T-test [Rosander 1951]. As Figure 6(a) shows, the physical interconnect failures with different shelf enclosure models are quite different ($2.66 \pm 0.23\%$ versus $2.18 \pm 0.13\%$). A T-test shows that this is significant at the 99.5% confidence interval, indicating that the hypothesis that physical interconnect failures are impacted by shelf enclosure models is very strongly supported by the data. Figure 6(b)–(d) shows similar observations with significance at 99.5%, 99.9%, and 99.9% confidence.

It is also interesting to observe that for different disk models, different shelf enclosure models work better. For example, for Disk-A2, storage subsystems using Shelf Enclosure B show better reliability than those using Shelf Enclosure A, while for Disk-A3, Disk-D2, and Disk-D3, Shelf Enclosure A is more reliable. Such observations might be due to component interoperability issues between disks and shelf enclosures. This indicates that we might not be able to make the best decision on selecting the most reliable hardware components without evaluating the components from a system perspective and taking the effect of interoperability into account.

4.3 Network Redundancy Mechanism

As we have seen, physical interconnect failures contribute to a significant fraction (27–68%) of storage subsystem failures. Since physical interconnect



(a) mid-range systems (b) high-end systems

Fig. 7. AFR for storage subsystems, broken down by the number of paths. The error bars show 99.9% confidence intervals for physical interconnect failures.

failures are mainly caused by network connectivity issues in storage subsystems, it is important to understand the impact of network redundancy mechanisms on storage subsystem failures.

For the mid-range and high-end systems studied in this article, FC drivers support a network redundancy mechanism, commonly called *active/passive multipathing*. This network redundancy mechanism connects shelves to two independent FC networks, and redirects I/O requests through the redundant FC network when one FC network experiences network component failures (e.g., broken cables).

To study the effect of this network redundancy mechanism, we look at the data collected from mid-range and high-end storage systems, and group them based on whether the network redundancy mechanism is turned on. As we observed from our dataset, about one-third of storage subsystems are utilizing the network redundancy mechanism, while the other two-third are not. We call these two groups of storage subsystems *dual-paths* systems and *single-path* systems, respectively. In our dataset, there are very few disk models used in both configurations; other disk models are mainly used in either dual-paths systems or single-path systems. Therefore, we cannot further break down the results based on disk models and shelf enclosure models.

Finding (7): Storage subsystems configured with network redundancy mechanisms experience much lower (30–40% lower) AFR than other systems. AFR for physical interconnects is reduced by 50–60%.

Implications: Network redundancy mechanisms such as multipathing can greatly improve the reliability of storage subsystems.

Figure 7(a) and (b) show the AFR for storage subsystems in mid-range and high-end systems, respectively. As expected, secondary path reduces physical interconnect failures by 50–60% ($1.82 \pm 0.04\%$ versus $0.91 \pm 0.09\%$ and $2.13 \pm 0.07\%$ versus $0.90 \pm 0.06\%$), with little impact on other failure types. Since physical interconnect failure is just a subset of all storage subsystem failures, AFR for storage subsystems is reduced by 30–40%. This indicates that

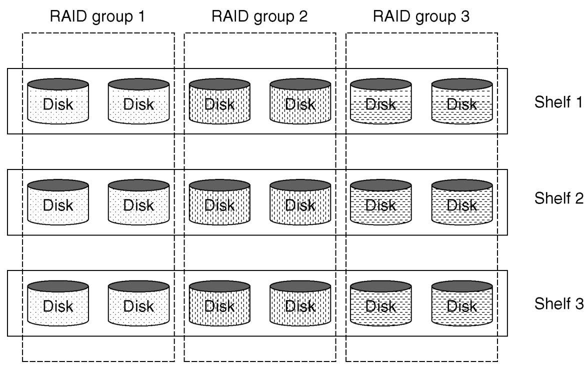


Fig. 8. Disk layout in shelf enclosures and RAID groups.

multipathing is an exceptionally good redundancy mechanism that delivers reduction of failure rates as promised. As we applied a T-test on these results, we found out that for both mid-range and high-end systems the observation is significant at the 99.9% confidence interval, indicating that the data strongly supports the hypothesis that physical interconnect failures are reduced by multipathing configuration.

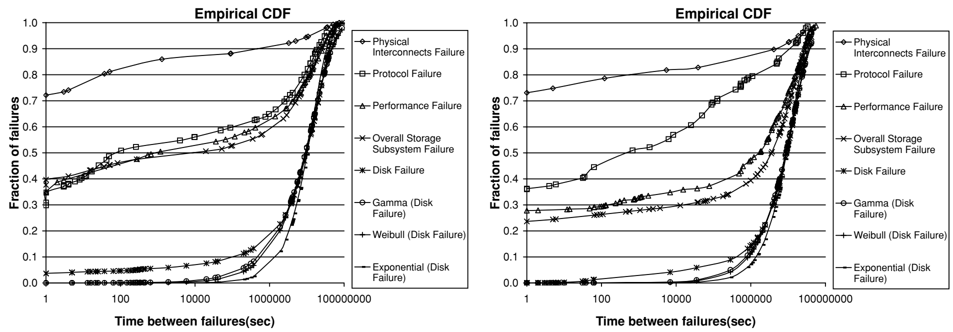
However, the observation also tells us that there is still further potential in network redundancy mechanism designs. For example, given that the probability for one network to fail is about 2%, the idealized probability for two networks to both fail should be a few magnitudes lower (about 0.04%). But the AFR we observe is far from the ideal number.

One reason is that not only failures from networks between shelves contribute to physical interconnect failures; other failures, such as shelf backplane errors, can also lead to physical interconnect failures, while multipathing does not provide redundancy for shelf backplane. Another possible reason is that most modern host adapters support more than one port, and each port can be used as a “logical” host adapter. If two independent networks are initiated by two “logical” host adapters sharing the same physical host adapter, a host adapter failure can cause failures of both networks.

5. STATISTICAL PROPERTIES OF STORAGE SUBSYSTEM FAILURES

An important aspect of storage subsystem failures is their statistical properties. Understanding statistical properties such as the failure distribution of modern storage subsystems is necessary to build the right testbed as well as fault injection models, to evaluate existing resiliency mechanisms and to develop better ones. For example, some researchers have assumed a constant failure rate, which means exponentially distributed time between failures, and that failures are independent, when calculating the expected time to failure for a RAID [Patterson et al. 1988].

Figure 8 illustrates how disks are laid out in storage subsystems. As Figure 8 shows, multiple disks are mounted in one shelf enclosure and share the cooling service, power supply, and intrashelf connectivity it provides.



(a) failure distribution in a shelf (b) failure distribution in a RAID group

Fig. 9. Distribution of time between failures in about 155,000 shelves and 230,000 RAID groups during 44 months.

The figure also shows how disks are assigned to build up RAID groups, which include both data disks and parity disks containing redundant data. In order to prevent shelf enclosure from being the single point of failures for a whole RAID group, it is a common practice to have a RAID group spanning disks from multiple shelf enclosures.

In this section, we will study the statistical properties of storage subsystem failures, both from a shelf perspective and from a RAID group perspective.

5.1 Time Between Failures

Figures 9(a) and 9(b) show the empirical cumulative distribution function (CDF) of time between storage subsystem failures from a shelf and from a RAID group, respectively. To study the failure distribution from different disks in the same shelf/RAID group, we filtered out all duplicate failures. Since we only know when the failures are detected instead of when the failures occur, the CDFs do not start from the “zero” point. As all the storage subsystems studied in this article send data verification requests to all disks hourly, as a proactive method to detect failures, we expect a short lag (up to an hour) between the occurrence and the detection of storage subsystem failures.

Finding (8): Physical interconnect failures, protocol failures, and performance failures show much stronger temporal locality (i.e., bursty pattern) than disk failures.

Implications: RAID-based resiliency mechanisms which are designed for handling disk failures, might not be effective in handling all storage subsystem failure types.

As can be seen in Figure 9(a), overall storage subsystem failures are very bursty. About 48% of overall storage subsystem failures arrive at the same shelf within 10,000 seconds of the previous failure. As expected, physical interconnect failures show the highest temporal locality, while even protocol failures and performance failures show strong temporal locality. None of these failure types follows the distributions commonly used in failure theory, such as exponential, Gamma, or Weibull distributions.

On the other hand, disk failures show a much less bursty pattern, and the Gamma distribution provides a best fit for disk failure. For disk failures, we cannot reject the null hypothesis that the follow the Gamma distribution with the Chi-square test at the significance level of 0.05.

Finding (9): Storage subsystem failures from a RAID group exhibit lower temporal locality (less bursty pattern) than failures from a shelf enclosure.

Implications: Spanning RAID groups across multiple shelves is an effective way to reduce the probability for multiple storage subsystem failures to happen during a short period of time.

As we mentioned earlier, it is common to build a RAID group across multiple shelves in order to prevent, shelf from being a single point of failure. As we found the from the storage logs, a RAID group on average spans about 3 shelves.

Figure 9(b) shows the CDF of time between failures from the same RAID group. Compared to Figure 9(a), the failures are less bursty. About 30% of failures arrive at the same RAID group within 10,000 seconds of the previous failure, lower than 48% for failures from the same shelf enclosure. For all failure types, the temporal locality is reduced. This observation supports the common practice of building a RAID group across multiple shelves and encourages storage system designers to distribute RAID groups more sparsely.

Finding (10): Storage subsystem failures of one RAID group still exhibit strong temporal locality.

Implications: We need resiliency mechanisms that can handle bursty failures.

However, Figure 9(b) still shows strong temporal locality, since multiple shelves may share the same physical interconnect, and a network failure can still affect all disks in the RAID group.

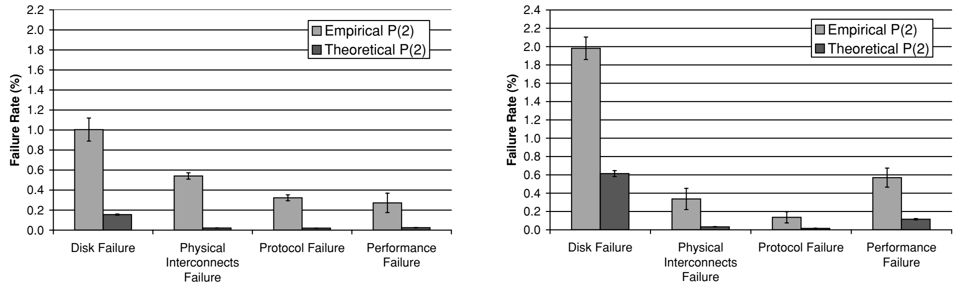
We repeated this analysis using data broken down by system classes and shelf enclosure models. In all cases, similar patterns and trends were observed.

5.2 Correlations Between Failures

Our analysis of the correlation between failures is composed of two steps.
(1) Derive the theoretical failure probability model based on the assumption that failures are independent.
(2) Evaluate the assumption by comparing the theoretical probability against empirical results.

Next, we describe the statistical method we use for deriving the theoretical failure probability model.

5.2.1 *Statistical Method.* We denote the probability for a shelf enclosure (including all mounted disks) to experience one failure during time T as $P(1)$



(a) shelf enclosure failures (b) RAID group failures

Fig. 10. Comparison of theoretical model against empirical results. Theoretical P(2) is calculated based on Eq. (3). The error bars show 99.5%+ confidence intervals.

and denote the probability for it to experience two failures during T as *P(2)*. Let *f(t)* specify the failure probability at moment t.

Assume failures are independent, then we know that

$$P(1) = \int_0^T f(t)dt \tag{1}$$

$$\begin{aligned} P(2) &= \int_{t2}^T \left(\int_0^{t2} f(t_1)dt_1 \right) dt_2 \\ &= \frac{1}{2} \left(2 * \int_{t2}^T \left(\int_0^{t2} f(t_1)dt_1 \right) dt_2 \right) \\ &= \frac{1}{2} \left(\int_0^T f(t)dt \right)^2 . \end{aligned} \tag{2}$$

Therefore,

$$P(2) = \frac{1}{2} P(1)^2 \tag{3}$$

and more generally (the proof is skipped due to limited space),

$$P(N) = \frac{1}{N!} P(1)^N . \tag{4}$$

We can derive the same formula for RAID group failure probability by replacing shelf enclosure with RAID group in the preceding derivation.

It is important to notice that the relation shown in Eq. (3) is a variation of a more common form.

$$P(A_1, A_2) = P(A_1) * P(A_2) \tag{5}$$

The main difference is that we do not care about the order of failures in Eq. (3).

In the next section, we will compare this theoretically derived model against the empirical results collected from storage logs.

5.2.2 *Correlation Results.* To evaluate the theoretical relation between *P(1)* and *P(2)* shown in Eq. (3), we first calculate *empirical P(1)* and *empirical P(2)* from storage logs. Empirical P(1) is the percentage of shelves (RAID groups) that have experienced exactly one failure during time T (we set T as one year), and empirical P(2) is the percentage of those that have experienced exactly two failures during time T. Only storage systems that have been in the field for one year or more are considered.

Finding (11): For each failure type, storage subsystem failures are not independent. After one failure, the probability of additional failures (of the same type) is higher.

Implications: The probability of storage subsystem failures depends on factors shared by all disks in the same shelf enclosures (or RAID groups).

Figure 10(a) shows the comparison between empirical P(2) and theoretical P(2), which is calculated based on empirical P(1). As we can see in the figure, empirical P(2) is higher than theoretical P(2). More specifically, for disk failure, the observed empirical P(2) is higher than theoretical P(2) by a factor of 6. For other types of storage subsystem failures, the empirical probability is higher than the theoretical correspondences by a factor of 10–25. Furthermore, T-tests confirm that the theoretical P(2) and empirical P(2) are statistically different with 99.5% confidence intervals.

This is a strong indication that when a shelf experiences a storage subsystem failure, the probability for it to have another increases. In other words, storage subsystem failures from the same shelves are not independent.

Figure 10(b) shows a similar trend for failures from the same RAID groups. Therefore, the same conclusion can be made for storage subsystem failures from the same RAID groups.

Although in Figure 10 we set T to be one year, the conclusion is general to different values of T. We have set T to three months, six months, and two years, and also grouped data based on other factors, such as system classes and shelf enclosure models. In all cases, similar correlations were observed.

5.2.3 *Causes of Correlation.* There are several reasons that can explain the correlation between each type of storage subsystem failure.

The disk failure probability depends on environmental factors such as temperature [Cole 2000]. Disks in the same shelf or the same RAID group are close to each other, sharing the same room temperature. Furthermore, disks in the same shelf are also sharing the cooling facility (e.g., fans) provided by the shelf. When the machine-room temperature is above or below the normal range, all disks in the same shelf and the same RAID group may experience a higher-than-normal failure probability. Similarly, when the shelf-cooling facility does not work properly, all disks in the same shelf may have higher probability to fail.

Most physical interconnect components, such as host adapters, cables, and FC terminators on the shelf, are shared by disks in the same shelf or in the same RAID group. When a physical interconnect component such as a host adapter experiences transient hardware errors, all disks in the same shelf or the same RAID group have a higher-than-normal probability of physical interconnect failures.

Similarly, drivers for disks in the same shelf or the same RAID group are usually updated around the same time. If a particular version is buggy or has compatibility issues, all disks will have a higher probability of protocol failures.

6. RELATED WORK

Disk failure characteristic studies. There are generally two categories of disk failure studies: vendor studies and user-experience studies.

For example, Seagate and Quantum study long-term reliability characteristics through accelerated life tests of small populations and collecting statistics from their return unit databases [Cole 2000; Yang and Sun 1999]. Based on such tests, they calculate the mean-time-to-failure (MTTF) and record it in a disk specification. For most of the disks, the specified MTTF is typically more than one million hours, equivalent to a lower than 1% annualized failure rate (AFR), which is slightly lower than what we observed (0.9–1.9%).

But vendor-specified MTTF is usually not what has been experienced by users. A study explained how disk manufactures and end customers can calculate MTTF in different ways [Elerath and Shah 2004].

Motivated by this observation, recently researchers have studied disk failures from a user's perspective by analyzing disk replacement logs collected in the field [Pinheiro et al. 2007; Schroeder and Gibson 2007]. Interestingly, they found disks are replaced much more frequently (2–4 times) than vendor-specified AFRs. More interestingly, Schroeder and Gibson [2007] found that the time between disk replacement in the same machine room does not follow the exponential distribution and exhibits significant levels of correlation. This finding is consistent with what we find about the time between storage subsystem failures in the same shelf and the same RAID group, while we further found out that different failure types show different statistical properties.

Additionally, some researchers analyzed the characteristics of disk latent sector errors, which can potentially lead to complete disk failures, using the data from Network Appliance AutoSupport Database as in Bairavasundaram et al. [2007]. Based on the same set of data, they further conducted a study on data corruption in Bairavasundaram et al. [2008]. They found enterprise class (e.g., FC) disks are more reliable than near-line (SATA) disks. Similarly, we discovered that FC disks have lower AFR (0.9%) compared to SATA disks (1.9%). However, we also observed that storage systems using FC disks are not necessarily more reliable than those using SATA disks, due to other component failures.

Some studies also look at the factors affecting disk failure rate, such as disk model, the number of disk heads, disk size, and environmental factors [Bairavasundaram et al. 2007; Elerath and Shah 2003; Pinheiro et al. 2007]. Similarly, in this article, we looked at factors affecting storage failure rate, and found that some factors strongly affecting storage failure rate have little impact on disk failure rate.

System component failure studies. Unfortunately, there is little work published on analyzing the reliability of storage system components. Early work [Schulze et al. 1989] presented a reliability analysis on disk arrays and claimed that other system components such as power supplies, HBAs, cooling equipment, and cabling cannot be ignored when analyzing the reliability of a disk array. However, their study was not based on real-world data. Instead, they estimated reliability of disk array based on formula- and datasheet-specified MTTF of each component, assuming component failures follow exponential distributions and that failures are independent.

One of the very few empirical studies on storage system failures was presented in Talagala and Patterson [1999]. That paper presented an analysis of hardware failures in their prototype storage systems during 6 months. They found out that disks are among the most reliable components in the system, while SCSI components (physical interconnects in their prototypes) generated a considerable number of failures. These findings are consistent with our study. However, limited by the scale of the study, their failure sample size (limited to 16 storage systems and a few hundred failures) is too small to study important characteristics of failures such as failure distribution and failure correlations, nor to identify factors affecting storage system reliability. Another related empirical study looked at storage system outages based on 4,400 system-year records, and categorized the outages based on their root causes [Lancaster and Rowe 2001]. Although sharing the similar goal of categorizing failures, our study looks into the details of the storage subsystem failure, which is considered as one outage category in Lancaster and Rowe [2001]. Furthermore, our study is based on data on a much larger scale (about 137,000 system years).

Beyond storage systems, an analysis of tandem systems found that software errors are comprising an increasing portion of failures reported by customers [Gray 1990]. Similarly, we found that protocol stacks account for 5–10% of storage subsystem failures.

7. CONCLUSION

This article presents a study of the real-world storage subsystem failures, examining the contribution of different failure types, the effects of some factors on failures, and the statistical properties of failures.

Our study is based on support logs collected from 39,000 commercially deployed storage systems, which contain about 1,800,000 disks mounted in about 155,000 shelf enclosures. The studied data cover a period of 44 months. The result of our study provides guidelines for designing more reliable storage systems and developing better resiliency mechanisms.

Although disks are the primary components of storage subsystems and disk failures contribute to 20–55% of storage subsystem failures, other components such as physical interconnects and protocol stacks also account for significant percentages (27–68% and 5–10%, respectively) of storage subsystem failures. The results clearly show that the rest of storage subsystem components cannot be ignored when designing a reliable storage system.

One way to improve storage system reliability is to select more reliable components. As data suggests, storage system reliability is highly dependent on both disk model and shelf enclosure model. We also found out that there might be a different "better" model for different storage systems, depending on other components used in the systems. Another way to improve reliability is to employ redundancy mechanisms to tolerate component failures. One such mechanism studied in the article is multipathing, which can reduce AFR for storage systems by 30–40% when the number of paths is increased from one to two. Storage system designers should also think about using smaller shelves (fewer disks per shelf) but more shelves in storage systems, since data indicates that spanning a RAID group across multiple shelves can reduce the probability of "bursty" failures.

We also found out that storage subsystem failure and individual storage subsystem failure type exhibit strong self-correlations. In addition, these failures also exhibit bursty patterns. These results motivate a revisiting of resiliency mechanisms such as RAID that assume independent failures.

Future work will compare the impact of different failure types and study how to design resiliency mechanisms targeting individual failure types, given that different failure types show different statistical properties. Another future direction is to design storage failure prediction algorithms based on component errors. We also want to extend this study to other components of storage systems beyond the storage subsystem.

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