Circular Business Model for Worn Out SSDs Using Proofs of Space and Time

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Executive Summary

NAND flash is used across virtually every market segment, from mobile phones, laptops, cars, and data centers. As E-waste is a growing issue, a move to circular business models can help reduce e-waste by finding a second or third use for devices that are still functioning. It is well known that major cloud service providers, hyperscale datacenters, and enterprise server and storage companies still use physical destruction at the end of first use for storage devices. The largest reason of this is data security risk and liability - although modern SSDs can perform a cryptographic erase instantly rendering the data unreadable through a sanitize command, this is slowly changing. New use cases for used storage devices will be needed as companies move to more circular business models finding second and third use for storage devices. We investigate an even more interesting use for drives that are worn out, or at the end of their rated endurance.

After much support from Solidigm Technology, known as 'a leading global provider of innovative NAND flash memory solutions' and Chia Cryptocurrency, this project allows us to see a future for SSDs where they can be part of a circular economy. The task is to look at how we can use Chia Cryptocurrency with a worn drive as a possible way to decrease the carbon footprint of these drives in the future. With the accomplishment of this goal, the hope is to deliver a message to all data centers and users that it is possible to give our SSDs a second life by allowing them to be part of Proof of Space and Time, known as Chia.

Objective and Implementation

To achieve our goal, the following objective were completed throughout the project implementation:

1. Obtain an SSD that is worn out, or used 100% of the rated endurance.
2. Perform plotting and farming in the Chia environment and determine if the drive is affected by the errors.

Implementation of Objective 1

We quickly found out a limitation of the finding an SSD that is worn out, but mostly because this is extremely time consuming. Enterprise SSDs have petabytes of rated endurance, and the time to wear out a drive can be measured in years. The first objective focused on determining a way we can simulate a worn drive instead. Worn drives exhibit errors, so we found a way to induce an error with a write uncorrectable command on the drive. By performing this, it will cause our drive's Uncorrectable Bit Error Rate (UBER) to fluctuate, showing a drive with errors, similar to that of a worn drive. As we try to perform uncorrectable, Windows required support of other hardware in order to write on the drive. As a result, we saw that while a variety of operating systems could be supported, Linux provides the most flexibility for sending commands directly to the drive without obstruction. NVMe has a set of open source tools called nvme-cli that can be used to send the write uncorrectable command to the SSD. The following steps were taken and for more details, there are commands in section 3.2.3 of chapter 3.

Steps to perform uncorrectable on Linux:

1. Check that the device supports the command by reading the identify controller information
2. Send the write uncorrectable command to a range of LBAs
3. Verify that the command worked

Implementation of Objective 2

The second objective is to determine whether these drive with induced errors can run in Chia's environment without running into any software errors. While a drive with errors can easily fail in its usual environment of data storing, it is important to see how the drive is affected in Chia's environment. Chia contains tools to allow us to verify the proofs of space in an accelerated fashion, instead of relying to many years of farming. There is a chia plots check command that sends out a series of deterministic challenges to all plot files in the current working directory given. The response will be an output of a certain number of proofs found for a given number of challenges. Additionally, Chia developed tools to fully walk through a plot and check every single proof. With a longer test time, we could induce a certain number of errors via write uncorrectable, walk through the entire plot file (which contains over 4 billion proofs of space), and record the number of proofs done before the uncorrectable was hit. If we create one error per plot, we would be close to simulating 10-10 UBER rate. In chapter 4, Figure 6, we can see the result of speeding up 9 years' worth of farming by send 1 million challenges and how the drive reacts in the Chia's environment.

Discussion and Conclusion

As we send write uncorrectable commands to 2 separate LBA ranges, with a count of 10 LBAs. This puts the UBER at a devastating rate for storing any user data. Then we test 1,000,000 challenges (as seen in Figure 6 below), which will simulate about 9 years' worth of farming on a drive. The drives were written with uncorrectable to imitate a worn drive's behavior at its end of life where the drive often begins to enter its read only mode. Even with the errors, the drive is able to function properly in a Chia environment. As these drives are not suitable to be used in their original purpose, data storing, these drives are able to farm in Chia. A SSD with a high amount of program-erase cycles may not be able to continue to store data sufficiently in a typical environment, such as a Datacenter. While some SSDs may have mechanisms to slow or stop programing to a drive near its end of endurance rating, showing new secondary usages for these SSDs, may encourage limiting such restrictions in the future. One secondary usage proven here are Cryptocurrency applications such as Chia. In conclusion, as drives reach the end of life of their first usage, they can continue to be of use through proof of space and time, Chia.

Abstract

Solid-State Drives (SSDs) have an intrinsically limited amount of endurance (endurance rating) or ‘total data written to the device’, due wear out of the NAND Flash Floating Gate. Read/write cycling of the NAND flash in the SSDs stresses the oxide layer that isolated the floating gate, leading to its breakdown over time and increased uncorrectable bit error rate (UBER). SSD vendors will set the endurance ratings in their warranty to ensure it is well before the drive begins to fail. Replacement of SSDs, prior to reaching their endurance rating and warranty, is a common place. Circular business models, where product life cycles are designed to maximize value delivery and minimize environment impact, are becoming increasingly essential in the Information and Communications Technology (ICT) industry. The significant carbon impact of manufacturing complex storage devices is leading to a desire to ensure the SSDs are used to their absolute maximum utilization. Today there are limited use cases for SSDs that have reached their warranty endurance rating as Total Terabytes Written (TBW). We hypothesize that storage-based cryptocurrency based on proofs of space can utilize SSDs that have a large amount of ware and exhibit a higher UBER. Providing valuable secondary usages for such SSDs, provides grater overall value in connection to the manufacturing carbon footprint to build the SSD.

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1. Introduction

Nearly 330 million Solid-State Drives shipped in 2020, equaling to approximately 207EB (exabyte as a unit of computer data storage) [15]. As forecasted by Semiconductor Equipment and Materials International (SEMI), NAND flash market is estimated to reach 56.6 billion U.S dollars worldwide, as seen in Figure 1 [16]. As the market consists of Samsung, WDC, SK Hynix, Kioxia, Intel, there are very few that has a method to best recycle these drives that took great effort and expenses to purchase. As we search the world wide web, some of the options include shredding the drives or hand the drive in to receive a discount on the next product. However, it is concerning how sustainable the options mentioned may be, as it does not allow users to continue using the drive until its end of life. Additionally, these options does not help decrease the carbon footprint of these drives, disabling them to continue to be apart of the circular economy.

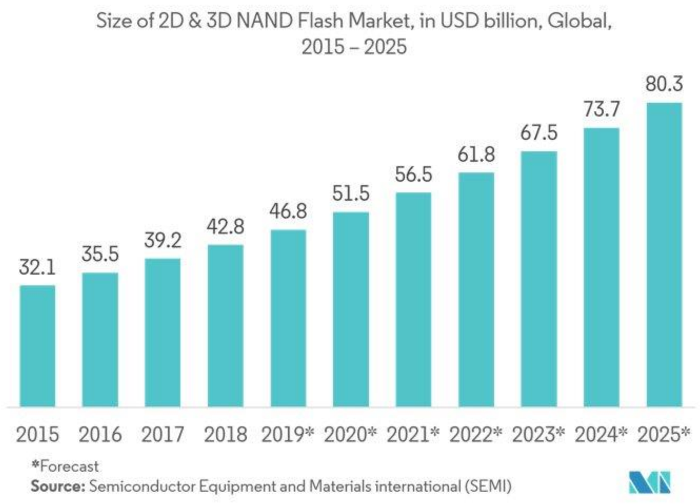

Figure 1 Global Market for 2D and 3D NAND Flash in 2015 to 2025 [16]

NAND flash is used across virtually every market segment, from mobile phones, laptops, cars, and data centers. The total market size for SSDs alone reached over 426 million units in 2021. [IDC SSD Forecast Update Dec 2021]. E-waste is a growing issue. The amount generated worldwide in 2019 was roughly 54 million metric tons [20]. A move to circular business models can help reduce e-waste by finding a second or third use for devices that are still functioning. It is well known that major cloud service providers, hyperscale datacenters, and enterprise server and storage companies still use physical destruction at the end of first use for storage devices. The largest reason of this is data security risk and liability - although modern SSDs can perform a cryptographic erase instantly rendering the data unreadable through a sanitize command, this is slowly changing. New use cases for used storage devices will be needed as companies move to more circular business models finding second and third use for storage devices. We investigate an even more interesting use for drives that are worn out, or at the end of their rated endurance.

The goal of this project is to find a sustainable approach that could enable drive to be used to its limit during its lifetime. In this project we will involve storage-based cryptocurrency based on proofs of space to utilize SSDs that have a large amount of ware and exhibit a higher UBER. By being able to provide valuable secondary usages for these Solid-State Drives (SSD), users could provide greater overall value in connection to the manufacturing carbon footprint to build the SSD.

2. Literature Review

2.1. Endurance of SSD

SSD reliability and failure mechanisms are well understood. Drive's reliability generally is concerned with drive failures, uncorrectable errors, and silent errors. Mainstream SSDs today use NAND flash technology to store data. NAND is high performance, scalable, and low cost - justifying its use in virtually every computing segment from mobile phones, SD cards, consumer laptops, and data centers. NAND must be erased at block level each time before the cell can be programmed (written) with new data, a process known as a program-erase cycle [12]. These cycles can only be performed a certain number of times before NAND cell wear-out leads to failures that are beyond the capability of the error correction capabilities of the SSD and if can no longer reliably store user data [2]. This leads to an SSD that no longer meets the UBER (uncorrectable bit error rate) specification, retention time falls below specification (how long the device can store user data safely while powered off, at a given temperature), or a functional failure (device can no longer power on). The metrics to measure endurance of an SSD are defined in total Terabytes Written, or TBW, at a certain workload as seen in equation (1) and (2) below. The workload defined is generally the JESD219 workload from JEDEC organization.

$$WAF\ (write\ amplification\ factor) = \frac{(NAND\ writes)}{(Host\ writes)} \qquad (1)$$

$$TBW\ (terabytes\ written) = \frac{(raw\ capacity\ in\ TB*program\ erase\ cycles)}{(WAF)} \qquad (2)$$

It is important to note that the architecture of NAND flash is that reads and writes are performed at the Page level and Erase occurs at the much larger Block level. Due to this architecture, the total amount of program-erase cycles placed on the NAND flash within a SSD is higher than just the used data being written [13]. Additionally, an SSD will perform wear-leveling, a process to ensure all NAND flash on the SSD see approximately the same number of program-erase cycles. These features all lead to the actual amount of wear on SSD to be higher than just the user data written.

2.2. UBER

UBER is defined as "A metric for the rate of occurrence of data errors, equal to the number of data errors per bits read." In Hard-Disk Drives (HDDs) and SSDs, UBER is generally reflected in lifetime values for an entire population, but the actual rates of error and rate of increase are dependent on many factors including time, temperature, and amount of wear on the storage media [14]. In SSDs this is adjusted for and measured per the JESD218B specification which defines UBER for SSDs using the numerator is the total count of data errors detected over the full TBW rating for the population of SSDs, or the sample of SSDs in the endurance verification. Table 1 further shows the calculations of Uber versus data read. We can see what happens when the uncorrectable bit error rate is accelerated and how that affects different factors on a drive.

Table 1 Calculations of UBER vs Data Read

UBER accelerated	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
TB read per error	0.08	0.8	8	80	800	8000	80000	800000

errors per TB	12.5	1.25	0.125	0.0125	0.00125	0.000125	0.0000125	0.00000125
HDD days	0.00463	0.04630	0.46296	4.63	46.30	462.96	4629.63	46296.30
SSD days	0.00046	0.00463	0.04630	0.46	4.63	46.30	462.96	4629.63

Note: Assuming 200MB/s for HDD and 2000MB/s for SSD for basic UBER calculations

2.3. Proof of Space and Time (PoST) - Chia

Chia is a cryptocurrency and blockchain smart transaction platform aiming to achieve higher levels of decentralization and security than leading proof of work systems like Bitcoin at a fraction of the energy utilization. Chia uses a consensus called proof of space and time, in which participants prove to the network that they are storing a certain amount of data through a process called farming. Proofs of space must be generated in a process called plotting, which is defined in the Chia proof of space construction document and first introduced in Beyond Hellman [1]. The naming of farming implies that it is much more environmentally friendly than mining, in cryptocurrencies that use a Proof of Work mechanism for blockchain consensus (e.g. Bitcoin). The Chia proof of space construction, seen in Figure 1, is designed for efficient and quick verification of proofs, making the farming process very lightweight.

The final disk format is the following:

Table	Data	Disk Storage	Approximate N
$Table_1$	$E_{\{1,i\}} = x_L, x_R$	Mapped to line point, deltafied, encoded, and parked	$0.798 * 2^k$
$Table_2$	$E_{\{2,i\}} = pos_{1;L}, pos_{1;R}$	Mapped to line point, deltafied, encoded, and parked	$0.801 * 2^k$
$Table_3$	$E_{\{3,i\}} = pos_{2;L}, pos_{2;R}$	Mapped to line point, deltafied, encoded, and parked	$0.807 * 2^k$
$Table_4$	$E_{\{4,i\}} = pos_{3;L}, pos_{3;R}$	Mapped to line point, deltafied, encoded, and parked	$0.823 * 2^k$
$Table_5$	$E_{\{5,i\}} = pos_{4;L}, pos_{4;R}$	Mapped to line point, deltafied, encoded, and parked	$0.865 * 2^k$
$Table_6$	$E_{\{6,i\}} = pos_{5;L}, pos_{5;R}$	Mapped to line point, deltafied, encoded, and parked	2^k
$Table_7$	$E_{\{7,i\}} = pos_{6;L}$	Parked	2^k
C_1	f_7	Byte aligned storage	$\frac{2^k}{param\_c_1}$
C_2	f_7	Byte aligned storage	$\frac{2^k}{param\_c_1 * param\_c_2}$
C_3	f_7	Deltafied, encoded, and parked	$\frac{2^k}{param\_c_1}$

Figure 2 Chia Proof of Space Plot Format [17]

Farmers respond to network challenges to earn rewards for securing the Chia network, which involves generating proofs of space from stored data. The protocol for farming and harvesting was designed for quick and efficient verification of proofs of space while minimizing disk io (input/output). A harvester service checks plot files for partial proofs of space when a challenge is received. There is a plot filter designed to significantly reduce the amount of disk io (input/output) required by requiring that a hash of the plot id and challenge contains a certain number of zeros. The Chia farming workload differs from traditional enterprise or consumer storage use cases since the data stored in plot files contains no user data [5]. The Chia farming workload is read-only, completely random distribution, and a low amount of data transferred between the device and host. A typical K=32 plot using the Chia proof of space construction, is laid out in plotting tables to prevent various attacks, as seen in Figure 2.

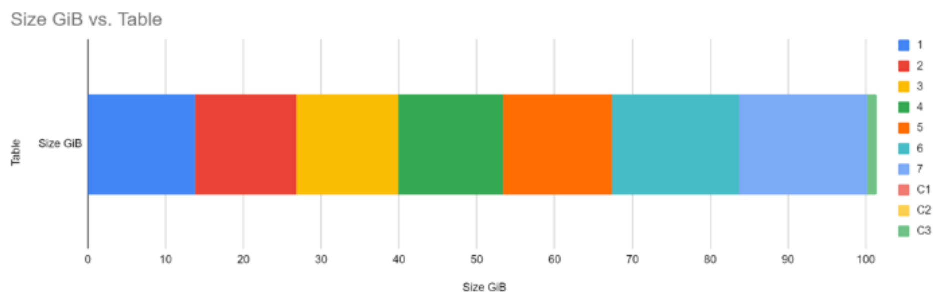

Figure 3 Chia Plot Files of Size k=32, 101.3 GiB or 108.8 GB, Size per Table.

2.4. Circular Versus Linear Economy

In linear economy, products are produced and used until they are discarded and disposed of as waste. While the circular economy goes far beyond finding a recycling solution at end-of-life. As seen in Figure 3, we can visually see the differences between the two economies. More information [10]. Circular business models are essential for the ICT industry, as a significant percentage of energy and carbon emissions come from manufacturing products.

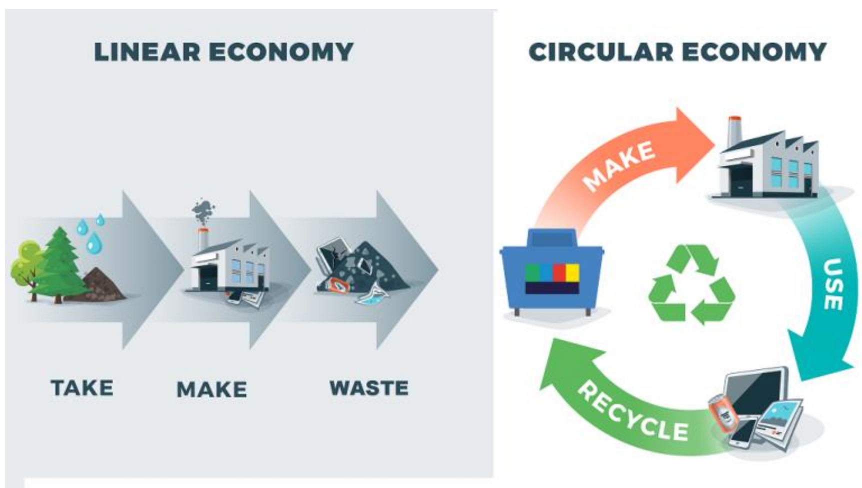

Figure 4 Linear Versus Circular Economy [18]

SSDs happen to be well designed for circularity because they have had the functionality for secure erase and sanitize, the ability to safely remove user data with a single command by changing the media encryption key, performing a full NAND block erase including spare area and non-user accessible data, and metadata. NVMe Sanitize is an official way to purge data in a way that makes it infeasible with state-of-the-art equipment to recover any user data.

Data bearing devices (DBDs: SSDs and HDDs) are typically physically destroyed at the end of first use due to extreme caution of leaking user data. In a circular economy, drive can be used in other purposes at the end of first use after the data is sanitized, thanks to the enhancements over the years in cryptography and media sanitization. A greater purpose for a drive after it has been errored or worn out, is to use it for farming in cryptocurrency—a Chia environment (upcycling). Even if the drive is not suitable for storing valuable user data, it is however suitable for farming cryptocurrency that uses proof of space of hashed data and earning valuable block rewards.

3. Methodology

Before we can test the drives in Chia's environment, it was important to ensure that there are uncorrectable on it to imitate a used drive nearing its worn-out stage. The following section will go in depth on the hypothesis and explain the procedure taken to successfully ensure uncorrectable were written on the drive and how the drive ran in a Chia environment. Additionally, there will be explanation of the result, conclusion of this project and the future work that could be performed to optimize this project.

3.1. Hypothesis

Data durability (defined as the probability of not losing user's data) and error rate requirements for Chia are significantly reduced compared to storing user data and may constitute a new class of storage media and promote used hardware that otherwise would not be suitable. In a storage system containing user data, an uncorrectable read error on a single storage device is handled by redundancy or parity, generally through RAID, erasure code, mirror, or backup of the data. Plot files contain random cryptographic hashes. If a device containing plots fails, no useful data is lost. Therefore, the best practice for Chia is not to include any data protection. If there is a single uncorrectable read error somewhere on the storage device, we could therefore calculate the probability of reading that LBA (logical block address) by using the estimated amount of data read per day in the Chia farming workload - because the reads are perfectly random, each read request coming from the harvester service will have an equal probability of being accessed [8]. The Chia farming workload reads very little data off the drive, in the range of 5-14kB/s depending on the number of plots on the drive, as seen in Figure 4.

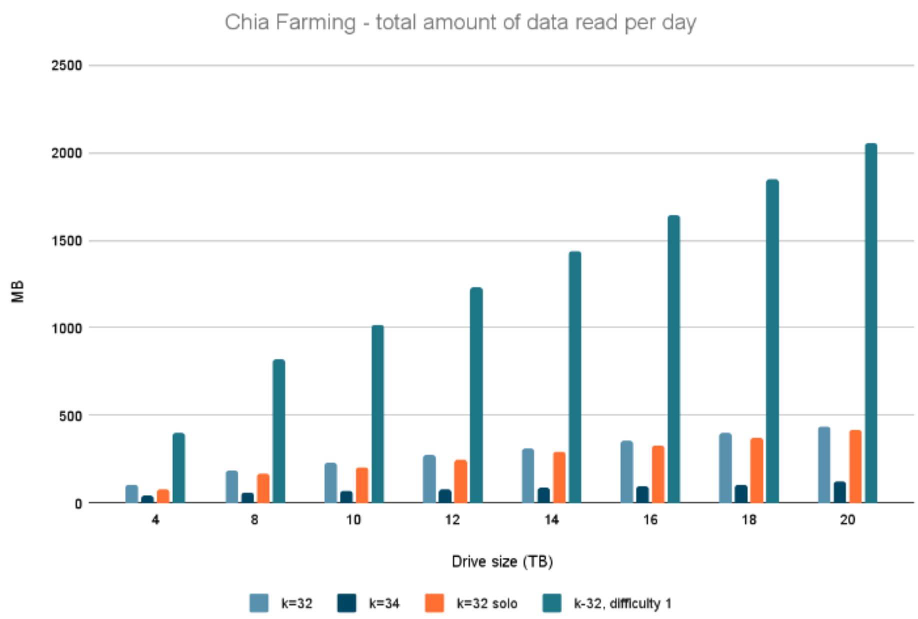

Figure 5 Chia farming in standard pool, drive size vs plot size vs MB/s read by harvester each day [19]

3.2 Materials and Methods

3.2.1 System Used

A standard desktop or server is perfectly adequate for testing, no need for specialized hardware. The personal PC used includes the recommended specification of 32GB of RAM and an 8-core system. A real system optimized for Chia plotting will prioritize performance, opting for a higher number of cores and fast NVMe ephemeral storage [11]. Chia supports a variety of operating systems, but Linux provides the most flexibility for sending commands directly to the drive without obstruction. The ideal test setup would be to obtain an SSD that is already worn out, defined by the SMART percentage used at or above 100%. We will discuss the limitations of this later in the paper, due to typical enterprise SSD firmware.

3.2.2 Lab Test Layout

The purpose of the test is to show users how worn-out drives are able to perform in a Chia environment. The drive that was used for testing is 800p 128GB Optane Boot Drive. However, the command used also works for any NVMe drive. To begin, we ran a basic test that uses write uncorrectable to simulate the UBER. It is important to note that ideally users will want to test on a drive that has reached its end of life. After this step, we would fill the drive with plots. Due to time frame limitation, we used a simulation to fast forward the proofs. The steps we took to perform our test are as follow.

Procedure:

1. Install SSD to be used for ephemeral storage to create plots, install SSD to perform the test on
2. Install chia-blockchain from github
3. Power on system under test
4. List all NVMe devices in the system - nvme list
5. Format the plotting drive to xfs file system, create a temporary directory
6. Format the drive under test, create ext4 filesystem, and mount
7. Generate a plot with chia software, using the temporary storage and device under test as the destination
8. Figure out which drive LBAs correspond to the 108.8GB plot file, via filefrag
9. Send write uncorrectable command to a random LBA in the file range
10. Perform Chia plots check command to send random challenges to the plot file, and expect proof responses
11. Check dmesg for encountering uncorrectable error, and chia plots check output

3.2.3 Tools

NVMe has a set of open source tools called nvme-cli that can be used to send the write uncorrectable command to the SSD.

We can check that the device supports the command by reading the identify controller information

sudo nvme id-ctrl /dev/nvme1n1 -H | grep "Write Uncorrectable Supported"

[1:1] : 0x1 Write Uncorrectable Supported

Send the write uncorrectable command to a range of LBAs sudo nvme write-uncor -s 10000 -c 100 /dev/nvme1n1

Verify that the command worked

sudo nvme read -s 10000 -c 100 -z 128k /dev/nvme1n1

NVMe status: READ_ERROR: The read data could not be recovered from the media(0x6281)

In actual farming, the error will go through the kernel, as opposed to the NVMe io queue as above. The kernel will throw an error when it encounters an uncorrectable. For example, if one does a simple file copy of a file that contains an uncorrectable error, the process fails and gives us an error message like below (found in dmesg).

[332736.323453] blk_update_request: critical medium error, dev nvme1n1, sector 9984 op 0x0:(READ) flags 0x200000 phys_seg 1 prio class 0

[332773.030418] blk_update_request: critical medium error, dev nvme1n1, sector 9984 op 0x0:(READ) flags 0x200000 phys_seg 2 prio class 0

Chia contains tools to allow us to verify the proofs of space in an accelerated fashion, instead of relying to many years of farming. There is a chia plots check command that sends out a series of deterministic challenges to all plot files in the current working directory given. The response will be an output of a certain number of proofs found for a given number of challenges.

Additionally, Chia developed tools to fully walk through a plot and check every single proof. With a longer test time, we could induce a certain number of errors via write uncorrectable, walk through the entire plot file (which contains over 4 billion proofs of space), and record the number of proofs done before the uncorrectable was hit. If we create one error per plot, we would be close to simulating $10 - 10e^{-10}$ UBER rate.

4.0 Result

To send a write uncorrectable command to 2 separate LBA ranges, with a count of 10 LBAs. This puts the UBER at a devastating rate for storing any user data. We test 1,000,000 challenges (as seen in Figure 6), which will simulate about 9 years' worth of farming on a drive. The number of partial and full proofs of space a given drive has to perform varies with the pool difficulty, number of plots per drive, size of the drive, and size of the plots in k value.

The data below shows that our hypothesis is directionally accurate. We do not encounter any errors during the short test (under 1 hour completion time).

```
2022-04-18T17:35:29.189 chia.plotting.check_plots    : INFO    Looking up qualities took: 1 ms.
2022-04-18T17:35:29.191 chia.plotting.check_plots    : INFO    Finding proof took: 3 ms
2022-04-18T17:35:29.192 chia.plotting.check_plots    : INFO    Looking up qualities took: 1 ms.
2022-04-18T17:35:29.194 chia.plotting.check_plots    : INFO    Finding proof took: 2 ms
2022-04-18T17:35:29.195 chia.plotting.check_plots    : INFO    Proofs 999031 / 1000000, 0.999
2022-04-18T17:35:29.195 chia.plotting.check_plots    : INFO
2022-04-18T17:35:29.195 chia.plotting.check_plots    : INFO
2022-04-18T17:35:29.195 chia.plotting.check_plots    : INFO   Summary
2022-04-18T17:35:29.195 chia.plotting.check_plots    : INFO   Found 1 valid plots, total size 0.09898 TiB
2022-04-18T17:35:29.195 chia.plotting.check_plots    : INFO   1 plots of size 32
```

Figure 6 Output from Chia Plots Check Commands for 1 Million Challenges

To double check the write uncorrectable command correctly induced an error by copying the plot file back to the ephemeral storage and encounter the uncorrectable read error (shown in Figure 7).

```
[694501.636614] blk_update_request: critical medium error, dev nvme2n1, sector 23592760 op 0x0:(READ) flags 0x84700 phys_seg 17 prio class 0
[694501.638173] blk_update_request: critical medium error, dev nvme2n1, sector 23592952 op 0x0:(READ) flags 0x0 phys_seg 1 prio class 0
[694501.640012] blk_update_request: critical medium error, dev nvme2n1, sector 23592952 op 0x0:(READ) flags 0x0 phys_seg 1 prio class 0
```

Figure 7 'dmesg' Output from Kernel Indicating Operating System has Encountered an Uncorrectable Read Error

5. Conclusion and Future Work

The drives were written with uncorrectable to imitate a used drive's behavior at its end of life. Even with the errors, the drive was able to function properly in a Chia environment. As these drives are not suitable to be used in their original purpose, data storing, these drives were able to farm in Chia. In conclusion, as drives reaches the end of life of their first usage, they can continue to be of use through plotting and farming. A SSD with a high amount of program-erase cycles may not be able to continue to store data sufficiently in a typical environment, such as a Datacenter. While some SSDs may have mechanisms to slow or stop programing to a drive near its end of endurance rating, showing new secondary usages for these SSDs, may encourage limiting such restrictions in the future. One secondary usage proven here are Cryptocurrency applications such as Chia.

Additionally, it is important to note that Intel's drives eventually go to read only mode to protect the user's data. However, this prevents the drives from being used in any other applications where data economy is not a concern. Future research can look at how to provide work arounds to these features and to find ways to build confidence to the secure erase methodologies that remove the requirements of physical destruction of SSDs to ensure user data is erased. Enabling SSDs to have the maximum life is key to ensuring the best return from the carbon footprint of the manufacturing of the SSD.

There are many other aspects of sustainability, like energy use and recycling of the materials after the drive does indeed finally fail, but those are out of scope for this study.

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