Performance Evaluation of Software RAID versus Hardware RAID for Windows 10 Home

Matthew C. Stepan

Athabasca University

mstepan1@athabasca.edu

***Abstract* – RAID storage arrays are an essential tool in data storage, providing redundancy and performance increases while combining multiple hard drives into one consistent storage pool. As the most popular desktop OS in the world [5] Windows 10 is an ideal candidate for testing configurations of RAID drives for use by the average consumer.**

Software and hardware RAID configurations were tested in order to determine which format provided the best performance for each array configuration. Single-drive performance was benchmarked against 4-disk arrays of RAID level 0, 1, and 5 for both Windows Storage Spaces and Intel Rapid Storage Technology on the Z390 chipset.

It was found that Intel Rapid Storage Technology was on average better than or comparable to Windows Storage Spaces for all RAID levels. Intel Rapid Storage Technology RAID 0 was the best performing configuration across all metrics, with the exception of large file writes, where it was second best.

1. Introduction

1.1. Motivation for Research

In today's world, data and information is a ubiquitous part of our daily lives. With an estimated 463 exabytes of data (1000^6 bytes) set to be generated every day by 2025 [9], storage for this data becomes increasingly important. As the cost in secondary disk storage diminishes, RAID arrays continue to be a popular choice for creating storage pools in home and enterprise systems. By stringing together a large number of disks, a Redundant Array of Independent Disks (RAID) can improve both the performance and reliability of data in a storage environment.

The primary motivation of this paper is to perform an evaluation of RAID performance on consumer level hardware and software. The literature contains many different evaluations carried out on enterprise level hardware and software configurations that are unrealistic for the average consumer. The principal goal is to determine whether a software RAID configuration performs better than a hardware RAID configuration on the Windows 10 operating system.

Single-drive performance will be tested against the three most common RAID levels:

RAID 0 (striping), RAID 1 (mirroring), and RAID 5 (parity). Each level will be created with both the Windows 10 Storage Spaces software, as well as the Intel Rapid Storage Technology (RST) controller on the Intel Z390 chipset. Each array will consist of 4 identical 500gb SATA hard drives connected to the motherboard.

Windows Storage Spaces is the Windows 10 built in utility for multi-disk management. For Windows 10 Home users, it is the only way to create striped, mirrored, and parity disk volumes; many of the features in Disk Management have now been made unavailable for Windows 10 Home users. As setting up volumes in Storage Spaces is significantly easier for the average user then navigating the BIOS to set up hardware controllers, it will be interesting to see the performance metrics. For the less technically inclined users, a simple to navigate GUI and ease of setup would outweigh a small boost in performance over a dedicated controller.

1.2. Literature Review

"Performance Evaluation of Software RAID vs. Hardware RAID for Parallel Virtual File System" by Hsieh, Stanton, & Ali [8] explored the performance impact of software and hardware RAID 5 on the UNIX PVFS. Their tests were performed on a cluster of 24 server racks, with 3 18BG drives per rack for a total of 72 disks . Software RAID was configured via an Adaptec AIC 7899 RAID Controller, and hardware RAID configured via a PowerEdge Expandable RAID Controller. They found that in most cases, software RAID performed equal to hardware RAID. They noted that in sequential access tests, most comparable to normal user operations, software RAID outperformed hardware RAID. In all cases, software RAID had higher CPU load then hardware RAID.

"A Performance Evaluation of RAID Architectures" by Chen and Towsley [12] investigated the performance difference between RAID 1 and RAID 5. They conducted tests for two scenarios: one for applications requiring small I/O requests, such as day-to-day transactions; one for applications requiring large I/O requests, such as image processing. Their results for small I/O requests found that RAID 1 outperformed RAID 5, for both configurations with the same number of disks and same amount of storage. They note that it must be taken into consideration that RAID 1 requires twice as many disks as RAID 5 to attain the same storage capacity, and that this cost must be factored into any performance difference noted between the two configurations. For large I/O requests, RAID 5 was found to have better performance. These results were not as definitive as in the small I/O request tests.

"Performance Analysis of RAID Storage Server with Software-based Accelerator PernixData FVP" by Hermanoy, Marcel, and Kristianto [7] looked at the effect of a software-based accelerator on RAID performance across RAID 0, 1+0, 5, and 50 arrays. While the results of the software accelerator on performance are not within the scope of this paper, the benchmarking comparisons between the RAID levels without the accelerator provide a useful benchmark for our own testing results. They utilized CrytalDisk Mark [3] as the benchmarking tool, running the Sequential, 4K, Sequential Q32T1, and 4K Q32T1 tests. CrystalDisk Mark performed each test 5 times, giving its result as an average of these tests. The researchers performed each set of these tests 8 times to get the data they presented. Across these tests, the disk read speed for RAID 0 and 5 were within 10%, however the write speed for RAID 0 was always faster, ranging between a 2.5x increase in 4k writes, all the way to a 21.8x increase in sequential Q32T1 write speeds.

"A Case for Redundant Arrays of Inexpensive Disks (RAID)" by Patterson, Gibson, and Katz [4] is a seminal paper on the implementation on RAID drives and their theoretical performance metrics. Of use to this paper is their observations on writes-per-second between RAID levels. Hermanov et al., did not include a RAID 1 configuration (RAID 1+0 is not comparable), so the results displayed in the graphs in Figure 1 will help to indicate whether our own testing agrees with the theoretical results. From these results, we expect to see RAID 5 outperforming RAID 1 by a factor of ~1.3 in large I/O tasks, and RAID 1 outperforming RAID 5 by a factor of ~1.3 in small I/O tasks.

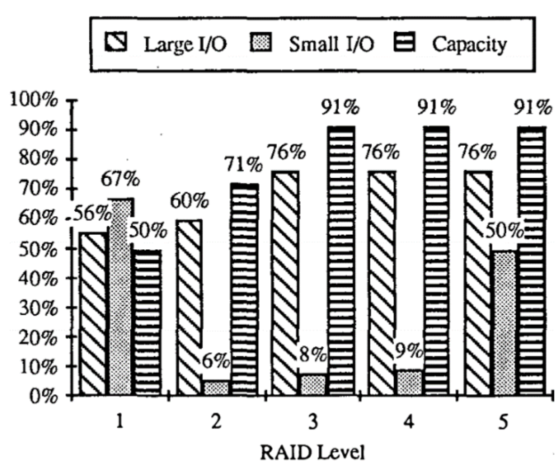

Figure 1 *Relative plot of large I/O, small I/O and useable storage capacity for RAID levels 1 through 5*

Adapted from [4]

2. Background

2.1. Windows 10

First released in 1983 as a GUI for the MS-DOS operating system, Windows has been at the forefront of consumer PC operating systems ever since. Windows 10 is the most recent version of Microsoft's Windows operating system, and has surpassed its predecessor Windows 7 as the most widely adopted OS in the world [5].

2.1.1. NTFS File System

A file system in an operating system is responsible for providing the mechanisms to access, store, create, delete, and modify files. They are made up of two parts: the collection of all files in the system, and a directory that provides information on all of the files [1].

NTFS is the default file system for Windows 10 and other modern Windows operating systems dating back to Windows Server 2003 [14]. Microsoft claims the benefits of NTFS to include increased security through Access Control Lists (ACL), BitLocker Drive Encryption, and support for large volumes and files (up to 256 TB with a cluster size of 64 KB) [10]. With the default cluster size of 4 KB, NTFS supports volumes and files up to 16 TB in size.

2.2. RAID

Redundant arrays of independent disks (RAID), are collection of techniques used to organize data storage across multiple disks [1]. The I in RAID initially stood for "inexpensive", as one of the primary goals of RAID was increasing storage capacity by using a collection of smaller cheaper drives, which were notably less expensive than one larger drive. With the price of storage diminishing, nowadays RAID is used more for boost its to performance and data redundancy then cost savings.

According to Bokare et al. [11], there are three main techniques used in RAID storage.

- ❖ Striping – Data are split at either the bit or block level, and these chunks of data are written across the disks of the array. Striping can minimize the response time of large data accesses and improve the performance of multiple small page accesses [1].
- ❖ Mirroring – In the mirroring technique, each data write is carried out identically on two or more disks. Failure of one disk in the array allows for data to be restored from its mirrored disk.
- ❖ Parity – The total number of "1"s in a byte is either an even or an odd number, this is known as the parity of the byte. By storing the "parity bit" of each byte as a 0 for even parity and 1 for odd, we can detect bit level errors in data by computing the parity and checking it against the parity bit.

2.2.1. RAID Levels

RAID is broken down into various "levels", each of which represents a different storage configuration. The three levels utilized in this research are RAID 0, RAID 1, and RAID 5.

2.2.1.1. RAID 0

RAID 0 utilizes block level data striping across a minimum of two disks. RAID 0 gives the best performance of any RAID level by not including any mirroring or parity calculations designed to improve data redundancy [2].

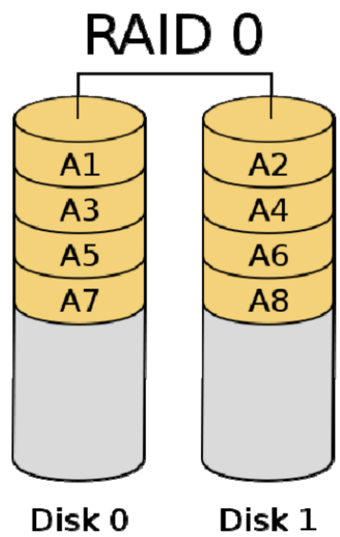

Figure 2 *RAID 0*

Adapted from [7]

2.2.1.2. RAID 1

RAID 1 utilizes the disk mirroring technique to write each set of data to a redundant disk. This impacts the performance of the array as each piece of information must be written twice.

2.2.1.3. RAID 5

RAID 5 combines the disk striping of RAID 0 along with the parity technique. By writing the parity data to all disks in the array, data is able to be reconstructed in the event of the total loss of a drive. RAID 5 is the optimal solution for minimizing loss of disk capacity while still providing data redundancy [2].

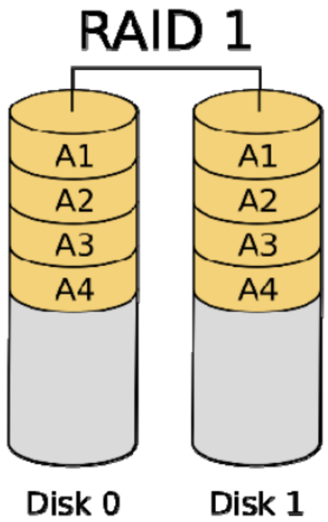

Figure 3 *RAID 1*

Adapted from [7]

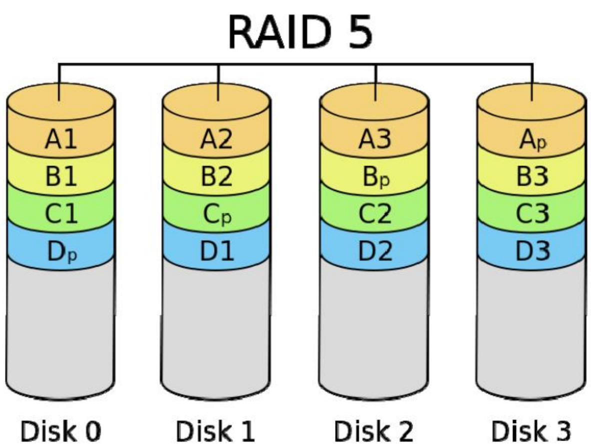

Figure 4 *RAID 5*

Adapted from [7]

2.2.2. Software RAID

Software RAID refers to arrays that are created and managed by software applications in the operating system. One of the primary advantages of a software RAID setups is the cost of entry is significantly lower, if not free, when compared to hardware RAID controllers. The most notable downside is that the array does not have the benefit of the extra processing power of a standalone hardware controller and relies on your systems CPU and memory to handle drive performance.

2.2.2.1. Storage Spaces

Storage Spaces is the software RAID package bundled with Windows 10. While it does not conform to the naming protocols of RAID levels, Microsoft [13] offers the following three drive configurations:

- Simple spaces – Equivalent to RAID 0. Combines the storage of two or more drives without any data redundancy.
- Mirror spaces – Equivalent to RAID 1. In addition to the default two-way mirroring found in RAID 1, mirror spaces offers three-way mirroring of data in arrays of at least five drives.
- Parity Spaces – Equivalent to RAID 5. Failure of single drive is protected with a minimum of three drives, and failure of two drives is protected against with at least seven drives.

2.2.3. Hardware RAID

Hardware RAID refers to arrays that are created through a separate RAID controller or directly on the motherboard, with disks connected through SATA, IDE, or SCSI ports [11]. External hardware controllers are typically expensive and are often only found on servers or enterprise level systems. They traditionally enjoy a boost in performance over software RAID implementations due to the standalone nature of the hardware reducing competition for the main systems CPU and memory. With more powerful desktop hardware, and robust software RAID applications, it is no longer a given that hardware RAID is superior to software RAID in all cases.

2.2.3.1. Intel Rapid Storage Technology (RST)

Intel Rapid Storage Technology (RST) is a technology that utilizes the motherboard as a hardware RAID controller on certain Intel chipsets. As there is not an external controller, online users have collectively referred to such setups as “Fake RAID”. The grey area is that while there is no separate hardware for the RAID controller, the implementation of the array is handled above the operating system, unlike a software RAID array. As the RST is aligned with the definition of hardware RAID running directly on the motherboard, any further discussion on RST as fake RAID versus hardware RAID is beyond the scope of this research.

3. Methods

3.1. Problem

This paper makes an evaluation of hardware and software RAID solutions on Windows 10, aiming to answer the following two questions:

1. What is the difference in performance between Windows Storage Spaces and Intel Rapid Storage Technology?

2. How do the results of these performance evaluations compare to the results established in the literature?

3.2. Testing Methodology

All testing will be performed on Windows 10 Home Edition.

The benchmarking will be performed using CrystalDisk Mark [3]. CrystalDisk Mark is a free open-source benchmarking suite for testing the transfer speed of storage devices provided under the MIT License.

The following drive configurations will be tested:

- ❖ Single disk
- ❖ Storage Spaces
    - o Simple Space (4 disks)
    - o Mirror Space (2 disks, two-way mirror)
    - o Parity Space (4 disks)
- ❖ Intel RST
    - o RAID 0 (4 disks)
    - o RAID 1 (2 disks)
    - o RAID 5 (4 disks)

The AHCI SATA mode will be used for both single disk and Storage Spaces configurations.

Storage Spaces will be set up as per Microsoft [13]. Intel RST will be set up as per ASRock [6] (motherboard manufacturer).

The benchmarking will follow the procedure carried of Hermanoy et al. [7] where possible in order to compare results. The primary differences will be not running on a virtual machine, Sequential 1MiB Q32T1 is not available in the current version of CrystalDisk Mark so it has been replaced with Sequential 1MiB Q16T1, and the file sizes used will be split between small and large in order to see if the results of Hsieh et al. [8] hold true in our testing. Q32 means a queue depth of 32, in other words, the number of requests on the disk controller. T1 means that only one thread is being used to read/write to disk.

Benchmark setup:

1. Windows 10 and all drivers running on the most up to date patches
2. CrystalDisk Mark 7.0.0 x64 will run four tests: Sequential 1 MiB, Random 4KiB, Sequential 1 MiB Q16T1, Random 4KiB Q32T1. Default affinity is disabled.
3. CrystalDisk Mark will run each test 5 times, taking an average of the results
4. Each CrystalDisk Mark run will be at each of the following file sizes: 16 MiB, 32 MiB, 1 GiB, 4 GiB; the results of the two lowest and two highest file sizes will be combined as "Small I/O Requests" and "Large I/O Requests", respectively.

3.3. *Hardware Configuration*

The hardware specifications of the benchmarking PC are as follows:

- CPU – Intel i9-9900K @3.6GHz, 5.0GHz Boost
- RAM – 32 GB Corsair Vengeance DDR4 @3200MHz
- Motherboard – ASRock Z390 Taichi
- Storage – 4x Toshiba HDD2J12 500GB 2.5" SATA HDD, 5400 RPM, 8MB Cache

3.4. *Software Configuration*

- The operating system used in this test is Microsoft Windows 10 Home x64, Version 10.0.18362 (Build 18362).
- All benchmarking will be done in Safe Mode for consistency and reduction of unnecessary background processes.
- The benchmarking tool CrystalDisk Mark is running the latest stable release, version 7.0.0 x64.

4. Results and Findings

4.1. *Results*

4.1.1. *Small I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	86.187	83.466	100	100
Storage Spaces Simple	68.678	68.686	80	82
Storage Spaces Mirror	76.340	68.682	89	82
Storage Spaces Parity	62.597	39.112	73	47
RAID 0	301.773	228.909	350	274
RAID 1	88.912	77.906	103	93
RAID 5	217.245	6.710	252	8

***Table** 1 Sequential 1MiB (Q= 1, T= 1) Small I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	87.453	75.292	100	100
Storage Spaces Simple	69.311	69.417	79	92
Storage Spaces Mirror	146.579	59.657	168	79
Storage Spaces Parity	92.070	66.376	105	88
RAID 0	519.053	246.398	594	327
RAID 1	140.498	64.276	161	85
RAID 5	366.394	18.559	419	25

***Table** 2 Sequential 1MiB (Q= 16, T= 1) Small I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	0.637	2.322	100	100
Storage Spaces Simple	0.595	2.092	93	90
Storage Spaces Mirror	0.692	1.981	109	85
Storage Spaces Parity	0.566	1.923	89	83
RAID 0	25.276	4.893	3,971	211
RAID 1	9.693	1.623	1,523	70
RAID 5	14.553	0.261	2,286	11

***Table 3** Random 4KiB (Q= 1, T= 1) Small I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	1.091	2.230	100	100
Storage Spaces Simple	0.939	2.326	86	104
Storage Spaces Mirror	2.016	1.866	185	84
Storage Spaces Parity	2.180	2.211	200	99
RAID 0	82.908	11.727	7,603	526
RAID 1	33.246	2.178	3,049	98
RAID 5	24.875	0.618	2,281	28

***Table 4** Random 4KiB (Q= 32, T= 1) Small I/O*

4.1.2. Large I/O

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	83.046	82.737	100	100
Storage Spaces Simple	68.996	69.518	83	84
Storage Spaces Mirror	77.490	68.784	93	83
Storage Spaces Parity	143.018	39.009	172	47
RAID 0	278.915	277.242	336	335
RAID 1	79.580	79.055	96	96
RAID 5	209.809	6.815	253	8

***Table 5** Sequential 1MiB (Q= 1, T= 1) Large I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	83.049	83.154	100	100
Storage Spaces Simple	66.896	70.045	81	84
Storage Spaces Mirror	142.915	65.743	172	79
Storage Spaces Parity	150.574	63.650	181	77
RAID 0	281.541	263.616	339	317
RAID 1	77.595	75.185	93	90
RAID 5	212.544	11.743	256	14

***Table 6** Sequential 1MiB (Q= 16, T= 1) Large I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	0.435	1.016	100	100
Storage Spaces Simple	0.438	2.159	101	213
Storage Spaces Mirror	0.435	0.959	100	94
Storage Spaces Parity	0.447	4.830	103	475
RAID 0	0.938	4.237	216	417
RAID 1	1.083	0.982	249	97
RAID 5	0.943	0.270	217	27

***Table 7** Random 4KiB (Q= 1, T= 1) Large I/O*

	Read MB/s	Write MB/s	% of Single Disk Read	% of Single Disk Write
Single Disk	0.918	0.997	100	100
Storage Spaces Simple	2.026	2.302	221	231
Storage Spaces Mirror	1.746	0.977	190	98
Storage Spaces Parity	2.605	6.248	284	627
RAID 0	3.266	4.365	356	438
RAID 1	1.687	0.979	184	98
RAID 5	3.255	0.839	355	84

***Table 8** Random 4KiB (Q= 32, T= 1) Large I/O*

4.1.3. Graphs

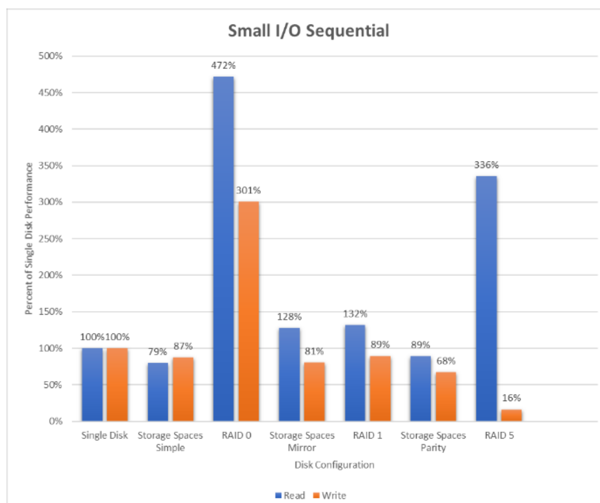

***Figure 5** Small I/O Sequential Performance*

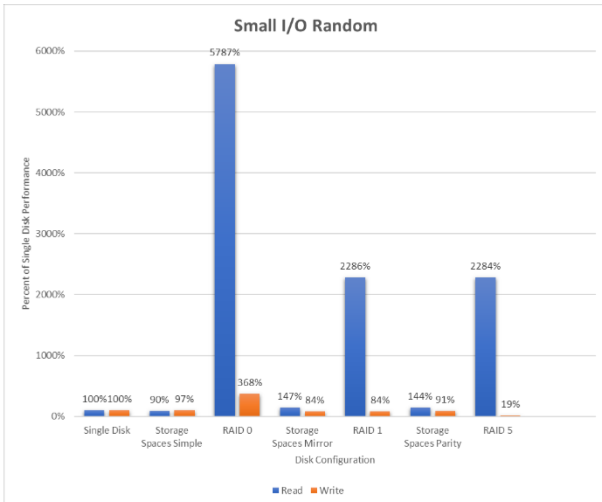

Figure 6 *Small I/O Random Performance*

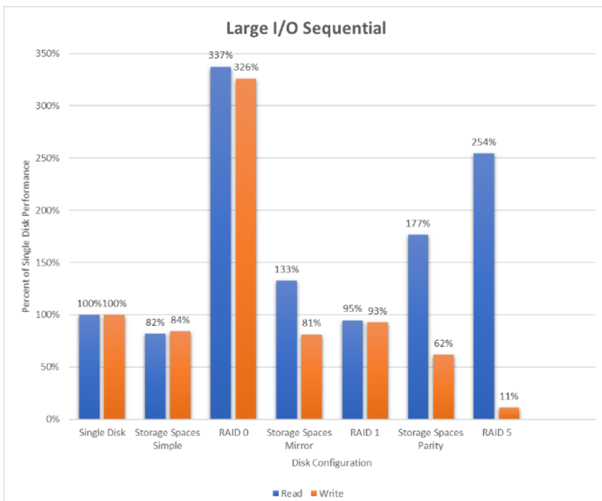

Figure 7 *Large I/O Sequential Performance*

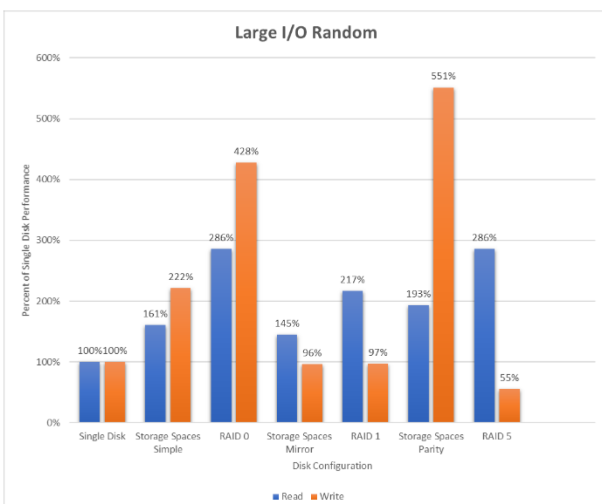

Figure 8 *Large I/O Random Performance*

4.2. Analysis

Based on the results, Intel RST RAID outperformed Windows Storage Spaces overall. By far the best performing of all configurations was RST RAID 0, losing out only to Storage Space Parity in random writes to large file sizes (Figure 8).

As can be seen in the results, there is a significant increase in performance in small I/O random reads compared to large I/O reads. This jump is more appreciable between the 16MiB file size and the 32MiB file size, as shown in Appendix A. One hypothesis for this is due to the size of the cache on the disks used for the benchmarking. At 8Mb each, in a 4-disk RAID 0 array they are the perfect size to cache a majority of the striped file and generate speeds orders of magnitude higher than any other result.

4.2.1. Storage Spaces Simple versus RAID 0

The results are definitive that RAID 0 was better in every metric when compared to Storage Spaces Simple. The Simple configuration was beaten by the single disk performance in all but large I/O random accesses. It is clear from the results that Storage Spaces Simple is not built upon a framework that resembles RAID 0; this configuration should be avoided at all costs.

4.2.2. Storage Spaces Mirror versus RAID 1

These are the two most evenly matched configurations in the tests. They are within 10% of one another on all disk writing tests. RAID 1 has significantly better small I/O random reads and marginally better large I/O reads, whereas Storage Spaces Mirror outperforms it in large I/O sequential reads. With the advantages in small I/O accesses that most users encounter, RAID I/O is the better choice between these configurations, however Storage Spaces Mirror is perfectly acceptable.

4.2.3. Storage Spaces Parity versus RAID 5

This is the most divisive comparison between configurations. RAID 5 provides incomparably faster read times for small I/O, and a healthy advantage in large I/O reads. This comes at a cost of the write speed however, as Storage Space Parity beats it by at least a factor of two in all tests, providing the highest overall write speed for large random writes. The poor write speeds, and lower reads than RAID 0 make RAID 5 hard to recommend unless the redundancy is a factor. In which case, RAID 1 offers comparable read speeds, better write speeds, and full one-to-one redundancy. Storage Spaces Parity should be considered by users who plan on using their machines for high I/O processes such as video rendering, and who want the added security not afforded by RAID 0.

5. Related Work

Hsieh et al. [8] found that for most cases the performance of software RAID was equivalent to hardware RAID. It was found that software RAID was faster for some cases of sequential writing. For our testing configuration, we did not find that the performance of software RAID was equivalent to hardware RAID; Intel RST performed better on average than Storage Spaces. Our results partially agree with their findings that software RAID showed better write speeds, as this was the case for all configurations except RAID 0 versus Storage Spaces Simple. Some of the testing discrepancies may come from our benchmarks using single threaded performance tools, whereas the primary methodology of Hsieh et al. was using parallel file systems. They also used a 2Gb file for I/O, which is in line with our large I/O results being the closest match to their data.

Chen et al. [12] found that for small I/O requests, RAID 1 performed better than RAID 5, and that for large I/O requests, RAID 5 performed better than RAID 1. These results are supported by the literature from Patterson et al. [4] who found similar results, shown in Figure 1. These results match our findings when comparing Storage Spaces performance, as shown in Figures 5 through 8. For Intel RST however, reads are faster on RAID 5 for both small and large I/O, and writes were found to be faster for both small and large I/O.

Hermanoy et al. [7] found in their testing that RAID 5 and RAID 0 had performance results within 10% of each other on I/O reads, with RAID 0 exhibiting up to 30 times faster write speeds. Our results partially agree with their data. In testing, only large random I/O reads were within 10% of one another, where every other case RAID 0 had faster speeds. Small sequential I/O reads were approximately 1.4 times as fast (Figure 5), and small random I/O reads were approximately 2.5 times as fast. Our results agreed across the board that RAID 0 has faster write times than RAID 5. Comparing the 21.8 times faster RAID 0 versus RAID 5 sequential Q32T1 write noted in the literature review, our results found that for our equivalent sequential Q16T1 write test RAID 0 had 22.5 times faster write speed than RAID 5.

6. Future Work

There is ample opportunity for continuing work on this topic. While Windows Storage Spaces was an obvious choice due to its inclusion in the Windows 10 operating system, the results of our tests when compared to the literature suggest that more powerful software suites are available. A comparison of RAID 10 (levels 1 + 0) should also be considered, as it is an extremely common setup, yet does not have a lot of literature around its performance.

Aside from disk configurations, more evaluations can be done on different hard disks. The 8Mb cache on the Toshiba drives used in this test appeared to skew some of the lower I/O numbers. A comparison on drives with varying amounts of cache and disk speeds would be warranted. Due to the proliferation of solid-state drives (SSDs), it would be pertinent to compare software versus hardware RAID for SSD arrays, as well as compare performance from SSD arrays to hard disk arrays.

Testing on more dedicated hardware RAID controllers would be beneficial in order to see how Intel RST stacks up in comparison.

Having a benchmarking tool that uses file sizes less than 16Mb to test smaller I/O levels is another avenue of research to explore.

7. Conclusion

This paper has evaluated the performance of software RAID versus hardware RAID in the Windows 10 operating system. It was found that overall the hardware Intel Rapid Storage Technology RAID configuration performed better than the Windows Storage Spaces software RAID configuration. Intel RST was found to be the best performing of all configurations. For users who do not need the redundancy features of other configurations, this is clearly the best solution of those tested. The Storage Spaces Simple configuration performed worse than single disk across all but one metric and should be avoided. Users looking to perform large I/O writes may gain some advantage with the Storage Spaces Parity array. Both Storage Spaces Mirror and RAID 1 offered similar levels of performance, with RAID 1 being preferred due to marginally better small I/O access speeds.

References

[1] A. Silberschatz, P. Galvin, and G. Gagne, *Operating System Concepts, 9th Edition*. John Wiley & Sons, 2012.

[2] "Cisco UCS Servers RAID Guide", *Cisco*, 2020. [Online]. Available: https://www.cisco.com/c/en/us/td/docs/unified_computing/ucs/c/sw/raid/configuration/guide/RAID_GUIDE/IntroToRAID.html.

[3] "CrystalDiskInfo", *Crystal Dew World [en]*, 2020. [Online]. Available: https://crystalmark.info/en/software/crystaldiskinfo/.

[4] D. Patterson, G. Gibson, R. Katz, “A case for Redundant Arrays of Inexpensive Disks (RAID),” (1988).

ACM SIGMOD Record. 17. 10.1145/50202.50214.

[5] "Desktop Windows Version Market Share Worldwide", *StatCounter Global Stats*, 2020. [Online]. Available: https://gs.statcounter.com/os-version-market-share/windows/desktop/worldwide.

[6] "Guide to SATA Hard Disks Installation and RAID Configuration", *ASRock.com*. [Online]. Available: https://download.asrock.com/Manual/RAID/Z390%20Taichi/English.pdf.

[7] E. Hermanoy, Marcel and E. Kristianto, "Performance analysis of RAID storage server with software-based accelerator PernixData FVP," 2016 International Conference on Information Technology Systems and Innovation (ICITSI), Bandung, 2016, pp. 1-5, doi: 10.1109/ICITSI.2016.7858190.

[8] J. Hsieh, C. Stanton and R. Ali, "Performance evaluation of software RAID vs. hardware RAID for Parallel Virtual File System," Ninth International Conference on Parallel and Distributed Systems, 2002. Proceedings., Taiwan, China, 2002, pp. 307-313, doi: 10.1109/ICPADS.2002.1183417.

[9] J. Desjardins, "How much data is generated each day?", *World Economic Forum*, 2019. [Online]. Available: https://www.weforum.org/agenda/2019/04/how-much-data-is-generated-each-day-cf4bddf29f/.

[10] "NTFS overview", *Docs.microsoft.com*, 2019. [Online]. Available: https://docs.microsoft.com/en-us/windows-server/storage/file-server/ntfs-overview.

[11] S. Bokare, S. Pote and B. Shinde, "Evaluation of Performance Parameters of Heterogeneous Storage Cluster using RAID and Erasure Code," 2017 International Conference on Computing, Communication, Control and Automation (ICCUBEA), Pune, 2017, pp. 1-5, doi: 10.1109/ICCUBEA.2017.8463724.

[12] S. Chen and D. Towsley, "A performance evaluation of RAID architectures," in IEEE Transactions on Computers, vol. 45, no. 10, pp. 1116-1130, Oct. 1996, doi: 10.1109/12.543706.

[13] "Storage Spaces in Windows 10", *Support.microsoft.com*, 2016. [Online]. Available: https://support.microsoft.com/en-us/help/12438/windows-10-storage-spaces.

[14] "What Is NTFS?: Local File Systems", *Docs.microsoft.com*, 2009. [Online]. Available: https://docs.microsoft.com/en-us/previous-versions/windows/it-pro/windows-server-2003/cc778410(v%3dws.10).

Appendix A – Data

Single Disk								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	88.493	83.671	91.228	66.902	0.686	2.569	1.147	2.632
32MiB	83.88	83.261	83.677	83.681	0.587	2.075	1.034	1.828
1G	82.836	82.632	85.563	83.678	0.453	1.036	1.007	1.041
4G	83.255	82.842	80.535	82.63	0.416	0.996	0.828	0.952
Small I/O	***86.1865***	***83.466***	***87.4525***	***75.2915***	***0.6365***	***2.322***	***1.0905***	***2.23***
Large I/O	***83.0455***	***82.737***	***83.049***	***83.154***	***0.4345***	***1.016***	***0.9175***	***0.9965***

Storage Spaces Simple								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	68.579	68.581	71.299	69.42	0.609	2.373	0.992	2.744
32MiB	68.777	68.79	67.322	69.413	0.581	1.811	0.886	1.907
1G	68.995	69.408	66.895	70.045	0.458	2.249	2.036	2.426
4G	68.997	69.628	66.896	70.044	0.418	2.069	2.015	2.178
Small I/O	***68.678***	***68.6855***	***69.3105***	***69.4165***	***0.595***	***2.092***	***0.939***	***2.3255***
Large I/O	***68.996***	***69.518***	***66.8955***	***70.0445***	***0.438***	***2.159***	***2.0255***	***2.302***

Storage Spaces Mirror								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	75.499	68.787	150.984	55.987	0.764	2.208	2.183	2.104
32MiB	77.18	68.576	142.174	63.327	0.619	1.753	1.849	1.628
1G	83.675	68.569	143.008	65.428	0.453	0.96	1.876	1.03
4G	71.305	68.999	142.821	66.057	0.416	0.958	1.616	0.923
Small I/O	***76.3395***	***68.6815***	***146.579***	***59.657***	***0.6915***	***1.9805***	***2.016***	***1.866***
Large I/O	***77.49***	***68.784***	***142.9145***	***65.7425***	***0.4345***	***0.959***	***1.746***	***0.9765***

Storage Spaces Parity								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	59.98	42.364	91.858	66.482	0.606	2.407	2.336	2.039
32MiB	65.214	35.86	92.281	66.269	0.526	1.438	2.023	2.382
1G	143.029	42.574	150.144	63.754	0.461	4.97	2.624	3.801
4G	143.007	35.444	151.004	63.545	0.433	4.69	2.586	8.695
Small I/O	***62.597***	***39.112***	***92.0695***	***66.3755***	***0.566***	***1.9225***	***2.1795***	***2.2105***
Large I/O	***143.018***	***39.009***	***150.574***	***63.6495***	***0.447***	***4.83***	***2.605***	***6.248***

RAID 0								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	301.788	189.381	732.558	221.232	47.648	7.851	156.999	12.184
32MiB	301.757	268.436	305.547	271.563	2.904	1.934	8.817	11.27
1G	278.899	275.578	281.018	263.813	0.974	4.898	3.424	4.953
4G	278.93	278.906	282.064	263.418	0.901	3.575	3.108	3.777
Small I/O	***301.7725***	***228.9085***	***519.0525***	***246.3975***	***25.276***	***4.8925***	***82.908***	***11.727***
Large I/O	***278.9145***	***277.242***	***281.541***	***263.6155***	***0.9375***	***4.2365***	***3.266***	***4.365***

RAID 1								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	93.521	79.055	189.991	58.295	17.52	2.242	62.315	2.394
32MiB	84.303	76.756	91.005	70.257	1.865	1.004	4.177	1.961
1G	79.475	79.056	76.544	76.968	0.922	1.034	1.856	1.027
4G	79.684	79.053	78.646	73.401	1.244	0.929	1.517	0.93
Small I/O	***88.912***	***77.9055***	***140.498***	***64.276***	***9.6925***	***1.623***	***33.246***	***2.1775***
Large I/O	***79.5795***	***79.0545***	***77.595***	***75.1845***	***1.083***	***0.9815***	***1.6865***	***0.9785***

RAID 5								
	Sequential Q1T1		**Sequential Q16T1**		**RND Q1T1**		**RND Q32T1**	
	Read MB/s	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**	**Read MB/s**	**Write MB/s**
16MiB	217.243	6.71	496.428	16.776	26.513	0.257	42.043	0.541
32MiB	217.247	6.71	236.36	20.341	2.593	0.264	7.706	0.695
1G	210.119	6.919	212.637	17.615	0.981	0.272	3.478	0.866
4G	209.498	6.711	212.45	5.871	0.905	0.267	3.032	0.811
Small I/O	***217.245***	***6.71***	***366.394***	***18.5585***	***14.553***	***0.2605***	***24.8745***	***0.618***
Large I/O	***209.8085***	***6.815***	***212.5435***	***11.743***	***0.943***	***0.2695***	***3.255***	***0.8385***