

Mini Project 3 Report

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Class: Advanced Computer Systems

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1. Introduction

The purpose of this mini-project is to develop first-hands knowledge and deeper understanding of modern memory and storage devices. In order to achieve this the software Intel Memory Latency Checker, as well as Flexible IO tester will be used. Tests will be run in order to analyze and compare both lab partners' hardware performance, and storage/memory tests will also be cross checked with the Intel Data Center NVMe SSD D7-P5600. The first computer which will be referred to as "Device 1" has an intel i7-8700k processor overclocked at 4.45 GHz. It has 32 GB of DDR4 ram installed with a 3600 MHz clock rate. The SSD installed is the Samsung SSD 960 Evo, with 500GB of storage. The second computer which will be referred to as "Device 2" has an Intel Core i7 8705G with a clock rate of 3.1 GHz. It has 8 GB of DDR4 ram installed with a 2400 MHz clock rate. The SSD installed is the Samsung PM981 M.2 SSD, with 256GB of storage.

The Intel Memory Latency Checker runs a variety of tests in order to measure the memory latency of your Intel processor. It measures idle memory latencies, peak injection memory bandwidth, memory bandwidth, latency at different bandwidths, as well as latency between caches in the processor. All of these tests vary some sort of input, such as socket origination/destination, read/write size, bandwidth, etc. The output of each of these tests is a matrix which can be used to compare different processors' performance.

Flexible IO tester was originally created in order to simulate an I/O workload with many varying parameters such as number of processes or threads. Given that a fake workload can be created by giving FIO a "job," test cases can be run in order to understand how your device's storage devices function, and how effective they are in various situations.

This report will cover the results of all of our experiments and analysis with both Intel MLC, as well as FIO. All command lines and shell output will be presented in the appendices at the end of the document, and all data will be cleanly presented in graphs, when necessary, in the results section.

2. Intel Memory Latency Checker Results and Analysis

2.1 Peak Injection Bandwidth

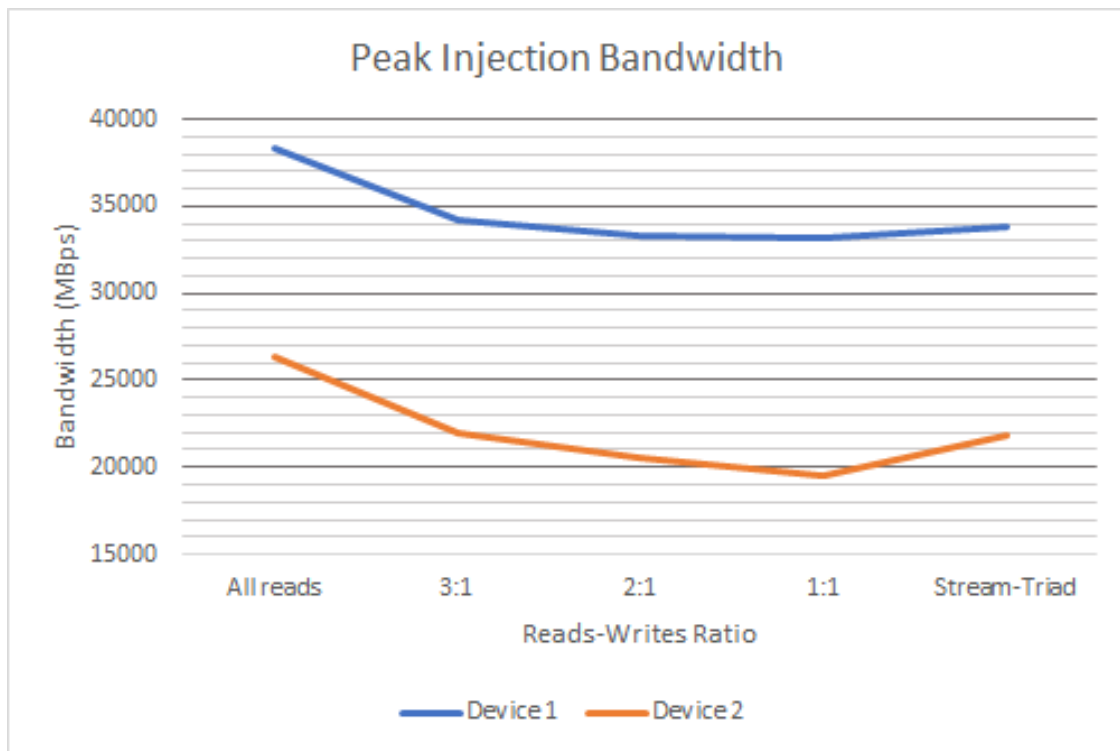


Figure 1: Peak injection bandwidth of Device 1 and 2 at different read-write ratios

According to the Intel MLC readme, peak injection bandwidth is when each core is generating requests as fast as it can, therefore maxing out your cache and memory in order to achieve as many reads and writes as possible. Above is a graph of the peak injection bandwidth in MBps of both Device 1 and Device 2. This shows how bandwidth is affected by altering the read-write ratio, with STREAM-triad also included for additional context. Typically cache and memory have a higher peak injection associated with more reads than writes. Our test results are consistent with our expectations, given that 1:1, our highest quantity of writes, showed the lowest bandwidth.

STREAM triad is included by the memory latency checker in order to show how the device operates when performing a more complex operation, see the explanation from the Intel website below.

Triad

Of all the vector kernels Triad is the most complex scenario and is highly relevant to HPC.

The STREAM Triad kernel is as follows:

```
1 | #pragma parallel for
2 |     for (i = 0; i < N; i++) {
3 |         a[i] = b[i] + c[i] * SCALAR;
4 |     }
```

Figure 2: STREAM Triad kernel explanation

Given the information we learned when researching STREAM triad, we expected it to be less efficient than 1:1 read-write, but the actual result was consistently between 3:1 and 2:1, therefore making it exceed our expectations for both devices. It is also worth noting that there are other STREAM operations that MLC does not test, such as copy, scale, and sum.

name	kernel	bytes/iter	FLOPS/iter
COPY:	$a(i) = b(i)$	16	0
SCALE:	$a(i) = q * b(i)$	16	1
SUM:	$a(i) = b(i) + c(i)$	24	1
TRIAD:	$a(i) = b(i) + q * c(i)$	24	2

Figure 3: Stream Operations

2.2 Maximum Memory Bandwidth

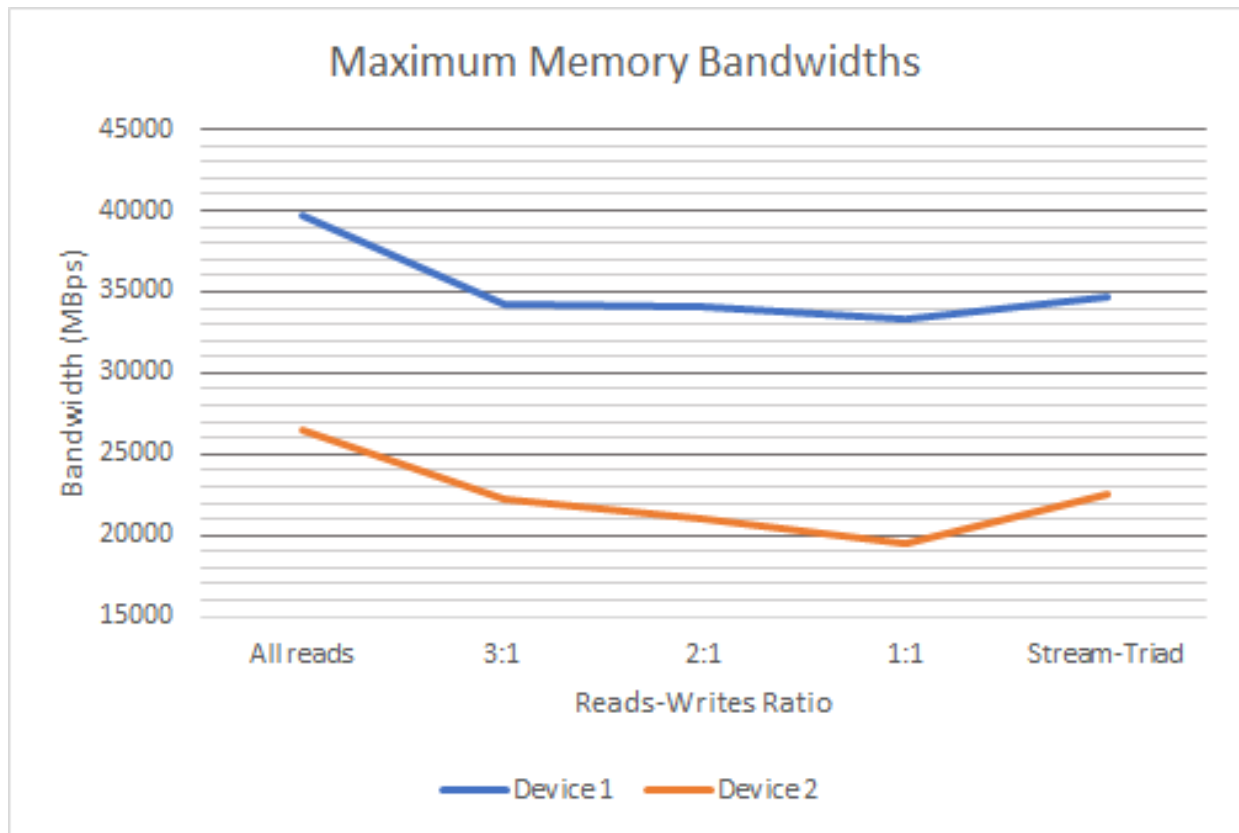


Figure 4: Maximum memory bandwidths of Device 1 and 2 at different read-write ratios

Maximum memory bandwidth, as defined by Intel, is the “maximum rate at which data can be read from or stored into a semiconductor memory by the processor.” This tells us that our results should theoretically be in line and fully consistent with our peak injection bandwidth. Given our test results seen for both Device 1 and Device 2 in the graph above, this is true with the only exception being that STREAM-triad saw slightly better results. The graph as a whole is also more “smooth” from 3:1 to 1:1 read-writes. There is a clear linear relationship with decreasing efficiency as more writes are attempted. As a whole, across all cache and memory tests, our results showed greater efficiency and less of a load on each device when performing read operations even at maximum capacity. This was as expected as there is an extra workload associated with writing operations in cache and memory.

2.3 Loaded Latencies

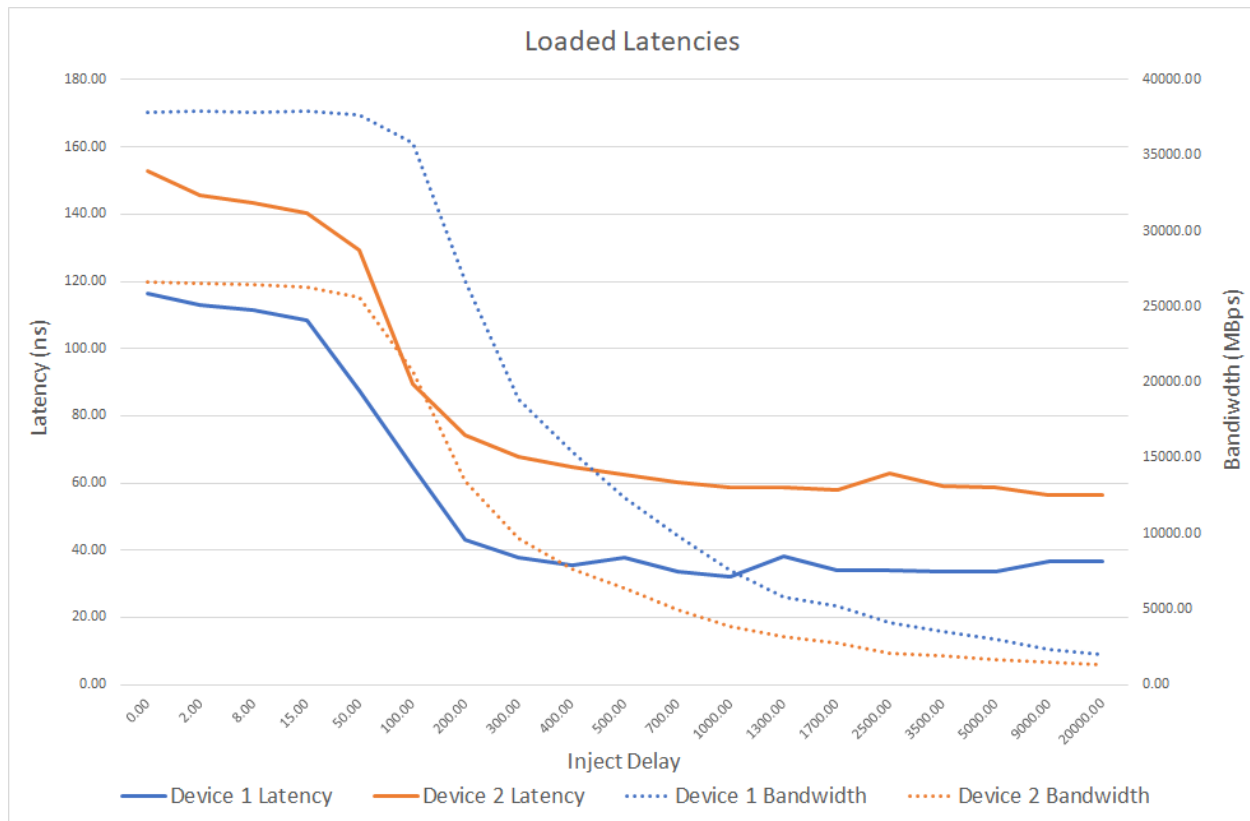


Figure 5: Loaded latencies of Device 1 and 2 at different inject delays

The loaded latency command is for truly seeing how bandwidth can come to influence latency. As shown by the graph above, latency increases with overall bandwidth, and decreases with a decreasing bandwidth. As injection delay is varied, bandwidth and latency both change and follow roughly the same correlation. If you focus on the lower end of the graph (0 to 15000 MBps bandwidth) the latency is almost negligible, however, as bandwidth increases the latency becomes more and more of an issue, especially with device 2. Although the axes aren't equivalent (the latency is not scaled to bandwidth) the latency disproportionately increased with increasing bandwidth greatly affecting performance. With lower end hardware, the ratio of latency to bandwidth is relatively similar, but assuming you have a minimum performance standard, in a limited hardware environment the latency can really cause issues for the system.

This idea of latency increasing with bandwidth was one of the goals set out by the research project to identify. As a result, our data is in line with our expectations and it was interesting to see how the devices compared to each other and to see if they followed the same trends. Understanding performance even in lesser quality hardware

environments is important not only for maximizing high quality enterprise grade hardware, but also for getting the most out of consumer grade hardware.

2.4 Additional Intel MLC Data

MLC can also be used to collect more data which was not fully explored and elaborated on in this section. Idle latencies as well as cache-to-cache transfer latency was also measured. The results were in line with our expectations and there was not much to elaborate on other than just providing the terminal output. See appendix A for more information as well as command line input and output.

3. Flexible I/O Tester (FIO) Tests and Analysis

3.1 Reads vs Writes test

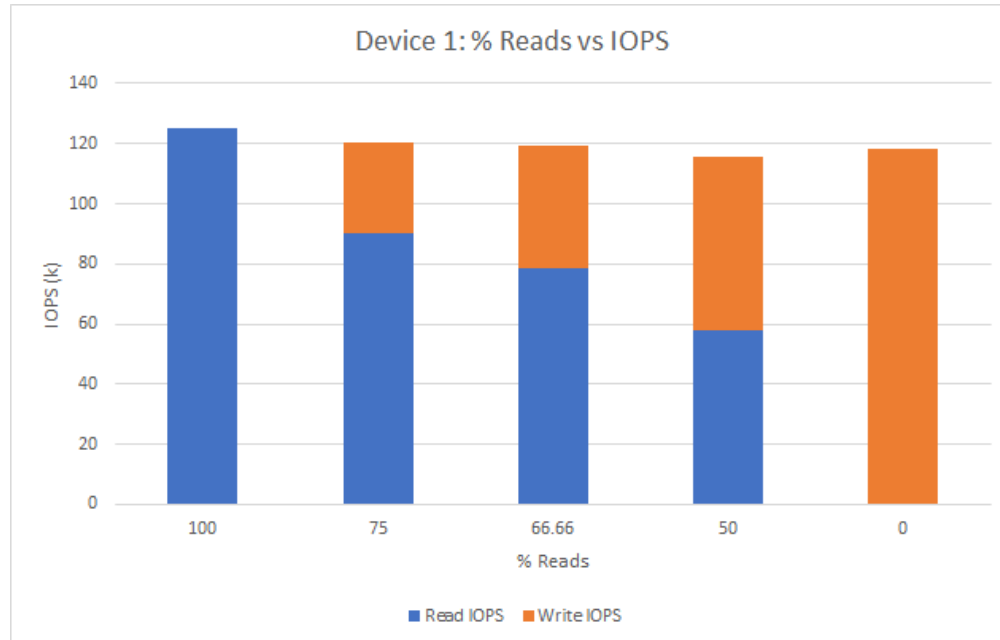


Figure 6: IOPS of Device 1 at varying reads/writes

The Flexible I/O tester (FIO) was used to run a test work load on storage devices to test for the IOPS for different ratios of read/write. The IOPS measured for Device 1, ranged from 30.4k IOPS to 125k IOPS varying with the ratio of read operations to write operations. The total IOPS throughout the different read/write tests are relatively consistent, ranging from around 118k IOPS to 125k IOPS. In the Figure X below, the results from running FIO on Device 2 are shown. The IOPS ranged from 3k IOPS to 41.5k IOPS. The IOPS for this device is significantly lower than the expected IOPS of the SSD installed, determined by the spec sheet on the manufacturer's website, had far less throughput when compared with Device 1. This was expected given the limited hardware environment of device 2.

The total efficiency peaked when Device 1 was doing purely reads, which was expected, and efficiency decreased, minimizing at 1:1 reads to writes. The efficiency slightly increased when switching back to only write statements. This is as expected as writing has a higher overhead than read and given the lack of a two way channel, reading and writing at the same time are the worst efficiency possible. All results for Device 1 were as expected, Device 2 however was somewhat of an anomaly. This could be a result of the age and past use of Device 2, but it overall gained efficiency the

more write statements that were made, and reading had an overall far worse efficiency. The throughput and latency greatly increased especially when reading.

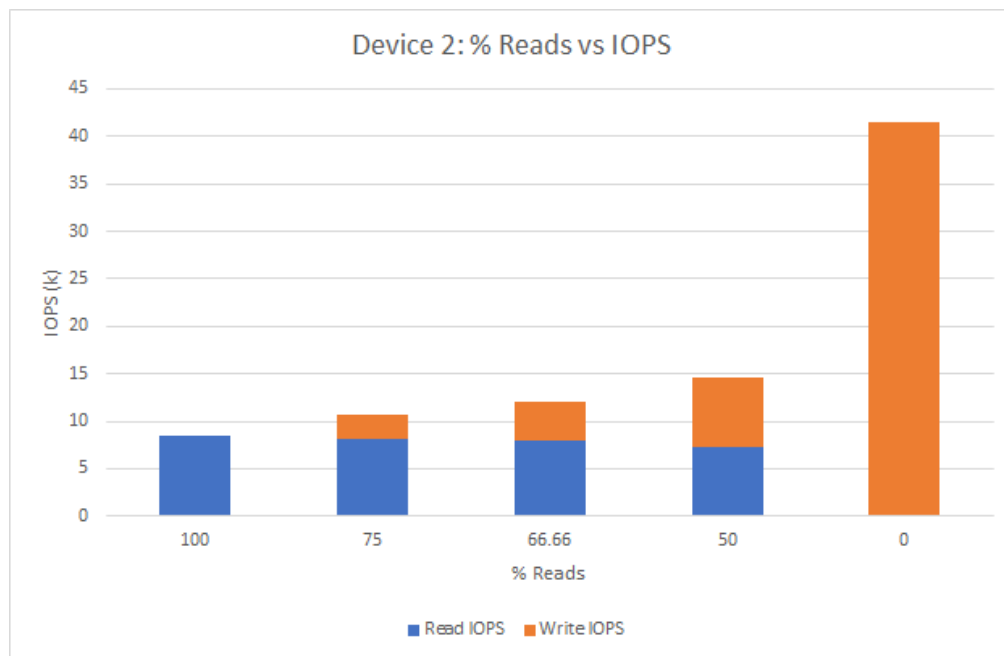


Figure 7: IOPS of Device 2 at varying reads/writes

3.2 Latency Tests

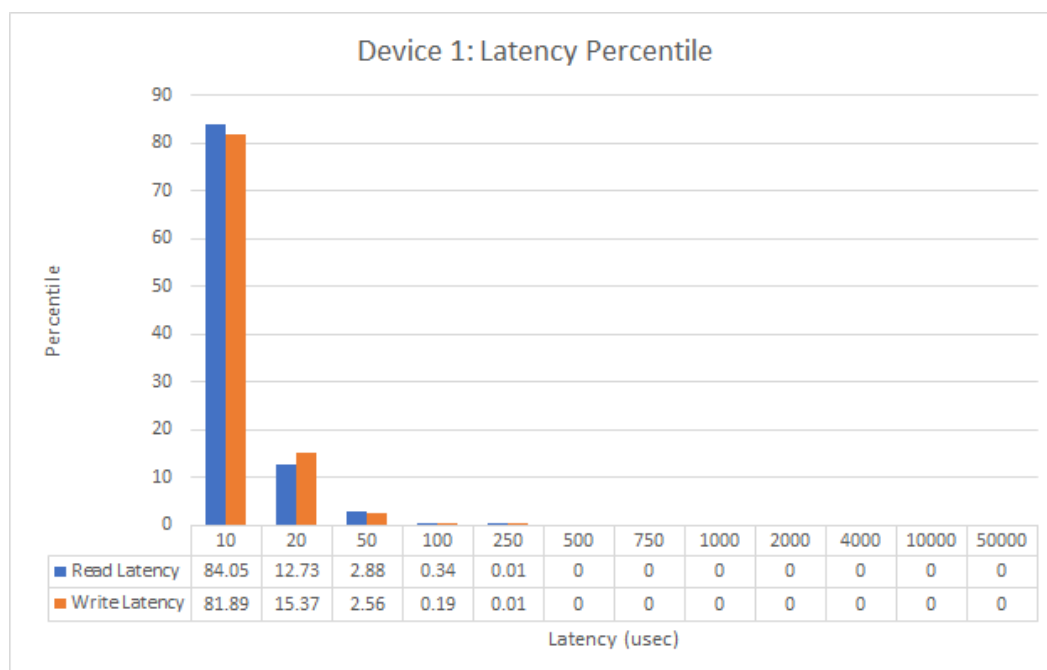


Figure 8: Latency Percentile of Device 1

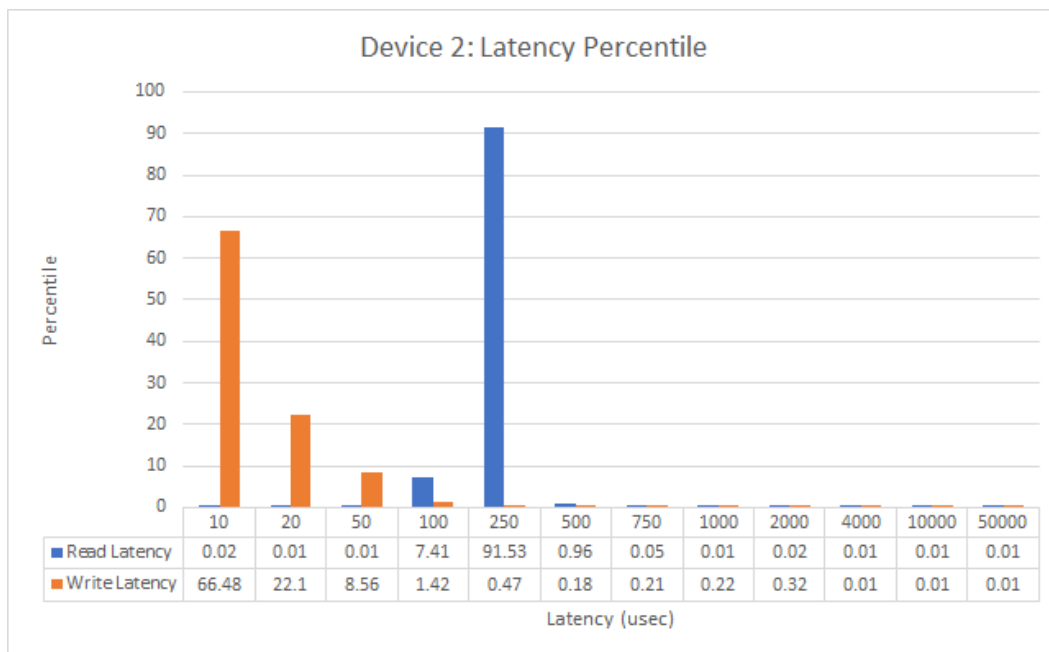


Figure 9: Latency Percentile of Device 2

Above are two charts showing the latency of Device 1 and 2 when performing all reads, or all writes. As a whole, Device 1 functioned exactly as expected, minor latency across the board, with a few outliers of 50+ microseconds. In addition, the latency increased with throughput when we ran additional tests. Device 2 continued to function irregularly, but aligned with our expectations set forth by the previous tests. The latency of read was far higher for Device 2 which explains why the read IOPS was significantly decreased for Device 2 in the previous tests. Device 1 and 2 despite having different baselines of both latency, IOPS, etc. followed the same increase in latency as throughput was increased.

3.3 Comparison to the Intel Data Center NVMe SSD D7-P5600 (1.6TB)

The Intel Data Center has an advertised read-only 4KB IOPS of 400k and write-only 4KB IOPS of 118k. Our devices both functioned with far less efficiency for reading, but device 1 had a write IOPS that was actually slightly superior. Both of our devices were significantly used and aged, and not optimized at all for the operations we're doing, they also both have file systems installed. This was unexpected partially because the expectation was that Device 1, a workstation grade SSD, would be far inferior to the enterprise grade Intel Data center. Device 2, a consumer grade SSD, functioned mostly as expected for an SSD of its age and quality. The Samsung SSD contained in Device 1 is expected to function over 300k IOPS read and write, but these tests are done in a controlled environment on a fresh SSD that is optimized for stress tests of this caliber, complete with a 2 way file system to simultaneously read and write. The Intel Data Center NVMe SSD functions far superior to device 2, but device 1 in its prime could technically compete which is quite impressive for a workstation grade SSD.

4. Conclusion

As a whole the results of our tests were mostly in line with our expectations. All of the Intel MLC results were as expected regarding the cache and memory. Most of the variance in expectations or results occurred in the FIO storage and memory category of testing. Device 1 functioned as expected, but not necessarily as efficiently as expected in the context of FIO, storage, and memory. That can be attributed to both its age as well as the filesystem installed. Device 2 functioned irregularly in the context of storage and memory especially, given that it found incredible difficulty in achieving high throughput when reading, the latency was growing increasingly and it is indicative that there are significant issues with the functionality with Device 2's SSD.

Consistently across the board there was a decrease in latency with lower throughput, and a higher latency with higher throughput. In addition, for storage and memory, device 2 was the only device that functioned with reading at a decreased IOPS/throughput. Device 1 proved to be far superior while also being consistent and in line with expectations set out by both the information available prior to testing and the manufacturer's spec sheet.

Appendix A: Intel Memory Latency Checker

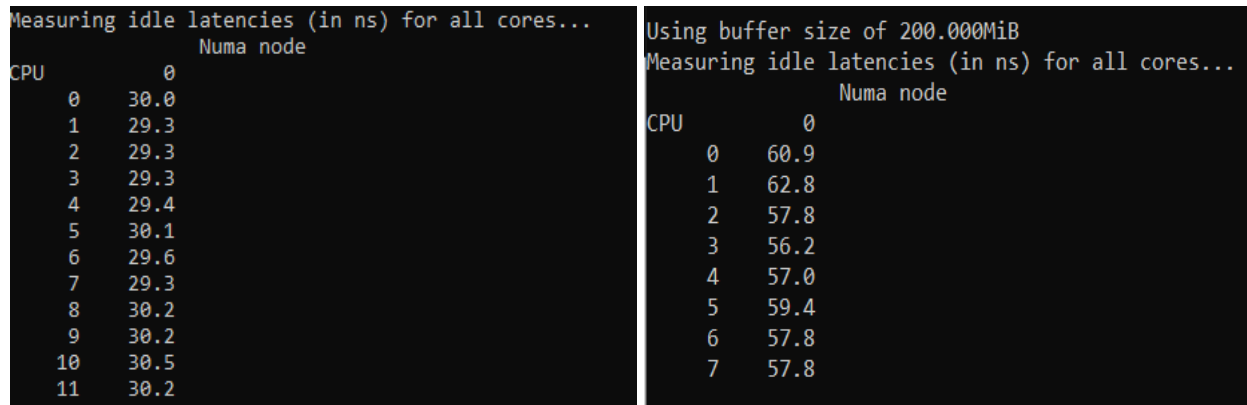


Figure 10: Latency matrix on all CPUs (Device 1: left, Device 2: right)

```
Measuring Peak Injection Memory Bandwidths for the system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
Using traffic with the following read-write ratios
ALL Reads      :      38342.4
3:1 Reads-Writes :      34171.4
2:1 Reads-Writes :      33277.8
1:1 Reads-Writes :      33129.2
Stream-triad like:      33868.2
```

```
Measuring Peak Injection Memory Bandwidths for the system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
Using traffic with the following read-write ratios
ALL Reads      :      26363.6
3:1 Reads-Writes :      21919.8
2:1 Reads-Writes :      20502.4
1:1 Reads-Writes :      19540.3
Stream-triad like:      21786.9
```

Figure 11: Peak injection memory bandwidths (Device 1: top, Device 2: bottom)

(a) 100% Read, 0% Write

```
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
Using Read-only traffic type
      Numa node
Numa node      0
      0      38643.9
```

(b) 75% Read, 25% Write

```
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      32912.7
```

(c) 66.66% Read, 33.37% Write

```
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      32145.8
```

(d) 50% Read, 50% Write

```
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      31720.2
```

(e) 0% Read, 100% Write

```
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      37970.6
```

Figure 12: Memory Bandwidth Matrices of Device 1

(a) 100% Read, 0% Write

```
Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
Using Read-only traffic type
      Numa node
Numa node      0
      0      25708.7
```

(b) 75% Read, 25% Write

```
Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      14969.9
```

(c) 66.66% Read, 33.37% Write

```
Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      15230.0
```

(d) 50% Read, 50% Write

```
Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      19346.9
```

(e) 0% Read, 100% Write

```
Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes
Measuring Memory Bandwidths between nodes within system
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
      Numa node
Numa node      0
      0      23949.0
```

Figure 12: Memory bandwidth matrices of Device 2


```

Measuring Maximum Memory Bandwidths for the system
Will take several minutes to complete as multiple injection rates will be tried to get the best bandwidth
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
Using traffic with the following read-write ratios
ALL Reads      :      39631.59
3:1 Reads-Writes :      34263.82
2:1 Reads-Writes :      34054.57
1:1 Reads-Writes :      33291.68
Stream-triad like:      34718.75

```

```

Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes

```

```

Measuring Maximum Memory Bandwidths for the system
Will take several minutes to complete as multiple injection rates will be tried to get the best bandwidth
Bandwidths are in MB/sec (1 MB/sec = 1,000,000 Bytes/sec)
Using all the threads from each core if Hyper-threading is enabled
Using traffic with the following read-write ratios
ALL Reads      :      26537.77
3:1 Reads-Writes :      22186.29
2:1 Reads-Writes :      21045.80
1:1 Reads-Writes :      19512.95
Stream-triad like:      22518.58

```

Figure 13: Maximum Memory Bandwidths (Device 1: Top, Device 2: Bottom)

```

Command line parameters: --idle_latency

Using buffer size of 200.000MiB
*** Unable to access mlcdrv.sys to modify prefetchers
*** So, enabling random access for latency measurements
Each iteration took 107.3 core clocks ( 29.0 ns)

Intel(R) Memory Latency Checker - v3.9
Command line parameters: --idle_latency

Using buffer size of 200.000MiB
Each iteration took 175.3 core clocks ( 56.7 ns)

```

Figure 14: Idle Latency (Device 1: Top, Device 2: Bottom)

```

Measuring cache-to-cache transfer latency (in ns)...
Using small pages for allocating buffers
Local Socket L2->L2 HIT latency      12.6
Local Socket L2->L2 HITM latency     20.3

Measuring cache-to-cache transfer latency (in ns)...
Using small pages for allocating buffers
Local Socket L2->L2 HIT latency      22.3
Local Socket L2->L2 HITM latency     25.6

```

Figure 15: Cache to Cache Transfer Latency (Device 1: Top, Device 2: Bottom)

```

Measuring Loaded Latencies for the system
Using all the threads from each core if Hyper-threading is enabled
Using Read-only traffic type
Inject Latency Bandwidth
Delay (ns) MB/sec
=====
00000 116.44 37856.0
00002 112.93 37944.5
00008 111.29 37861.0
00015 108.56 37903.5
00050 87.71 37642.8
00100 64.78 35830.1
00200 43.03 26690.5
00300 37.93 18893.9
00400 35.63 15391.8
00500 37.93 12388.0
00700 33.57 9810.5
01000 32.28 7569.4
01300 38.16 5802.5
01700 34.12 5164.4
02500 34.17 4111.4
03500 33.56 3507.5
05000 33.77 3019.2
09000 36.73 2346.5
20000 36.56 2025.6

```

Using buffer size of 100.000MiB/thread for reads and an additional 100.000MiB/thread for writes

```

Measuring Loaded Latencies for the system
Using all the threads from each core if Hyper-threading is enabled
Using Read-only traffic type
Inject Latency Bandwidth
Delay (ns) MB/sec
=====
00000 152.83 26594.1
00002 145.78 26555.9
00008 143.54 26428.7
00015 140.43 26286.1
00050 129.12 25600.9
00100 89.38 20704.9
00200 74.09 13479.0
00300 67.81 9677.6
00400 64.63 7657.8
00500 62.59 6414.9
00700 60.23 4958.6
01000 58.83 3832.8
01300 58.73 3214.2
01700 57.81 2737.6
02500 62.80 2104.6
03500 59.07 1871.1
05000 58.56 1647.1
09000 56.46 1444.3
20000 56.29 1277.2

```

Figure 16: Loaded Latency (Device 1: Top, Device 2: Bottom)

Appendix B: Flexible I/O Tester (FIO)

(a) 100% Read, 0% Write

```
tskillz@DESKTOP-Q0778AD:~$ sudo fio --name=random-write --rw=randrw --rwmixread=100 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [r(1)][100.0%][r=492MiB/s][r=126k IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=1029: Tue Mar 9 18:18:58 2021
  read: IOPS=125k, BW=489MiB/s (513MB/s)(4096MiB/8378msec)
    clat (usec): min=4, max=163, avg= 7.62, stdev= 5.59
    lat (usec): min=4, max=163, avg= 7.66, stdev= 5.60
    clat percentiles (nsec):
      | 1.00th=[ 4704],  5.00th=[ 4896], 10.00th=[ 5152], 20.00th=[ 5408],
      | 30.00th=[ 5472], 40.00th=[ 5536], 50.00th=[ 5600], 60.00th=[ 5728],
      | 70.00th=[ 5920], 80.00th=[ 8640], 90.00th=[12864], 95.00th=[18048],
      | 99.00th=[29056], 99.50th=[41216], 99.90th=[64768], 99.95th=[73216],
      | 99.99th=[84480]
    bw ( KiB/s): min=480822, max=506466, per=97.90%, avg=490125.69, stdev=7448.09, samples=16
    iops       : min=120205, max=126616, avg=122530.88, stdev=1862.04, samples=16
    lat (usec) : 10=84.05%, 20=12.73%, 50=2.88%, 100=0.34%, 250=0.01%
    cpu        : usr=10.25%, sys=89.90%, ctx=0, majf=0, minf=31
    IO depths  : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=1048576,0,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency    : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=489MiB/s (513MB/s), 489MiB/s-489MiB/s (513MB/s-513MB/s), io=4096MiB (4295MB), run=8378-8378msec
```

(b) 75% Read, 25% Write

```
tskillz@DESKTOP-Q0778AD:~$ sudo fio --name=random-write --rw=randrw --rwmixread=75 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [m(1)][100.0%][r=357MiB/s,w=118MiB/s][r=91.4k,w=30.1k IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=1045: Tue Mar 9 18:20:44 2021
  read: IOPS=90.0k, BW=355MiB/s (373MB/s)(3070MiB/8637msec)
    clat (usec): min=4, max=184, avg= 7.65, stdev= 5.23
    lat (usec): min=4, max=184, avg= 7.68, stdev= 5.24
    clat percentiles (nsec):
      | 1.00th=[ 4768],  5.00th=[ 4960], 10.00th=[ 5280], 20.00th=[ 5472],
      | 30.00th=[ 5536], 40.00th=[ 5664], 50.00th=[ 5728], 60.00th=[ 5920],
      | 70.00th=[ 6240], 80.00th=[ 8768], 90.00th=[12736], 95.00th=[17280],
      | 99.00th=[27264], 99.50th=[34560], 99.90th=[63232], 99.95th=[73216],
      | 99.99th=[85504]
    bw ( KiB/s): min=344696, max=385408, per=98.07%, avg=356961.18, stdev=8535.99, samples=17
    iops       : min=86174, max=96352, avg=89239.94, stdev=2134.03, samples=17
  write: IOPS=30.4k, BW=119MiB/s (125MB/s)(1026MiB/8637msec); 0 zone resets
    clat (usec): min=4, max=130, avg= 8.37, stdev= 5.43
    lat (usec): min=4, max=130, avg= 8.41, stdev= 5.43
    clat percentiles (nsec):
      | 1.00th=[ 5152],  5.00th=[ 5536], 10.00th=[ 5728], 20.00th=[ 5920],
      | 30.00th=[ 6112], 40.00th=[ 6240], 50.00th=[ 6432], 60.00th=[ 6624],
      | 70.00th=[ 7072], 80.00th=[ 9536], 90.00th=[13760], 95.00th=[18304],
      | 99.00th=[28544], 99.50th=[37120], 99.90th=[65280], 99.95th=[74240],
      | 99.99th=[87552]
    bw ( KiB/s): min=114864, max=127027, per=98.08%, avg=119308.18, stdev=2522.97, samples=17
    iops       : min=28716, max=31756, avg=29826.53, stdev=630.62, samples=17
    lat (usec) : 10=83.10%, 20=13.89%, 50=2.74%, 100=0.28%, 250=0.01%
    cpu        : usr=11.04%, sys=88.83%, ctx=0, majf=0, minf=32
    IO depths  : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=785920,262656,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency    : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=355MiB/s (373MB/s), 355MiB/s-355MiB/s (373MB/s-373MB/s), io=3070MiB (3219MB), run=8637-8637msec
  WRITE: bw=119MiB/s (125MB/s), 119MiB/s-119MiB/s (125MB/s-125MB/s), io=1026MiB (1076MB), run=8637-8637msec
```

(c) 66.66% Read, 33.37% Write

```
tskillz@DESKTOP-Q0778AD:~$ sudo fio --name=random-write --rw=randrw --rwmixread=66.66 --bs=4k --size=4g --numjobs=1
random-write: (groupid=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [m(1)][100.0%][r=301MiB/s,w=154MiB/s][r=76.9k,w=39.4k IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=1061: Tue Mar  9 18:22:32 2021
  read: IOPS=78.8k, BW=308MiB/s (323MB/s)(2703MiB/8784msec)
    clat (usec): min=4, max=661, avg= 7.69, stdev= 5.02
      lat (usec): min=4, max=661, avg= 7.72, stdev= 5.03
    clat percentiles (nsec):
      | 1.00th=[ 4704],  5.00th=[ 5024], 10.00th=[ 5280], 20.00th=[ 5472],
      | 30.00th=[ 5600], 40.00th=[ 5728], 50.00th=[ 5856], 60.00th=[ 5984],
      | 70.00th=[ 6432], 80.00th=[ 8896], 90.00th=[12992], 95.00th=[17024],
      | 99.00th=[26240], 99.50th=[32384], 99.90th=[56064], 99.95th=[64256],
      | 99.99th=[80384]
    bw (  KiB/s): min=290980, max=323209, per=98.04%, avg=308892.24, stdev=8443.91, samples=17
    iops       : min=72745, max=80802, avg=77222.59, stdev=2110.91, samples=17
  write: IOPS=40.6k, BW=159MiB/s (166MB/s)(1393MiB/8784msec); 0 zone resets
    clat (usec): min=4, max=3958, avg= 8.52, stdev= 8.67
      lat (usec): min=4, max=3958, avg= 8.57, stdev= 8.67
    clat percentiles (nsec):
      | 1.00th=[ 5152],  5.00th=[ 5600], 10.00th=[ 5856], 20.00th=[ 6112],
      | 30.00th=[ 6240], 40.00th=[ 6432], 50.00th=[ 6624], 60.00th=[ 6816],
      | 70.00th=[ 7392], 80.00th=[ 9920], 90.00th=[14016], 95.00th=[18048],
      | 99.00th=[27264], 99.50th=[34560], 99.90th=[57088], 99.95th=[67072],
      | 99.99th=[86528]
    bw (  KiB/s): min=152211, max=166590, per=98.08%, avg=159319.82, stdev=4401.32, samples=17
    iops       : min=38052, max=41647, avg=39829.59, stdev=1100.32, samples=17
  lat (usec)   : 10=82.24%, 20=14.88%, 50=2.71%, 100=0.17%, 250=0.01%
  lat (usec)   : 500=0.01%, 750=0.01%
  lat (msec)   : 4=0.01%
  cpu          : usr=9.78%, sys=90.01%, ctx=0, majf=0, minf=33
  IO depths    : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  issued rwts: total=691865,356711,0,0 short=0,0,0 dropped=0,0,0
  latency     : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=308MiB/s (323MB/s), 308MiB/s-308MiB/s (323MB/s-323MB/s), io=2703MiB (2834MB), run=8784-8784msec
  WRITE: bw=159MiB/s (166MB/s), 159MiB/s-159MiB/s (166MB/s-166MB/s), io=1393MiB (1461MB), run=8784-8784msec
```

(d) 50% Read, 50% Write

```
tskillz@DESKTOP-Q0778AD:~$ sudo fio --name=random-write --rw=randrw --rwmixread=50 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [f(1)][100.0%][r=242MiB/s,w=241MiB/s][r=61.8k,w=61.8k IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=262: Wed Mar 10 14:10:58 2021
  read: IOPS=59.2k, BW=231MiB/s (243MB/s)(2049MiB/8855msec)
    clat (usec): min=4, max=128, avg= 7.74, stdev= 5.19
    lat (usec): min=4, max=128, avg= 7.78, stdev= 5.20
    clat percentiles (nsec):
      | 1.00th=[ 4768],  5.00th=[ 5024], 10.00th=[ 5344], 20.00th=[ 5472],
      | 30.00th=[ 5600], 40.00th=[ 5728], 50.00th=[ 5856], 60.00th=[ 6048],
      | 70.00th=[ 6432], 80.00th=[ 8896], 90.00th=[12864], 95.00th=[17024],
      | 99.00th=[27264], 99.50th=[35072], 99.90th=[61696], 99.95th=[70144],
      | 99.99th=[84480]
    bw ( Kib/s): min=225789, max=244214, per=97.66%, avg=231450.18, stdev=4296.03, samples=17
    iops       : min=56447, max=61053, avg=57862.18, stdev=1073.98, samples=17
  write: IOPS=59.2k, BW=231MiB/s (242MB/s)(2047MiB/8855msec); 0 zone resets
    clat (usec): min=4, max=126, avg= 8.32, stdev= 5.34
    lat (usec): min=4, max=126, avg= 8.37, stdev= 5.35
    clat percentiles (nsec):
      | 1.00th=[ 5152],  5.00th=[ 5472], 10.00th=[ 5728], 20.00th=[ 5984],
      | 30.00th=[ 6112], 40.00th=[ 6240], 50.00th=[ 6368], 60.00th=[ 6560],
      | 70.00th=[ 7072], 80.00th=[ 9536], 90.00th=[13760], 95.00th=[18048],
      | 99.00th=[28032], 99.50th=[36608], 99.90th=[64256], 99.95th=[73216],
      | 99.99th=[87552]
    bw ( Kib/s): min=223929, max=242751, per=97.64%, avg=231084.65, stdev=4231.28, samples=17
    iops       : min=55982, max=60687, avg=57770.76, stdev=1057.77, samples=17
  lat (usec)  : 10=82.36%, 20=14.57%, 50=2.79%, 100=0.28%, 250=0.01%
  cpu         : usr=10.58%, sys=88.58%, ctx=0, majf=0, minf=32
  IO depths   : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=524625,523951,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency   : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=231MiB/s (243MB/s), 231MiB/s-231MiB/s (243MB/s-243MB/s), io=2049MiB (2149MB), run=8855-8855msec
  WRITE: bw=231MiB/s (242MB/s), 231MiB/s-231MiB/s (242MB/s-242MB/s), io=2047MiB (2146MB), run=8855-8855msec
```

(e) 0% Read, 100% Write

```
tskillz@DESKTOP-Q0778AD:~$ sudo fio --name=random-write --rw=randrw --rwmixread=0 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [w(1)][100.0%][w=491MiB/s][w=126k IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=1093: Tue Mar 9 18:25:03 2021
  write: IOPS=118k, BW=459MiB/s (482MB/s)(4096MiB/8919msec); 0 zone resets
    clat (usec): min=4, max=173, avg= 8.12, stdev= 4.85
    lat (usec): min=4, max=173, avg= 8.16, stdev= 4.85
    clat percentiles (nsec):
      | 1.00th=[ 5088],  5.00th=[ 5408], 10.00th=[ 5664], 20.00th=[ 5920],
      | 30.00th=[ 6048], 40.00th=[ 6176], 50.00th=[ 6304], 60.00th=[ 6496],
      | 70.00th=[ 6944], 80.00th=[ 9408], 90.00th=[13376], 95.00th=[17024],
      | 99.00th=[26240], 99.50th=[31872], 99.90th=[58112], 99.95th=[66048],
      | 99.99th=[81408]
    bw ( Kib/s): min=433421, max=472310, per=97.82%, avg=460030.88, stdev=9119.58, samples=17
    iops       : min=108355, max=118077, avg=115007.35, stdev=2279.84, samples=17
  lat (usec)  : 10=81.89%, 20=15.37%, 50=2.56%, 100=0.19%, 250=0.01%
  cpu         : usr=9.98%, sys=89.53%, ctx=0, majf=0, minf=30
  IO depths   : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=0,1048576,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency   : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  WRITE: bw=459MiB/s (482MB/s), 459MiB/s-459MiB/s (482MB/s-482MB/s), io=4096MiB (4295MB), run=8919-8919msec
```

Figure 17: Results from running fio with file size of 4GB and block size of 4KB for Device 1

(a) 100% Read, 0% Write

```
annxtao@Annie:~$ sudo fio --name=random-write --rw=randrw --rwmixread=100 --bs=4k --size=4g --numjobs=1
[sudo] password for annxtao:
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [r(1)][100.0%][r=31.3MiB/s][r=8010 IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=75: Wed Mar 10 12:06:37 2021
  read: IOPS=8470, BW=33.1MiB/s (34.7MB/s)(4096MiB/123788msec)
    clat (usec): min=4, max=26151, avg=116.82, stdev=52.93
    lat (usec): min=4, max=26151, avg=116.94, stdev=52.94
    clat percentiles (usec):
      | 1.00th=[ 90], 5.00th=[ 100], 10.00th=[ 101], 20.00th=[ 102],
      | 30.00th=[ 103], 40.00th=[ 105], 50.00th=[ 110], 60.00th=[ 117],
      | 70.00th=[ 119], 80.00th=[ 122], 90.00th=[ 135], 95.00th=[ 153],
      | 99.00th=[ 260], 99.50th=[ 367], 99.90th=[ 490], 99.95th=[ 529],
      | 99.99th=[ 1205]
    bw ( KiB/s): min=25421, max=35552, per=99.88%, avg=33840.60, stdev=1777.89, samples=247
    iops   : min= 6355, max= 8888, avg=8459.93, stdev=444.50, samples=247
    lat (usec) : 10=0.02%, 20=0.01%, 50=0.01%, 100=7.41%, 250=91.53%
    lat (usec) : 500=0.96%, 750=0.05%, 1000=0.01%
    lat (msec) : 2=0.02%, 4=0.01%, 10=0.01%, 50=0.01%
    cpu      : usr=2.61%, sys=20.89%, ctx=0, majf=0, minf=32
    IO depths : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=1048576,0,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency   : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=33.1MiB/s (34.7MB/s), 33.1MiB/s-33.1MiB/s (34.7MB/s-34.7MB/s), io=4096MiB (4295MB), run=123788-123788msec
```

(b) 75% Read, 25% Write

```
annxtao@Annie:~$ sudo fio --name=random-write --rw=randrw --rwmixread=75 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [m(1)][100.0%][r=33.5MiB/s,w=11.0MiB/s][r=8570,w=2823 IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=87: Wed Mar 10 12:09:58 2021
  read: IOPS=8066, BW=31.5MiB/s (33.0MB/s)(3070MiB/97435msec)
    clat (usec): min=4, max=15398, avg=118.22, stdev=92.00
    lat (usec): min=4, max=15398, avg=118.32, stdev=92.01
    clat percentiles (usec):
      | 1.00th=[ 88], 5.00th=[ 99], 10.00th=[ 100], 20.00th=[ 101],
      | 30.00th=[ 102], 40.00th=[ 104], 50.00th=[ 109], 60.00th=[ 116],
      | 70.00th=[ 118], 80.00th=[ 121], 90.00th=[ 135], 95.00th=[ 155],
      | 99.00th=[ 359], 99.50th=[ 379], 99.90th=[ 545], 99.95th=[ 1319],
      | 99.99th=[ 4293]
    bw ( KiB/s): min=17440, max=34704, per=99.90%, avg=32230.46, stdev=2562.02, samples=194
    iops   : min= 4360, max= 8676, avg=8057.39, stdev=640.46, samples=194
  write: IOPS=2695, BW=10.5MiB/s (11.0MB/s)(1026MiB/97435msec); 0 zone resets
    clat (usec): min=5, max=609, avg=12.90, stdev= 8.33
    lat (usec): min=5, max=609, avg=13.02, stdev= 8.35
    clat percentiles (usec):
      | 1.00th=[ 7], 5.00th=[ 7], 10.00th=[ 8], 20.00th=[ 10],
      | 30.00th=[ 11], 40.00th=[ 11], 50.00th=[ 11], 60.00th=[ 12],
      | 70.00th=[ 12], 80.00th=[ 15], 90.00th=[ 21], 95.00th=[ 26],
      | 99.00th=[ 45], 99.50th=[ 56], 99.90th=[ 86], 99.95th=[ 109],
      | 99.99th=[ 200]
    bw ( KiB/s): min= 5744, max=12200, per=99.90%, avg=10771.71, stdev=948.08, samples=194
    iops   : min= 1436, max= 3050, avg=2692.77, stdev=237.01, samples=194
    lat (usec) : 10=6.37%, 20=16.17%, 50=2.45%, 100=10.45%, 250=63.42%
    lat (usec) : 500=1.02%, 750=0.06%, 1000=0.01%
    lat (msec) : 2=0.01%, 4=0.02%, 10=0.01%, 20=0.01%
    cpu      : usr=2.84%, sys=22.95%, ctx=0, majf=0, minf=32
    IO depths : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=785920,262656,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency   : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=31.5MiB/s (33.0MB/s), 31.5MiB/s-31.5MiB/s (33.0MB/s-33.0MB/s), io=3070MiB (3219MB), run=97435-97435msec
  WRITE: bw=10.5MiB/s (11.0MB/s), 10.5MiB/s-10.5MiB/s (11.0MB/s-11.0MB/s), io=1026MiB (1076MB), run=97435-97435msec
```

(c) 66.66% Read, 33.37% Write

```
annxtao@Annie:~$ sudo fio --name=random-write --rw=randrw --rwmixread=66.66 --bs=4k --size=4g --numjobs=1
random-write: (groupid=0, jobs=1): err= 0: pid=99: Wed Mar 10 12:14:06 2021
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [m(1)][100.0%][r=27.5MiB/s,w=14.2MiB/s][r=7045,w=3645 IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=99: Wed Mar 10 12:14:06 2021
  read: IOPS=8002, BW=31.3MiB/s (32.8MB/s)(2703MiB/86457msec)
    clat (usec): min=4, max=14192, avg=116.96, stdev=50.70
    lat (usec): min=4, max=14193, avg=117.05, stdev=50.71
    clat percentiles (usec):
      | 1.00th=[ 89], 5.00th=[ 99], 10.00th=[ 100], 20.00th=[ 101],
      | 30.00th=[ 102], 40.00th=[ 104], 50.00th=[ 110], 60.00th=[ 116],
      | 70.00th=[ 118], 80.00th=[ 121], 90.00th=[ 135], 95.00th=[ 155],
      | 99.00th=[ 322], 99.50th=[ 367], 99.90th=[ 461], 99.95th=[ 510],
      | 99.99th=[ 2409]
    bw ( KiB/s): min=23944, max=33936, per=99.88%, avg=31969.73, stdev=1770.37, samples=172
    iops        : min= 5986, max= 8484, avg=7992.26, stdev=442.65, samples=172
  write: IOPS=4125, BW=16.1MiB/s (16.9MB/s)(1393MiB/86457msec); 0 zone resets
    clat (usec): min=4, max=389, avg=12.56, stdev= 7.86
    lat (usec): min=4, max=389, avg=12.68, stdev= 7.89
    clat percentiles (usec):
      | 1.00th=[ 7], 5.00th=[ 7], 10.00th=[ 8], 20.00th=[ 8],
      | 30.00th=[ 10], 40.00th=[ 11], 50.00th=[ 11], 60.00th=[ 12],
      | 70.00th=[ 12], 80.00th=[ 15], 90.00th=[ 20], 95.00th=[ 26],
      | 99.00th=[ 43], 99.50th=[ 54], 99.90th=[ 82], 99.95th=[ 100],
      | 99.99th=[ 180]
    bw ( KiB/s): min=12327, max=18259, per=99.87%, avg=16482.16, stdev=1015.26, samples=172
    iops        : min= 3081, max= 4564, avg=4120.31, stdev=253.85, samples=172
  lat (usec)   : 10=10.36%, 20=20.34%, 50=3.17%, 100=9.31%, 250=55.87%
  lat (msec)   : 500=0.92%, 750=0.02%, 1000=0.01%
  lat (msec)   : 2=0.01%, 4=0.01%, 10=0.01%, 20=0.01%
  cpu          : usr=3.25%, sys=23.80%, ctx=0, majf=0, minf=32
  IO depths    : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
    submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
    issued rwts: total=691865,356711,0,0 short=0,0,0,0 dropped=0,0,0,0
    latency    : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=31.3MiB/s (32.8MB/s), 31.3MiB/s-31.3MiB/s (32.8MB/s-32.8MB/s), io=2703MiB (2834MB), run=86457-86457msec
  WRITE: bw=16.1MiB/s (16.9MB/s), 16.1MiB/s-16.1MiB/s (16.9MB/s-16.9MB/s), io=1393MiB (1461MB), run=86457-86457msec
```

(d) 50% Read, 50% Write

```
annxtao@Annie:~$ sudo fio --name=random-write --rw=randrw --rwmixread=50 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [m(1)][100.0%][r=30.7MiB/s,w=30.4MiB/s][r=7870,w=7778 IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=111: Wed Mar 10 12:16:04 2021
read: IOPS=7305, BW=28.5MiB/s (29.9MB/s)(2049MiB/71808msec)
  clat (usec): min=4, max=9558, avg=122.83, stdev=115.02
  lat (usec): min=4, max=9558, avg=122.93, stdev=115.03
  clat percentiles (usec):
    | 1.00th=[ 89], 5.00th=[ 98], 10.00th=[ 99], 20.00th=[ 101],
    | 30.00th=[ 102], 40.00th=[ 104], 50.00th=[ 111], 60.00th=[ 116],
    | 70.00th=[ 118], 80.00th=[ 123], 90.00th=[ 141], 95.00th=[ 172],
    | 99.00th=[ 363], 99.50th=[ 392], 99.90th=[ 1598], 99.95th=[ 3064],
    | 99.99th=[ 4817]
  bw ( KiB/s): min=15040, max=32399, per=99.83%, avg=29173.81, stdev=3221.07, samples=143
  iops       : min= 3760, max= 8099, avg=7293.20, stdev=805.24, samples=143
write: IOPS=7296, BW=28.5MiB/s (29.9MB/s)(2047MiB/71808msec); 0 zone resets
  clat (usec): min=5, max=695, avg=12.12, stdev= 8.06
  lat (usec): min=5, max=695, avg=12.24, stdev= 8.09
  clat percentiles (usec):
    | 1.00th=[ 6], 5.00th=[ 7], 10.00th=[ 7], 20.00th=[ 8],
    | 30.00th=[ 8], 40.00th=[ 10], 50.00th=[ 11], 60.00th=[ 12],
    | 70.00th=[ 12], 80.00th=[ 15], 90.00th=[ 20], 95.00th=[ 26],
    | 99.00th=[ 44], 99.50th=[ 55], 99.90th=[ 85], 99.95th=[ 104],
    | 99.99th=[ 178]
  bw ( KiB/s): min=14336, max=33421, per=99.82%, avg=29133.80, stdev=3282.73, samples=143
  iops       : min= 3584, max= 8355, avg=7283.22, stdev=820.70, samples=143
  lat (usec) : 10=20.46%, 20=24.76%, 50=4.46%, 100=8.13%, 250=40.99%
  lat (usec) : 500=1.10%, 750=0.03%, 1000=0.01%
  lat (msec) : 2=0.01%, 4=0.03%, 10=0.01%
  cpu        : usr=3.94%, sys=27.33%, ctx=0, majf=0, minf=32
  IO depths  : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
  submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  issued rwts: total=524625,523951,0,0 short=0,0,0,0 dropped=0,0,0,0
  latency    : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  READ: bw=28.5MiB/s (29.9MB/s), 28.5MiB/s-28.5MiB/s (29.9MB/s-29.9MB/s), io=2049MiB (2149MB), run=71808-71808msec
  WRITE: bw=28.5MiB/s (29.9MB/s), 28.5MiB/s-28.5MiB/s (29.9MB/s-29.9MB/s), io=2047MiB (2146MB), run=71808-71808msec
```

(e) 0% Read, 100% Write

```
annxtao@Annie:~$ sudo fio --name=random-write --rw=randrw --rwmixread=0 --bs=4k --size=4g --numjobs=1
random-write: (g=0): rw=randrw, bs=(R) 4096B-4096B, (W) 4096B-4096B, (T) 4096B-4096B, ioengine=psync, iodepth=1
fio-3.16
Starting 1 process
Jobs: 1 (f=1): [w(1)][100.0%][w=206MiB/s][w=52.7k IOPS][eta 00m:00s]
random-write: (groupid=0, jobs=1): err= 0: pid=123: Wed Mar 10 12:17:21 2021
write: IOPS=47.1k, BW=184MiB/s (193MB/s)(4096MiB/22263msec); 0 zone resets
  clat (usec): min=5, max=15608, avg=20.60, stdev=104.41
  lat (usec): min=5, max=15608, avg=20.65, stdev=104.41
  clat percentiles (usec):
    | 1.00th=[ 6], 5.00th=[ 7], 10.00th=[ 7], 20.00th=[ 8],
    | 30.00th=[ 8], 40.00th=[ 8], 50.00th=[ 8], 60.00th=[ 9],
    | 70.00th=[ 12], 80.00th=[ 15], 90.00th=[ 22], 95.00th=[ 30],
    | 99.00th=[ 196], 99.50th=[ 824], 99.90th=[ 1336], 99.95th=[ 1516],
    | 99.99th=[ 3261]
  bw ( KiB/s): min=100120, max=397216, per=99.74%, avg=187905.93, stdev=46785.71, samples=44
  iops       : min=25030, max=99304, avg=46976.30, stdev=11696.37, samples=44
  lat (usec) : 10=66.48%, 20=22.10%, 50=8.56%, 100=1.42%, 250=0.47%
  lat (usec) : 500=0.18%, 750=0.21%, 1000=0.22%
  lat (msec) : 2=0.32%, 4=0.01%, 10=0.01%, 20=0.01%
  cpu        : usr=6.74%, sys=44.71%, ctx=0, majf=0, minf=31
  IO depths  : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
  submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  issued rwts: total=0,1048576,0,0 short=0,0,0,0 dropped=0,0,0,0
  latency    : target=0, window=0, percentile=100.00%, depth=1

Run status group 0 (all jobs):
  WRITE: bw=184MiB/s (193MB/s), 184MiB/s-184MiB/s (193MB/s-193MB/s), io=4096MiB (4295MB), run=22263-22263msec
```

Figure 18: Results from running fio with file size of 4GB and block size of 4KB for Device 2

References

1. fio - Flexible I/O tester rev. 3.25. (n.d.). Retrieved March 11, 2021, from https://fio.readthedocs.io/en/latest/fio_doc.html
- Axboe. (n.d.). Axboe/fio. Retrieved March 11, 2021, from <https://github.com/axboe/fio> [Pdenchfi](https://github.com/axboe/fio). (n.d.).
- Fio(1) - Linux man page. (n.d.). Retrieved March 11, 2021, from <https://linux.die.net/man/1/fio>
- Monroe, K. (2017, August 05). How to use Fio (FLEXIBLE i/o Tester) to measure disk performance in Linux. Retrieved March 11, 2021, from <https://dotlayer.com/how-to-use-fio-to-measure-disk-performance-in-linux/>
- Optimizing memory bandwidth on stream triad. (n.d.). Retrieved March 11, 2021, from [https://software.intel.com/content/www/us/en/develop/articles/optimizing-memory-bandwidth-on-stream-triad.html#:~:text=Introduction,Scale%2C%20Add%20and%20Triad\).&text=STREAM%20is%20also%20a%20part%20of%20the%20HPCC%20Benchmark%20suite](https://software.intel.com/content/www/us/en/develop/articles/optimizing-memory-bandwidth-on-stream-triad.html#:~:text=Introduction,Scale%2C%20Add%20and%20Triad).&text=STREAM%20is%20also%20a%20part%20of%20the%20HPCC%20Benchmark%20suite).
- Sample fio commands for block volume performance tests on Linux-based instances. Retrieved March 11, 2021, from <https://docs.oracle.com/en-us/iaas/Content/Block/References/samplefiocommandslinux.htm>
- Stream benchmark reference information. (n.d.). Retrieved March 11, 2021, from <http://www.cs.virginia.edu/stream/ref.html>
- Theoretical maximum memory bandwidth FOR Intel® Core™ X-Series... (n.d.). Retrieved March 11, 2021, from <https://www.intel.com/content/www/us/en/support/articles/000056722/processors/intel-core-processors.html>