



Performance Characterization of Modern Storage Stacks: POSIX I/O, libaio, SPDK, and io_uring

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Abstract

Linux storage stack offers a variety of storage I/O stacks and APIs such as POSIX I/O, asynchronous I/O (libaio), high-performance asynchronous I/O (emerging io_uring) or SPDK, the last of which completely bypasses the kernel. Despite their availability, there has not been a systematic study of their performance and overheads. In order to aid our understanding, in this work we systematically characterize performance, scalability and microarchitectural properties of popular Linux I/O APIs on high-performance storage hardware (Intel Optane SSDs). Our characterization reveals that: (1) at low I/O loads, all APIs perform competitively with each other, with polling helping the performance by 1.7×, but consuming 2.3× CPU instructions; (2) at high-loads and scale, io_uring is more than an order of magnitude slower than SPDK; (3) at high-loads and scale, the benchmarking tool (fio) itself becomes a bottleneck; (4) state-of-practice Linux block I/O schedulers (BFQ, mq-deadline, and Kyber) introduce significant (up to 50%) overheads, and their use of global locks hinder their scalability. All artifacts from this work are available at <https://github.com/atlarge-research/Performance-Characterization-Storage-Stacks>.

CCS Concepts: • Software and its engineering → Secondary storage; Operating systems.

Keywords: Linux storage stack, io_uring, SPDK, Efficiency, Measurements

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1 Introduction

Modern storage devices such as Intel Optane SSDs can deliver millions of IOPS (I/O operations per second) with single-digit microseconds (μsecs) I/O access latencies [7, 17]. Meanwhile, the CPU performance has remained relatively stable as Moore's Law driven performance gains stall [29]. Consequently, the stalled CPU performance with high-performance storage hardware has exposed many previously hidden software overheads in the storage stack implementations, thus leading to a series of efforts to redesign and optimize the storage stack focusing on lock contentions, polling, copy elimination, new interfaces, scheduling, context switches, asynchronous I/O paths, interrupt and system call eliminations [3, 18, 20, 25, 30, 36, 37, 39, 40, 45, 56, 59, 66, 68].

Beyond these optimizations, there have been many efforts to improve the user-kernel and user-storage APIs and abstractions. Linux supports two popular and widely used APIs called (synchronous) POSIX file I/O calls [12, 13] and an asynchronous API called libaio [3]. Both of these APIs interact via system calls (syscalls) with the Linux kernel which can have high overheads [22, 38, 55]. More recently, Linux developers have introduced a new high-performance I/O API called io_uring [8]. It takes many established ideas from the high-performance networking domain (shared-memory queues, asynchronous I/O, polling, shared I/O contexts) and applies them to storage in a unified manner [61, 62]. These advancements are now merged in the Linux storage stack (since v5.1 kernel version), and have shown to deliver high performance and CPU efficiency [22]. All of these APIs (POSIX, libaio, io_uring) work within the kernel.

The Linux kernel with its generic code execution, functionalities, and features can also introduce significant overheads [51], thus leading to the design of kernel-bypassing userspace storage stacks [24, 34, 69, 74]. The Storage Performance Development Kit (SPDK) is one of the most popular and widely used user space I/O libraries, which can deliver up to 10 million IOPS using a single CPU core [2]. However, user space I/O libraries lack many kernel-supported features such as fine-grained isolation, access control, file systems, multi tenancy, and QoS support [48, 64].

In summary, over the past decade, the in-kernel and userspace I/O stacks have undergone a significant development phase. Despite sharing a common functional goal

- *access to data from storage devices* - these I/O stack implementations prioritize different goals (performance, stability, security, efficiency). As a result, there is a lack of understanding about the performance, efficiency, and scalability of these stacks, specifically on modern high-performance storage devices such as Intel Optane SSDs. Closest to our work is the recently published work by Didona et al. that studies the performance and scalability of libaio, io_uring, and SPDK on flash SSDs [22]. We build on their findings and further report on performance breakdowns (microarchitectural, and instructions profiles), with I/O scheduler-related overheads.

In this paper, we take a step back and systematically study these storage stacks on modern high-performance storage devices. Our test bed consists of Intel Xeon CPUs with seven (7) Intel Optane devices in a single machine with the peak performance of 4.2 million IOPS (specification: 600 kIOPS \times 7 devices) (Table 1). We start our investigation by studying the performance (expressed as IOPS) of POSIX I/O, libaio, io_uring, and SPDK at a low load with a single outstanding I/O request on a single Optane device and a single CPU core, and quantify in detail their microarchitectural properties and CPU instructions breakdown. We then quantify their performance as we increase the number of outstanding requests (expressed as queue depth), and add CPU cores and NVMe devices (from 1 to 7). Lastly, we measure the impact of three state-of-the-practice block I/O schedulers (BFQ, mq-deadline, Kyber) on the performance of these stacks [10]. The primary contribution of this work is about performance and scalability characterization of state-of-the-practice Linux storage APIs. Our key findings demonstrate that:

1. At low I/O loads, we report 81.1-94.6 kIOPS for non-polling APIs (POSIX, libaio, and io_uring). Polling increases the performance to 108-138.9 kIOPS (1.7 \times increase) with io_uring and SPDK, with a proportional increase in the CPU instructions required per I/O operation (up to 2.3 \times). (§3.1).
2. At high-loads (128 queue depth, 7 devices), io_uring is more than an order of magnitude inefficient than SPDK. SPDK can saturate our hardware with 5 cores (using fio) or just a single core when using SPDK's light-weight perf benchmark. In contrast, the best performing io_uring configuration needs 13 cores. (§3.2).
3. At high-loads, the benchmarking tool (fio) itself becomes a bottleneck. In our setup, SPDK with fio takes 5 cores to deliver 4.2 Million IOPS. SPDK with its own perf benchmark [15] takes only one, thus showing 5 \times overheads with fio. (§3.2).
4. State-of-practice Linux I/O schedulers (BFQ, mq-deadline, and Kyber) introduce significant (up to 50%) overheads, and their use of global locks hinder their scalability. (§3.3).

To facilitate reproduction, our benchmarking code is available at <https://github.com/atlarge-research/Performance-Characterization-Storage-Stacks>.

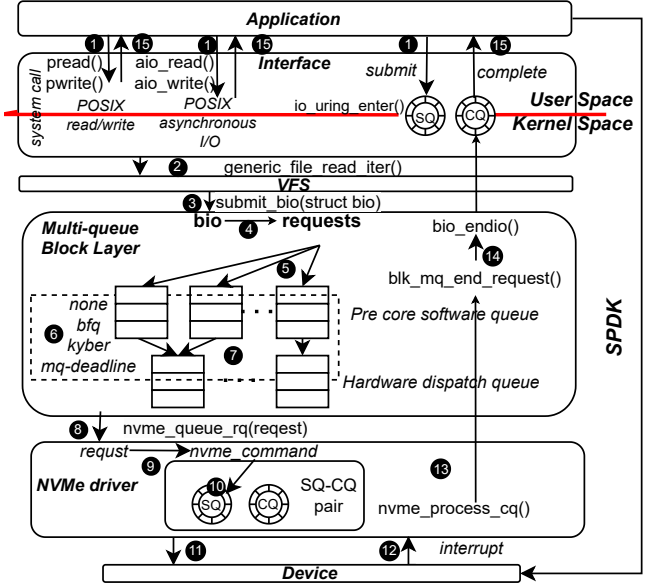


Figure 1. A high-level overview of the Linux storage stack.

2 Background

Before we start with benchmarking, we briefly recap the key concepts and details from the Linux storage stack (Figure 1).

2.1 Linux I/O Stack

Applications submit I/O requests to the I/O interface (step 1), such as POSIX read/write [12, 13] (referred to as psync), libaio [3], io_uring [8]. The I/O interface constructs struct kiocb and submits it to a file system via the VFS (step 2). The file system then resolves the relevant block address containing data, constructs a struct bio request and submits it to the block layer through submit_bio() (step 3). The Linux block layer converts struct bio to struct request (step 4) and puts it in a per-core software queue (step 5). These requests are then processed by a block I/O scheduler and put in a hardware dispatch queue (step 6-7). Requests in the hardware dispatch queue are processed by the NVMe driver by nvme_queue_rq() (step 8). The NVMe driver constructs an NVMe command according to the requests (step 9), and writes them to the submission queue (SQ) (step 10) to be processed by the device (step 11). After the command is processed by the device, the device writes the request to the completion queue (CQ) and generates an interrupt (step 12). The completion is processed by nvme_process_cq and then blk_mq_end_request() and bio_endio() are called to finalize the request in bio layer (step 14). At last, the application is notified of the completion results (step 15).

2.2 Emerging High-Performance io_uring API

io_uring maintains shared-memory, lock-free submission (SQ) and completion queues (CQ) between the kernel and

Table 1. Specification of the server machine.

CPU	Dual socket (2×) Intel(R) Xeon(R) Silver 4210R CPU 10 cores @ 2.40GHz, Hyper-threading disabled, Turbo disabled
Memory	256GB, DDR4
Storage	7× Intel Corporation Optane SSD 900P Series (512 bytes LBA, preconditioned 10×, spec: 550 KIOPS with 4KiB random read), all 7 NVMe SSDs connected to the CPU NUMA domain 1
Software	Ubuntu 22 with Linux kernel v5.15.79, built with default config, fio-3.32 (commit db7fc8d), SPDK 22.09 (commit aed4ece93)

application. The application writes to the SQ to submit I/O request and gets completion notification via the CQ. By default (identified as *iou*), when an application submits new requests to the SQ, it notifies the kernel by `io_uring_enter` syscall. The same syscall is used to retrieve completion events from the CQ. `io_uring` can use polling to eliminate syscalls and interrupts. The application can poll on the CQ, thus actively reaping completions without interrupts. If there are completions available on the CQ, these can be processed without a syscall, otherwise a syscall is issued to poll in the kernel for I/O completion. This mode is referred to as *completion polling* or *iou-c* (using `hipri` flag). To remove a syscall during SQ submission, the application can start a kernel thread to poll for I/O requests on the SQ on behalf of the application (using `sqthread_poll`), thus eliminating a need for a syscall. This mode is referred to as *submission polling* (*iou-s*, with the `hipri` flag).

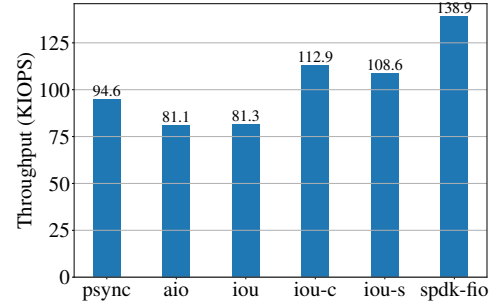
2.3 Kernel-bypassing Userspace SPDK API

Storage Performance Development Kit (SPDK) is a user space I/O library that provides zero-copy, high-performance, and efficient direct access to NVMe SSDs from the userspace leveraging a poll-based NVMe driver [69]. SPDK initializes and accesses NVMe I/O queues directly in the userspace, thus completely skipping the kernel during I/O operations. Currently, SPDK is considered the state-of-the-art I/O stack that can deliver the best performance to workloads and is used extensively [31, 38, 41, 67, 71].

3 Experiments

We now start with our study of the performance and efficiency of the Linux storage stack with its I/O APIs: POSIX I/O (*psync*), *libaio* (*aio*), *io_uring* (with 3 configurations: default as *iou*, completion polling *iou-c*, and submission with completion polling as *iou-s*), and SPDK. The purpose of our study is to answer:

- (Q1) *What is the performance gap among different I/O APIs and their configurations?*
- (Q2) *Why is there a performance gap, and how do these APIs use the CPU time, cycle, and instructions?*

**Figure 2.** Random read 4KiB throughput (IOPS).

- (Q3) *How does the performance gap scale with the number of CPU cores and storage devices?*
- (Q4) *What is the impact of I/O schedulers on the performance of these I/O APIs?*

We cover Q1-3 in §3.1 and §3.2, whereas §3.3 answers Q4.

To prepare for the benchmarking, we follow the best practices from [65] for Optane SSDs. All devices are formatted with the LBA size of 512 bytes, and are written completely 10 times. For our experiments we use the request size of 4KiB which shows the same performance as 512B requests. We choose `fio` as the workload generator [6]. All benchmarking processes are pinned to the CPU NUMA node 1 except when we use more than 10 cores (uses CPU/NUMA node 0). We run `fio` workloads for 140 seconds (2 minutes + 20 seconds warm up time). We use `perf` record to record microarchitectural event metrics from the CPU counters, and report an average of 10 times over 5 seconds runs while the `fio` workloads run. Table 1 presents the benchmarking environment.

3.1 The Efficiency of I/O Stacks

We start our benchmarking with a single NVMe Optane device with a single CPU core, except for *iou-s* that uses 2 cores. The reason for using 2 cores is the performance collapse due to the contention of `fio` and kernel threads polling on a single physical CPU core [22]. We collectively refer to *iou-c*, *iou-s*, and SPDK as *polling* libraries, and *psync*, *libaio*, and *iou* to as *non-polling* libraries.

3.1.1 Performance. We report on the maximum IOPS completed with 4KiB random reads with a single outstanding request (i.e., queue depth QD=1). Figure 2 shows our results with IOPS (y-axis, higher is better) and libraries on the x-axis. There are a few observations here. First, *iou* and *aio* have the worst performance compared with other libraries, 17% to 72% lower IOPS than *psync* and SPDK, respectively. *psync*, the oldest among the six configurations, has 17% higher IOPS compared with *aio* and *iou*. All non-polling libraries perform relatively close by 81.3-94.6 KIOPS. The use of polling increases the performance significantly. *iou-s* and *iou-c* (both polling based) have 34% and 39% higher IOPS than the non-polling *iou* configuration. SPDK has the highest IOPS, 71.3%

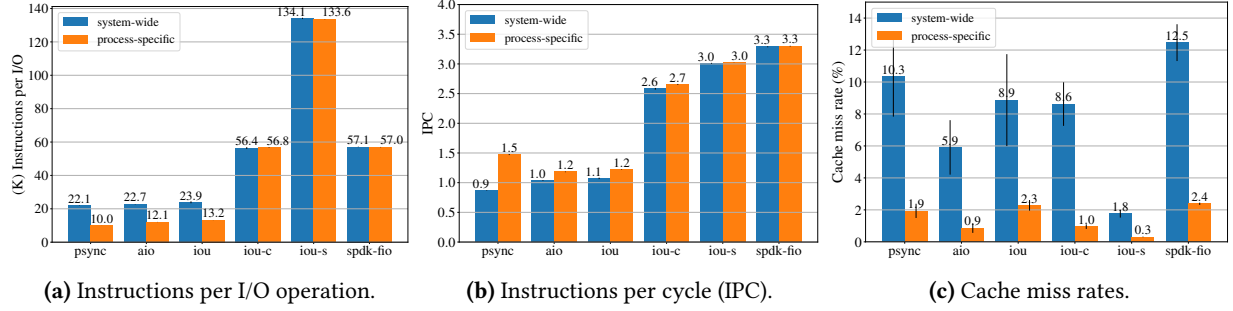


Figure 3. Comparison on micro-architecture efficiency of 6 different I/O libraries using a single thread and queue depth = 1.

higher than iou. In general, I/O APIs with polling improve the performance up to a margin of $1.7\times$ (81.3 vs 138.9 KIOPS).

3.1.2 Microarchitectural characterization. As a next step, we characterize their CPU profiles focusing specifically on: (i) instructions required to complete a 4KiB random read operation (capturing the software overhead), lower is better; (ii) code execution efficiency by calculating instruction retired per CPU cycle (IPC), higher is better; and (iii) data fetching efficiency of the code path by calculating the cache miss rates, lower is better. We calculate these quantities for two configurations, system-wide (–a flag with perf) and process-specific. The process-specific configuration only reports events that are attributed to the fio process, whereas the system-wide configuration captures all events happening in the system. Since fio is the only workload running on the idle server, all events are directly (process-specific) or indirectly (system-wide) attributed to fio. Nonetheless, we do report them separately and explain the gap between them when they diverge.

We show our results in figure 3. There are three primary observations here. First, non-polling libraries (psync, aio, and iou) all have equal or better instructions required per I/O operation than the polling libraries (iou-c, iou-s, and SPDK) as shown in figure 3a. This result is expected as polling libraries are constantly utilizing the CPU core to 100%, thus increasing the number of instructions executed. Consequently, for similar performance (IOPS), they show higher (worse) instructions/IOPS. iou-s takes $2.3\times$ more instructions to process each I/O request than iou-s and spdk-fio because it runs on the two cores. Note that there is $2\times$ difference between system-wide and process-specific instruction/IOPS for non-polling libraries. It is because when the CPU utilization is not 100%, the swapper process takes up half the instructions in a system-wide profile. The swapper process (PID 0) is a special process in the Linux kernel that is run by a CPU when there is no other processes to run (i.e., the CPU is idle). Hence, at low-load (QD=1), polling-based libraries need 5–12 \times more instructions to complete an I/O request than their non-polling counterparts.

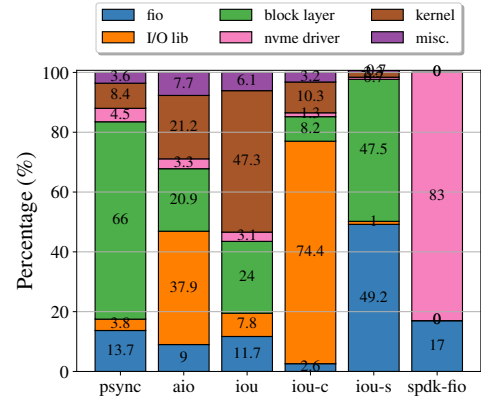


Figure 4. Instruction breakdown by %.

Second, with a streamlined execution of instructions for polling (an optimized code path), the polling libraries show better IPC than the non-polling libraries (figure 3b). A higher IPC implies the instructions are better structured so that they are executed with each CPU clock cycle without being stalled, hence, showing an efficient code path. The three non-polling libraries have lower IPC, about a one-third ($1/3^{rd}$) compared with the polling-based libraries on average. However, the higher IPC of the polling-based libraries does not mean they are more efficient as the CPU spends many instructions on polling. A polling code is typically well structured and optimized, leading to a higher IPC for the polling-based libraries. IPC becomes comparable when the workload increases (§3.2).

Lastly, figure 3c presents the cache miss rates (lower is better) that represent the data fetching efficiency of the code path. Even though psync has $1.6\text{--}2.5\times$ higher cache miss rates, it still delivers higher IOPS than its non-polling counterparts. SPDK has the highest cache miss rate, $14.1\times$ higher than the lowest one, iou-s and $1.5\times$ higher compared with the second highest one, psync. With SPDK, all DMA operations are done directly to user buffers, hence, all CPU initiated requests result in a mandatory cache miss. We do not observe a direct impact of such cache miss rates on the performance. We hypothesize that this is due to the small memory footprint of

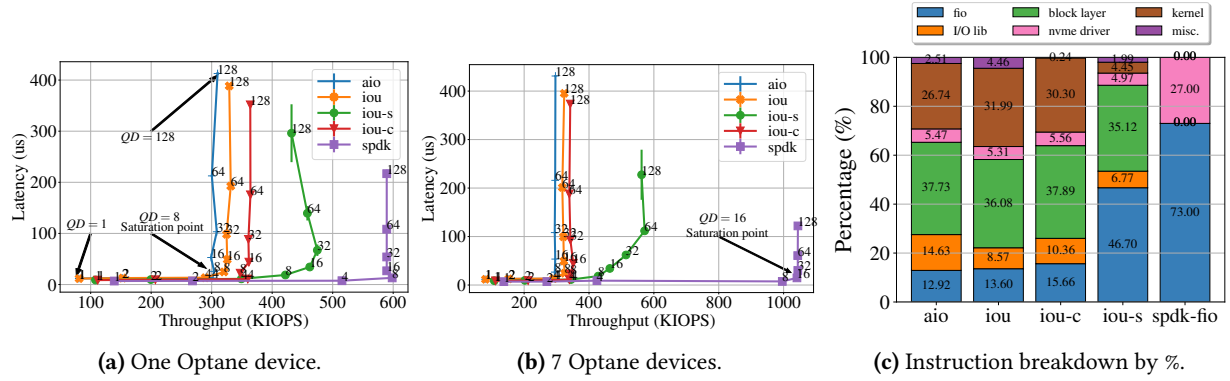


Figure 5. Throughput and latency with queue depth ranging 1-128, and the instruction breakdown at the saturation point.

the data request sizes involved. However, in our experiments, we notice that the process scheduler has a huge impact on the cache miss rate. When the threads are not pinned in a single node and the user and kernel threads of iou-s are mapped to different nodes, the cache miss rate is higher than 95% (not shown).

3.1.3 Instruction breakdown. As the last step in our analysis, we break down the different components where the CPU has spent time by executing instructions. Figure 4 shows our results in five distinct categories: (i) fio, the workload; (ii) I/O library specific code in the user or kernel space; (iii) block layer specific routines; (iv) NVMe device driver; and lastly (v) kernel-specific symbols (scheduling, memory allocation, etc.). The rest is marked misc. In an ideal setting, all CPU instructions (100%) are to be consumed by the fio, thus showing a zero-cost ideal I/O API, however, such a system is unrealistic. psync spends a significant amount of instructions (66%) in the block layer, whereas its own psync-specific code only requires 3.8%. In contrast, libaio spends nearly 40% of its instruction budget on its own implementation [21]. The default iou is somewhere in between, however, as polling is introduced, iou-c spends the majority of its instructions with completion polling (triggered via `io_do_iopoll` in the kernel, attributed to I/O lib). iou-s evenly splits between fio-based polling for completion (`fio_ioring_getevents`) and block-layer kernel thread polling as expected. Lastly, SPDK spends 83% of its instructions on polling as attributed to the NVMe driver (a part of the SPDK) with 17% instructions left for the fio benchmark.

3.1.4 Summary. At low I/O loads, non-polling and polling APIs perform competitively with each other, respectively. We report 81.1-94.6 KIOPS for non-polling APIs. Polling increases the performance to 108-138.9 KIOPS (1.7× increase) with io_uring and SPDK. However, the polling-based APIs take more CPU instructions per IOPS (up to 2.3×). The CPU instruction breakdown shows non-polling APIs spend a significant fraction of their instruction budget on non-fio code.

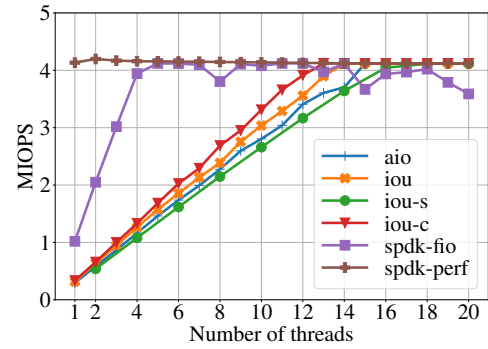


Figure 6. Multi-core scalability of different I/O libraries.

3.2 Scaling: I/O Depths and NVMe Devices

In the previous section, none of the configurations reached the single Optane hardware limit because the queue depth was the bottleneck (QD=1). In this subsection, we study the scalability properties (Q3) of these I/O APIs as we scale the load on the system (QD > 1) and increase the number of devices from 1 to 7. Due to its synchronous nature, we drop psync from the consideration here.

3.2.1 Performance. Figures 5a and 5b show our results with a single CPU core. The x-axis shows IOPS, and the y-axis shows the corresponding latency as we increase the queue depth by issuing 1-to-128 requests. A flat horizontal line is preferred. We observe that Optane devices can deliver more performance (600 KIOPS) than the peak throughput specification from the Intel spec sheet (550 KIOPS). With 7 devices, a single CPU core with SPDK can deliver close to 1.1 million IOPS (@7.4μsecs). All lines in the graph form a J shape line. At the start, throughput increases with a negligible increase in latency, then it stops increasing, and the latency increases dramatically as the CPU becomes saturated and it cannot keep up with the load. We call this point the *saturation point* (the heel of the J curve). aio, iou, iou-s, iou-c, and spdk-fio reach the saturation point when QD = 8, 8, 32, 8, 8 with a

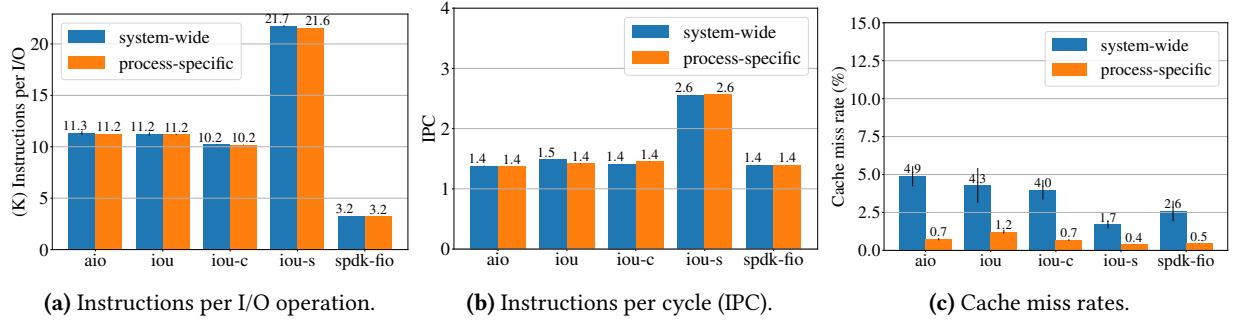


Figure 7. Comparison on micro-architecture efficiency of 5 different I/O libraries at saturation point

single device, respectively. The same queue depth is needed with 7 devices except for spdk-fio, which needs QD=16. In comparison, the other I/O libraries only deliver $0.79\times$ (474K vs. 600K IOPS for one device) to $0.53\times$ (549K vs. 1.1 million IOPS, for 7 devices), a fraction of the SPDK’s performance.

To showcase the scalability of performance, we now add more CPU cores at the peak performance with QD=128 with 7 Optane devices. Figure 6 shows our results. The y-axis is the throughput in million of IOPS, and the x-axis shows the number of cores. The figure shows that all I/O stacks can reach the peak hardware performance, however, with different CPU cores. The most efficient one among them is SPDK which only takes 5 CPU cores to deliver the peak 4.2 million IOPS. In comparison, the best `io_uring` variant (`iou-c`) takes 13 cores ($2.6\times$ inefficient).

At this configuration, we notice that the fio benchmarking code itself becomes a bottleneck. To verify this hypothesis, we use SPDK’s own benchmarking framework called SPDK-perf [5, 16]. With this, SPDK is able to deliver the peak performance of 4.2 million IOPS even with just a single core! In this configuration, SPDK-perf is $13\times$ more efficient than `iou-c` with fio. From our initial analysis, SPDK-perf is able to outperform fio because of its simple setup as it runs a set of independent threads that only send NVMe requests and poll them for completion. Notably, each thread resides on an independent core and does not coordinate with the other threads for job accounting and scheduling, runs minimal checks, and allocates DMA buffers directly with a simple memory pool without touching the data. SPDK-perf represents an unrealistic workload. However, it is useful in establishing the peak performance bounds.

3.2.2 Microarchitectural characterization. We now study the microarchitectural properties of the benchmark at the saturation point with 1 CPU core and 7 Optane devices (at the knee of the J curve in figure 5b). Figure 7a shows the instructions needed per IOPS. Notice the significant decrease in the number of instructions needed for 4KiB I/O from figure 3a (they have different y-axes). SPDK’s overheads have decreased by $17.9\times$ (needing only 3.2 thousand instructions/4KiB), whereas for non-polling libraries it only

decreases by $2\times$. Hence, at the saturation point, the polling-based libraries become more efficient than the non-polling ones. All libraries illustrate a similar IPC performance (figure 7b), thus hinting that the code complexity is similar across all libraries, but their code lengths differ, hence larger numbers of instructions/IOPS. Both non-polling and polling-based libraries have the same IPC at the saturation point, effectively amortizing the cost of polling. `iou-s` stands out as an anomaly as it uses 2 CPU cores. In comparison to figure 3c, the cache miss profile (figure 7c) shows improvements across the spectrum under load.

3.2.3 Instruction breakdown. Lastly, we now discuss the CPU instruction profile with single core and 7 devices. In comparison to figure 4 as the load on the system increases, SPDK spends fewer instructions on I/O processing (amortization, mostly on NVMe processing) and more on the benchmark fio (getting close to the ideal I/O stack). As we have demonstrated previously, eventually fio itself becomes a bottleneck. We further notice that all in-kernel stacks spend approx. 35% of their instruction budget on the block layer, which does not decrease or amortize beyond a point. In comparison with `iou` and `iou-c`, the kernel-related overheads are decreased in `iou-s`.

3.2.4 Summary. All I/O stacks scale to the peak hardware performance, but with significantly different CPU costs (Q3). `io_uring` is more than an order of magnitude inefficient than SPDK. SPDK-fio can saturate our hardware with 5 cores or just a single core when using SPDK-perf. In contrast, the best-performing `io_uring` configuration needs 13 cores. The microarchitectural profile indicates a similar level of code complexity (IPC) and data coverage (cache behavior), but with significantly longer code paths (instructions/IOPS) among the stacks. Furthermore, at high-loads, the benchmarking tool (fio) becomes a bottleneck as shown by SPDK-fio delivering 1.1 million IOPS and SPDK-perf delivering 4.2 million IOPS with a single core ($4\times$).

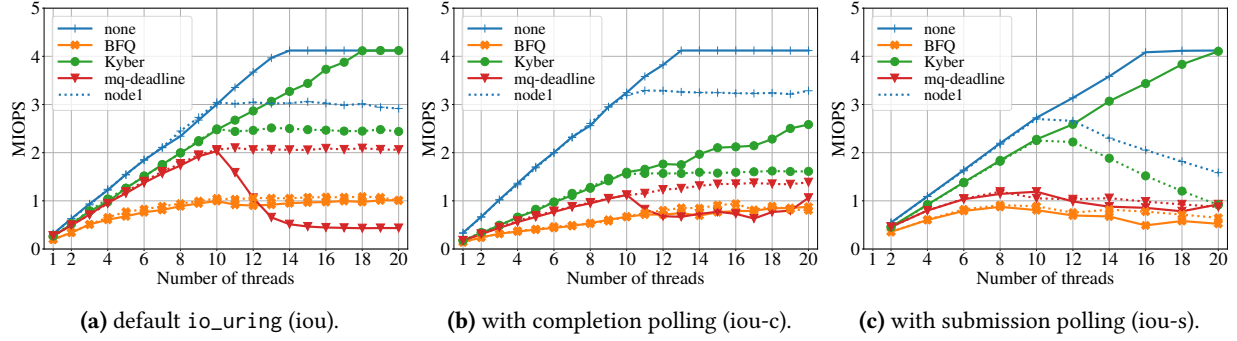


Figure 8. Comparison on the effect of Linux kernel I/O scheduler with increasing number of threads at queue depth = 128.

Table 2. Overheads from different block I/O schedulers.

	none	BFQ	Kyber	mq-deadline
iou	320.0 (1.0)	195.8 (0.61×)	264.6 (0.83×)	280.5 (0.86×)
iou-s	565.7 (1.0)	357.8 (0.63×)	470.1 (0.83×)	474.5 (0.84×)
iou-c	342.0 (1.0)	142.3 (0.43×)	175.3 (0.51×)	181.6 (0.53×)

3.3 Impact of I/O Schedulers

In this section, we investigate the overheads from three state-of-the-practice Linux block I/O schedulers [10], BFQ [4], Kyber [9], mq-deadline [11] (Q4). In this evaluation, we quantify overheads of I/O schedulers by comparing their IOPS performance with a none scheduler, which is a no-operation (no-op) scheduler. All schedulers are configured with their default parameters.

Originally designed for disks, BFQ (Budget Fair Queueing) is a proportional-share I/O scheduler that guarantees each application (using heuristics) a desired fraction of the storage throughput by assigning a budget to weighted queues (measured in sectors) [63]. Kyber is a self-regulating I/O scheduler that separates reads (synchronous) and writes (asynchronous) operations in separate queues, and only dispatches I/O requests to the hardware dispatch queue when it can maintain a certain target latency (configurable) [32]. Kyber prioritizes reads over writes. Lastly, just like Kyber, the mq-deadline scheduler also separates writes and reads into separate queues, but it also sorts them in an increasing logical block order. The sorting allows it to extract I/O merging opportunities. The I/O is issued in batches from the queues prioritizing reads. The past performance of read and write queues determines how priority to read over write is carried forward to the next round of batch I/O requests [1]. A design of a fair and proportionally-shared I/O scheduler for high-speed NVMe devices is a field of active research [27, 33, 35, 49, 53, 60, 64].

Table 2 presents the throughput of these schedulers with io_uring configurations with a single core and 7 devices at the saturation point. We show the raw numbers and show the relative slowdown against the none scheduler in the

parentheses. We report that all the I/O schedulers hurt the throughput. BFQ has the worst performance among the three schedulers, it delivers 0.43-0.63× of the none throughput. Kyber and mq-deadline are better than the BFQ, but these two schedulers still reduce the throughput by 14% to 47%. iou-c is more sensitive to I/O schedulers, losing 20-30% more throughput compared with iou and iou-s.

Figure 8 presents the throughput scaling of four schedulers with an increasing number of threads with QD=128. Keep in mind, iou-s takes 2× the number of cores, hence, it is only run till 1-10 fio threads, which effectively takes additional 1-10 kernel polling threads to get to 20 threads (solid lines). We report that all three schedulers hurt the throughput with Kyber having the least amount of overheads, thus the highest throughput. mq-deadline has a better throughput than BFQ before running on the remote NUMA node (more than 10 threads). In this setting, the throughput of the mq-deadline drops as it contends on a lock for a global variable in blk_mq_hw_ctx. This lock contributes to 79.6%, 28.7%, and 48.83% of the total CPU cycles for iou, ios-s, and iou-c with 16, 16, and 12 threads, respectively. Kyber does not use a global lock, which leads to a linear scalability of the throughput.

In order to limit the NUMA impact, we also report on a configuration (shown as the dotted line) where we restrict fio threads (1-20 threads) to the NUMA node 1. In this case, the mq-deadline does not deteriorate, while none and Kyber do not reach the hardware limits (figure 8a). For iou-s (with the kernel threads polling, whose CPU affinity we do not control), the NUMA restriction significantly hurts the performance scalability of none and Kyber schedulers.

Summary: All three state-of-the-practice block I/O schedulers have non-negligible performance overheads (14-57%). Apart from that, they all suffer from scalability issues on modern multi-socket NUMA machines. We plan to further investigate the reason for this.

4 Related Work

Linux storage stacks have undergone significant changes over the past decade. These changes include using multi-queue to avoid lock contention [20], optimizing the bottom-half interrupt handler [54], introducing asynchronous to the I/O path to hide latency [40], polling [18, 39, 70], eliminating copying [36, 56], designing light-weight storage layer [40], reducing interrupt and syscall costs [45, 59]. Yang et al. [68] compare the performance between polling and interrupts for low-latency SSDs. Xu et al. [66] analyze the performance of NVMe devices and their impact on data-intensive workloads like databases. Koh et al. [37] analyze the system challenge with ultra-low latency SSD. I/O schedulers have been studied in the past where their designs focus on fair sharing or QoS (quality of service) in a multi-tenant environment [28, 42, 48, 64]. However, even state-of-the-art I/O schedulers like D2FQ still harm performance with big access size (8KiB) and parallel access (6 threads) [64]. Userspace I/O stacks like SPDK [14, 69] are also used extensively as they allow to bypass kernel-related overheads (including schedulers) [24, 34]. Apart from optimizing the storage stack, there have been efforts to specialize it by using application-specialized codes such as using eBPF codes for caching or bypassing expensive I/O stacks for data processing [19, 43, 72, 73]. This specialization allows for efficiency by shortening the code path. Accelerators have also been used to execute these specialized codes for data processing [57, 58].

Closest to our work is the recently published work by Didona et al. that studies the performance and scalability of libaio, io_uring, and SPDK. We build on their findings and further report on: (i) analysis with Intel Optane SSD devices that are known to show different performance characteristics than NAND flash SSDs [65]; (ii) detailed performance breakdowns with microarchitectural, and instructions profiles; and (iii) I/O request scheduling related overheads with the three Linux block I/O schedulers.

5 Conclusion and Future Work

In this work, we systematically study the performance and scalability of the Linux I/O stack with four different I/O APIs: POSIX I/O, asynchronous libaio, io_uring, and userspace SPDK stacks. Our findings reveal that SPDK is still the de-facto winner in terms of raw performance and I/O efficiency (instructions/operation). Given enough CPU cores, the performance of io_uring does scale and matches the performance of SPDK, but consequently loses in terms of I/O efficiency. The Linux I/O scheduler can introduce significant overheads. We also report on the detailed instruction breakdown how the CPU instructions are used across different I/O stack components. Our results summarize that the Linux storage stack still has significant performance overheads, and scalability challenges in the presence of high-performance, low-latency NVMe devices. As a next step, we are expanding

our study to include file systems (ext4, F2FS, XFS), complex workloads (databases [26], key-value stores [23], machine learning training [47], bioinformatics [44], graph processing [50, 52]), mixed read-write workloads, and mixed priority tenants with/without a disaggregated setting [46].

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