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Improved Storage Performance Using the New Linux Kernel I/O Interface

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Agenda

- Existing Linux IO interfaces
- io_uring: The new efficient IO interface
- Liburing library
- Performance
- Upcoming features
- Summary

Existing Linux Kernel IO Interfaces

- Synchronous I/O interfaces:
  - Thread starts an I/O operation and immediately enters a wait state until the I/O request has completed
  - read(2), write(2), pread(2), pwrite(2), preadv(2), pwritev(2), preadv2(2), pwritev2(2)

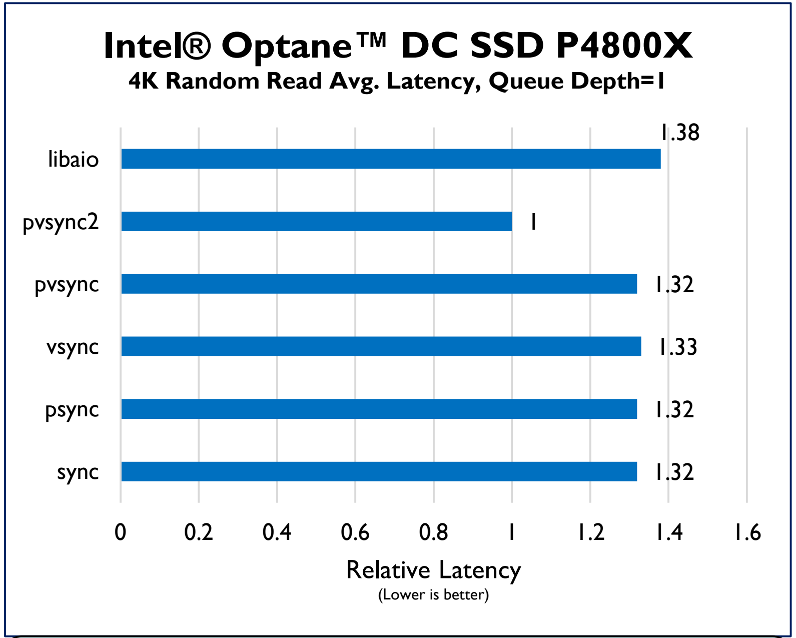
- Asynchronous I/O interfaces:
  - Thread sends an I/O request to the kernel and continues processing another job until the kernel signals to the thread that the I/O request has completed
  - Posix AIO: aio_read, aio_write
  - Linux AIO: aio

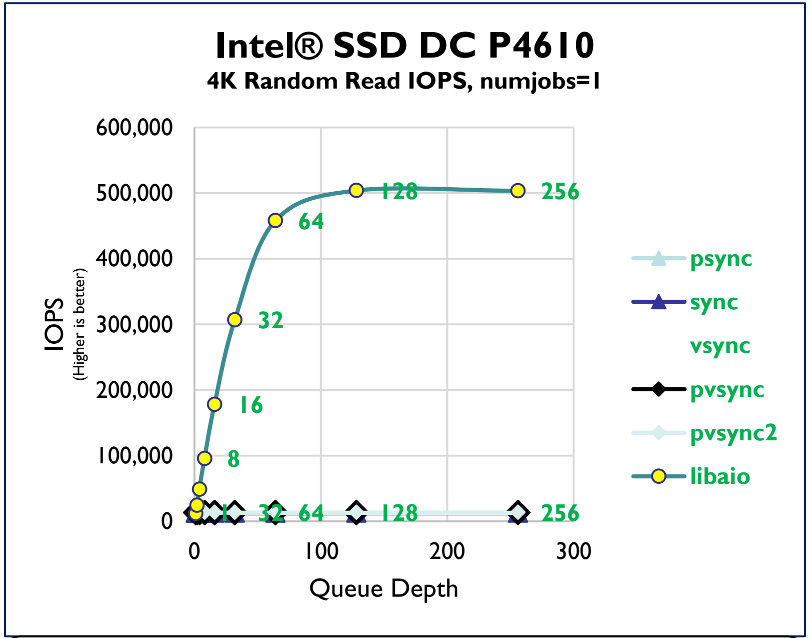
Existing Linux User-space IO Interfaces

- SPDK: Provides a set of tools and libraries for writing high performance, scalable, user-mode storage applications
- Asynchronous, polled-mode, lockless design
- https://spdk.io

This talk will cover Linux Kernel IO Interfaces

The Software Overhead Problem





Over 30% SW overhead with most of I/O interfaces vs. pvsync2 when running single I/O to an Intel® Optane™ P4800X SSD

Single thread IOPS Scale with increasing iodepth using libaio but other I/O interfaces doesn't scale with iodepth> 1

Test configuration details: slide 24

io_uring: The new IO interface

- High I/O performance & scalable:
  - Zero-copy: Submission Queue (SQ) and Completion Queue (CQ) place in shared memory
  - No locking: Uses single-producer-single-consumer ring buffers
- Allows batching to minimize syscalls: Efficient in terms of per I/O overhead.
- Allows asynchronous I/O without requiring O_DIRECT
- Supports both block and file I/O
- Operates in interrupted or polled I/O mode

Introduction to Liburing library

- Provides a simplified API and easier way to establish io_uring instance
- Initialization / De-initialization:
  - ***io_uring_queue_init():*** Sets up io_uring instance and creates a communication channel between application and kernel
  - ***io_uring_queue_exit():*** Removes the existing io_uring instance
- Submission:
  - ***io_uring_get_sqe():*** Gets a submission queue entry (SQE)
  - ***io_uring_prep_readv():*** Prepare a SQE with readv operation
    io_uring_prep_writev(): Prepare a SQE with writev operation
  - ***io_uring_submit():*** Tell the kernel that submission queue is ready for consumption

Introduction to Liburing library

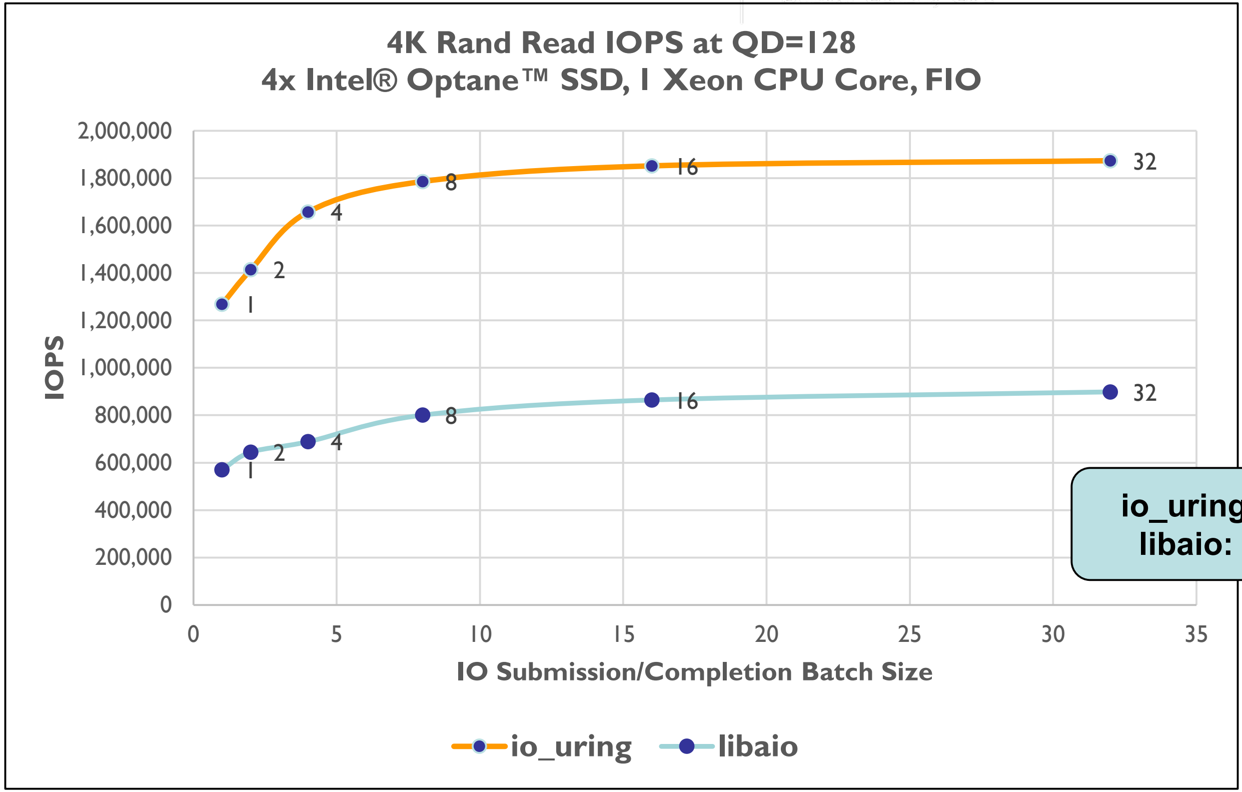
- Completion:
  - ***io_uring_wait_cqe():*** Wait for completion queue entry (CQE) to complete
  - ***io_uring_peek_cqe():*** Take a peek at the completion, but do not wait for the event to complete
  - ***io_uring_cqe_seen():*** Called once completion event is finished. Increments the CQ ring head, which enables the kernel
to fill in a new event at that same slot
- More advanced features not yet available through liburing
- For further information about liburing
  - *http://git.kernel.dk/cgit/liburing*

I/O Interfaces comparisons

SW Overhead	Synchronous I/O	Libaio	io_uring
System Calls	At least 1 per I/O	2 per I/O batch.	1 per batch, zero when using SQ submission thread.
		Batching reduces per I/O overhead	
Memory Copy	Yes	Yes – SQE & CQE	Zero-Copy for SQE & CQE
Context Switches	Yes	Yes	Minimal context switching polling
Interrupts	Interrupt driven	Interrupt driven	Supports both Interrupts and polling I/O
Blocking I/O	Synchronous	Asynchronous	Asynchronous
Buffered I/O	Yes	No	Yes

Performance

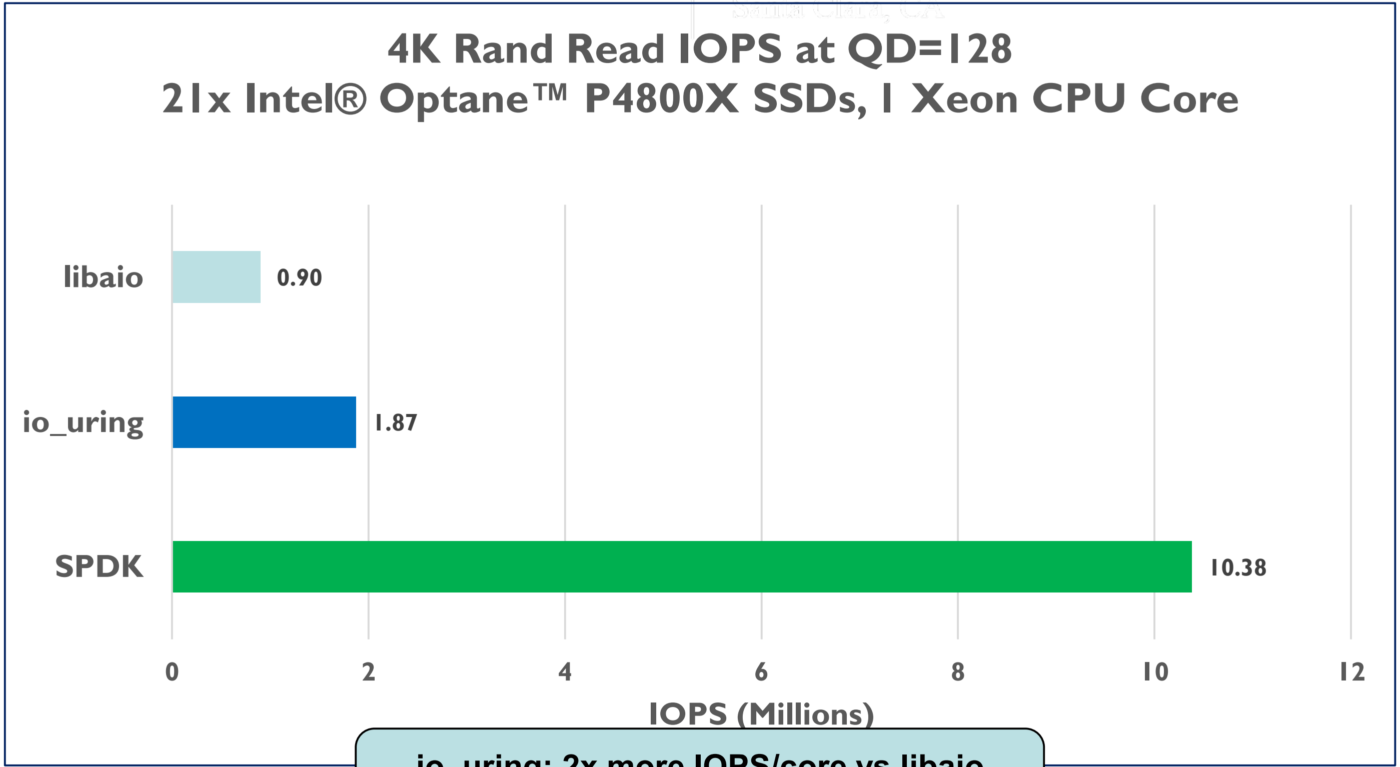
Single Core IOPS: libaio vs. io_uring



io_uring: 1.87M IOPS/core
libaio: ~900K IOPS/core

IO Submission and Completion batch sizes [1,32]
Test configuration details: slide 24

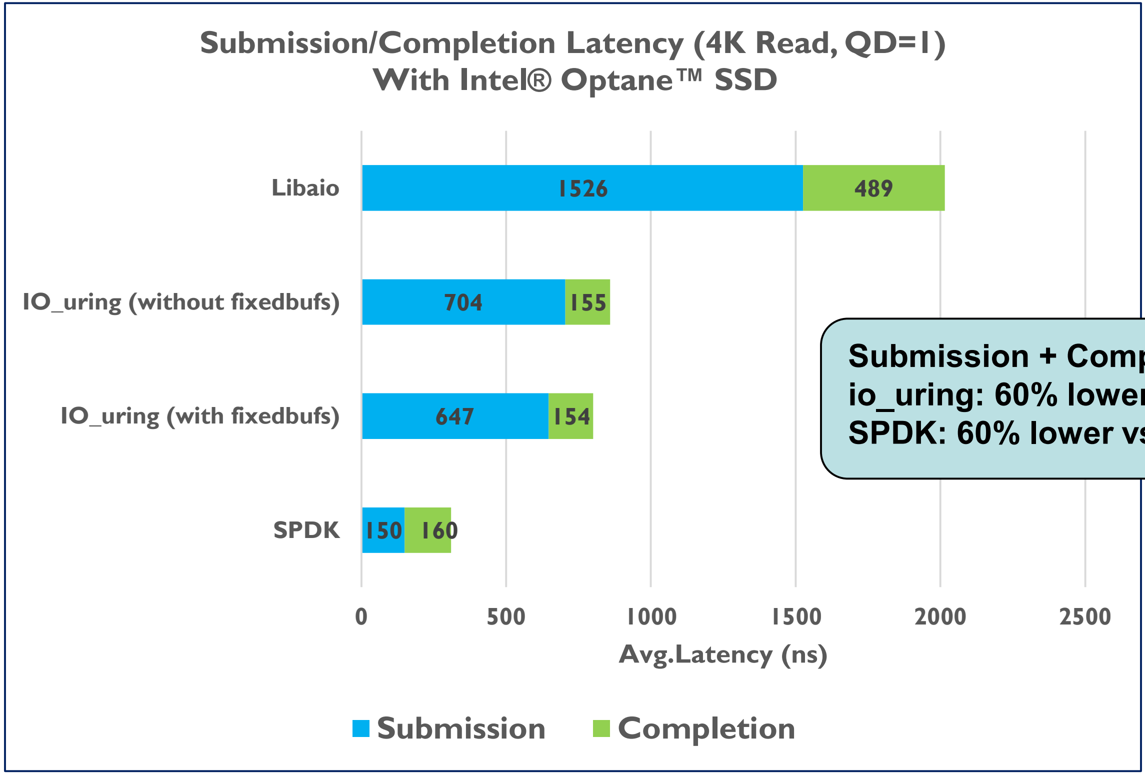
Single Core IOPS: libaio vs io_uring vs SPDK



io_uring: 2x more IOPS/core vs libaio
SPDK: 5.5x more IOPS/core vs io_uring

IO Submission/Completion batch sizes 32 for libaio & io_uring with 4x Intel® Optane™ P4800X SSDs. libaio data collected with fio, io_uring data collected with fio t & SPDK with perf. Test configuration details: slide 24

I/O Latency: libaio vs. io_uring vs. SPDK



Submission + Completion SW latency
io_uring: 60% lower vs. libaio
SPDK: 60% lower vs. io_uring

Submission Latency: Captures TSC before and after the I/O submission. **Completion Latency**: Captures TSC before and after the I/O completion check
Test configuration details: slide 24

libaio vs io_uring I/O path

SUBMISSION

```
85.17%     1.24%  fio     [kernel.vmlinux]   [k]
entry_SYSCALL_64
 |--85.12%--entry_SYSCALL_64
   |--81.86%--do_syscall_64
     |--45.28%--__x64_sys_io_submit
     |  |--44.08%--io_submit_one
     |    |--32.03%--aio_read
     |    |  |--30.38%--blkdev_read_iter
     |    |  |  |--30.13%--generic_file_read_iter
     |    |  |  |--29.30%--blkdev_direct_IO
...
```

COMPLETION

```
|--81.86%--do_syscall_64
   |--34.24%--__x64_sys_io_getevents
      |--33.49%--do_io_getevents
         |--31.87%--read_events
            |--16.93%--schedule
            |  |--15.18%--__schedule
...
            |--7.95%--aio_read_events
            |  |--2.24%--mutex_unlock
...
```

SUBMISSION + COMPLETION

```
--81.46%--entry_SYSCALL_64
        |--75.93%--do_syscall_64
        |        |--73.32%--__x64_sys_io_uring_enter
...
        |        |        |--31.24%--io_ring_submit
        |        |        |        |--30.83%--io_submit_sqe
        |        |        |        |        |--23.37%--__io_submit_sqe
        |        |        |        |        |        |--22.39%--io_read
        |        |        |        |        |        |        |--20.68%--blkdev_read_iter
...
        |        |        |--35.62%--io_iopoll_check
        |        |        |        |--33.80%--io_iopoll_getevents
        |        |        |        |        |--28.61%--blkdev_iopoll
...
        |        |        |        |        |        |--0.87%--nvme_poll
        |        |        |        |--1.34%--blkdev_iopoll
...
```

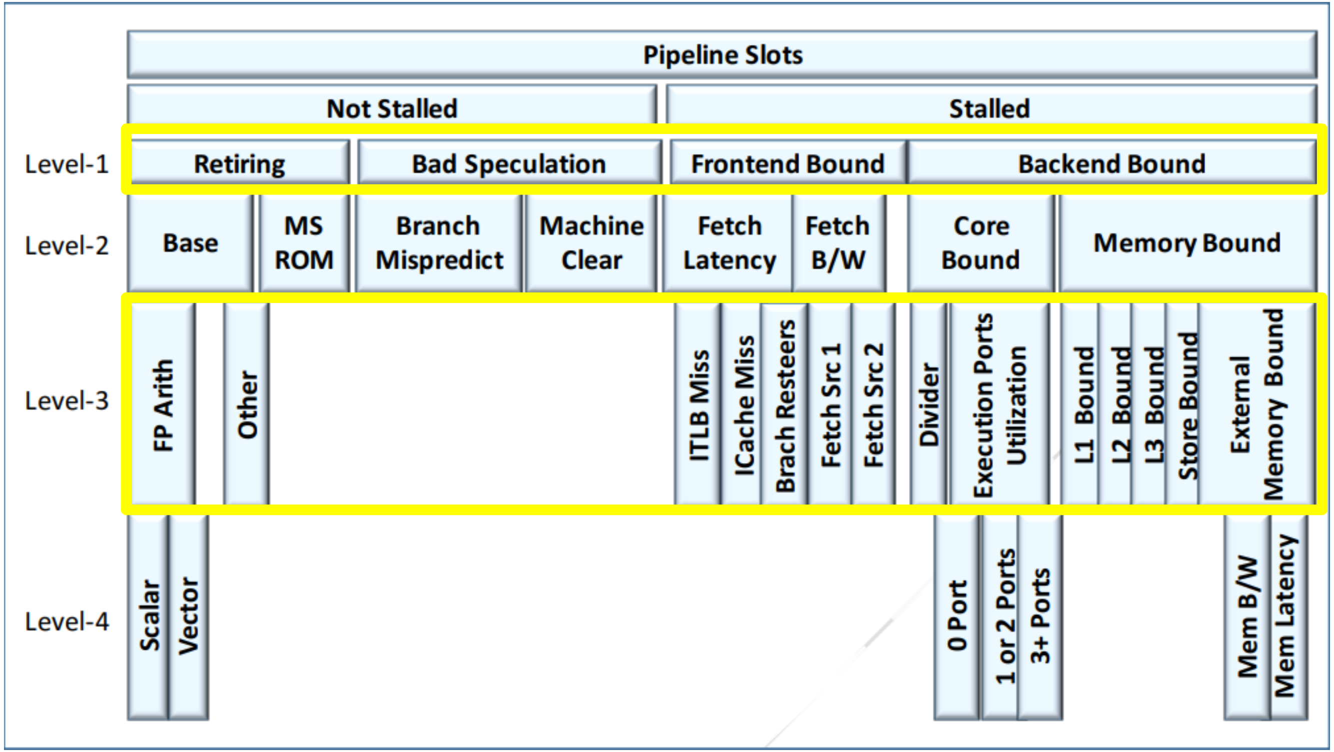
io_uring: submission + completion in 1 syscall

Interrupt and Context Switch

METRICS	libaio	io_uring	RATIONALE
HW Interrupts	172,417.78	251.80	io_uring polling eliminates Interrupts
Context Switch	112.27	1.47	Reduces context switches by 99%

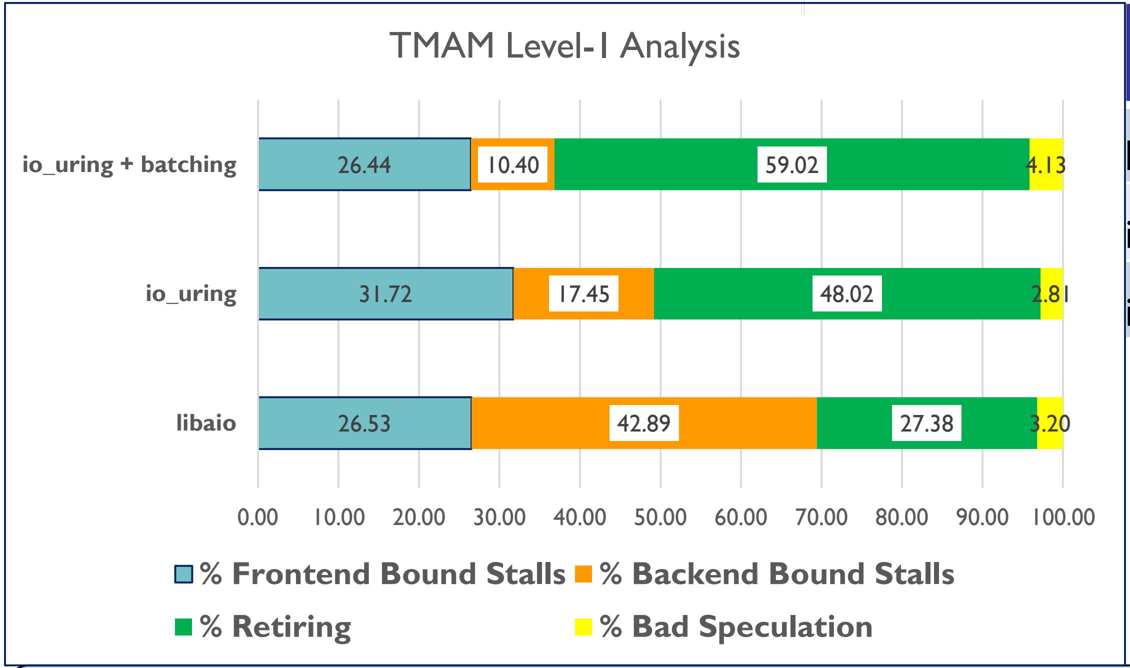
Workload: 4K Rand Read, 60 sec, 4 P4800, no batching.
HW interrupts & Context Switch metrics are per sec. We used fio for libaio test and fio t for io_uring.
Test configuration details: slide 24

Top-down Microarchitecture Analysis Methodology (TMAM) Overview



Source: https://fd.io/wp-content/uploads/sites/34/2018/01/performance_analysis_sw_data_planes_dec21_2017.pdf

TMAM Level-1 Analysis



I/O Interfaces	CPI (Lower is Better)
libaio	1.36
io_uring	0.58
io_uring + batching	0.45

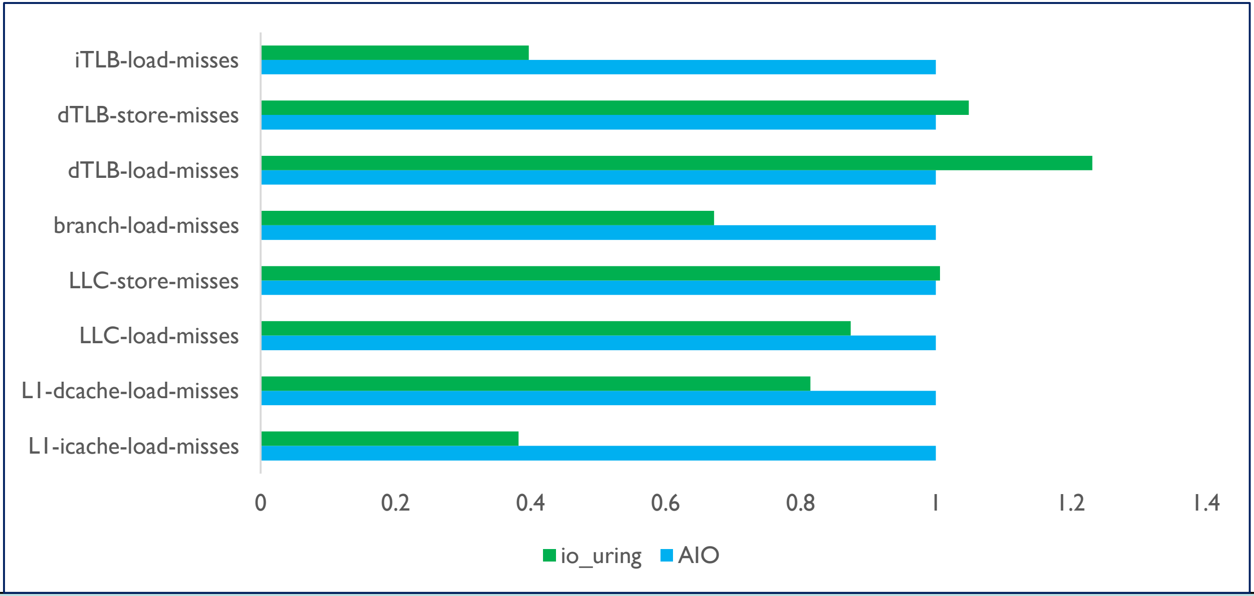
io_uring with batching:

- **32% reduction in backend bound stalls vs. libaio**
- **32% improvement in µOps retired vs. libaio. 66% lower CPI for io_uring vs. libaio**

Workload: 4K Rand Read, 60 sec, 4 P4800
Test configuration details: slide 24

TMAM Level-3 Analysis

Cache, Branch & TLB: libaio vs. io_uring

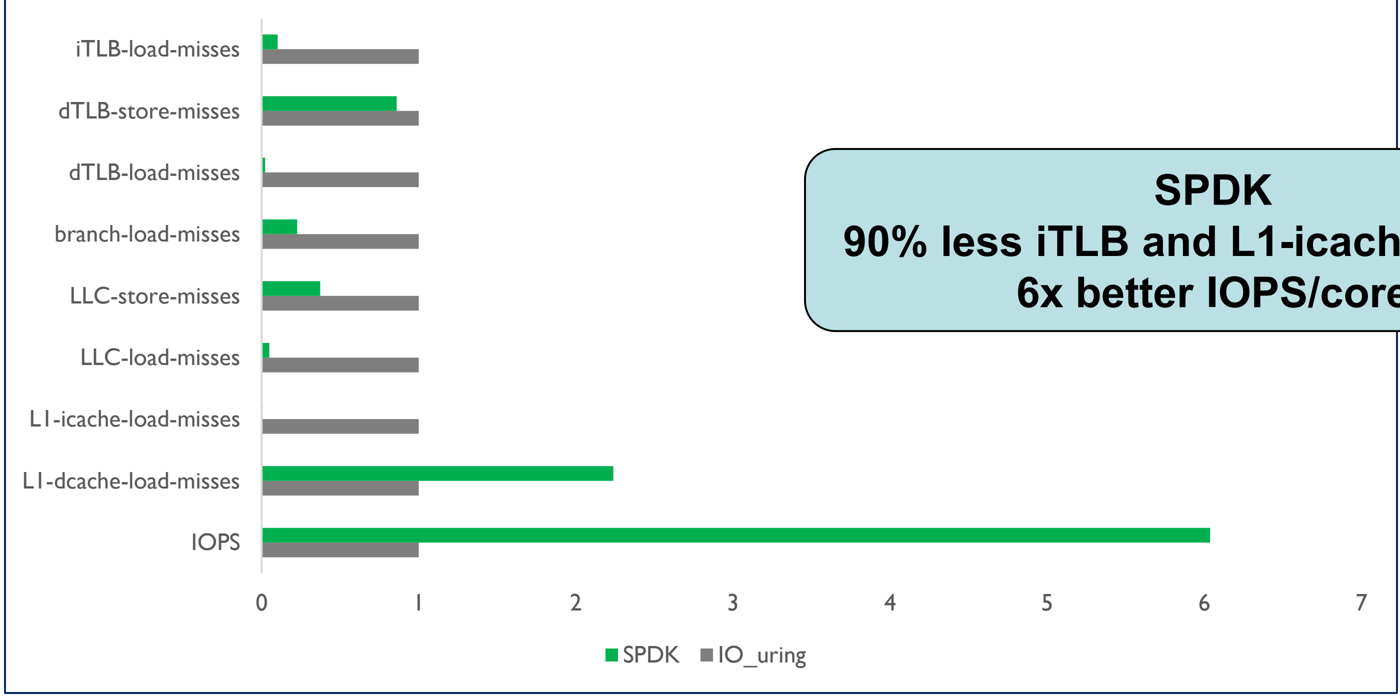


io_uring reduces icache & iTLB misses by over 60% vs. libaio

Workload: 4K Rand Read, 60 sec, 4 P4800
Test configuration details: slide 24

TMAM Level-3 Analysis

Cache, Branch & TLB: SPDK vs. IO_URING



SPDK
90% less iTLB and L1-icache misses
6x better IOPS/core

Workload: 4K Rand Read, 60 sec
Test configuration details: slide 24

What's Next for IO_URING

- io_uring for socket based I/O
  - Support already added for sendmsg(), recvmsg()
- Support for devices like RAID (md), Logical Volumes(dm)
- Async support for more system calls
  - Eg: open+read+close in a single call

Summary

- io_uring is the latest high performance I/O interface in the Linux Kernel (available since 5.1 release)
- Eliminates limitations of current Linux kernel async I/O interfaces
- Building an application for next generation of NVMe SSDs? io_uring enables
  - Less than 1 usec SW latency to submit/complete I/Os
  - 1 – 2 million IOPS/Core

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Backup

Performance Configuration

Performance configuration for slide 5 data:
Relative Latency: SuperMicro SYS-2029U-TN24R4T, Intel(R) Xeon(R) Platinum 8270 CPU @ 2.70GHz, 384GB DDR4, Ubuntu 18.04 LTS, Linux Kernel 5.2.0, **1x** Intel® Optane™ DC SSD P4800X 375GB SSD, fio-3.14-6-g97134, 4K 100% Random Reads, Iodepth=1, ramp time = 30s, direct=1 , runtime=300s, Data collected at Intel Storage Lab 07/17/2019

Throughput: SuperMicro SYS-2029U-TN24R4T, Intel(R) Xeon(R) Platinum 8270 CPU @ 2.70GHz, 384GB DDR4, Ubuntu 18.04 LTS, Linux Kernel 5.2.0, **1x** Intel® SSD DC P4610 1.6TB, fio-3.14-6-g97134, 4K 100% Random Reads, Iodepth=1 to 256 varied (exponential 2), ramp time= 30s, direct=1, runtime=300s, Data collected at Intel Storage Lab 07/17/2019

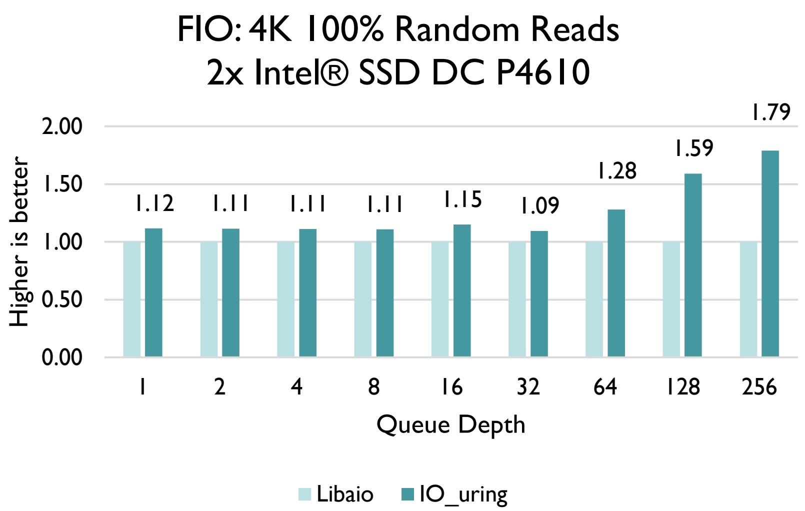
Performance configuration for slide 11, 12 & 19 data: Intel Server S2600WFT, Intel(R) Xeon(R) Platinum 8280L CPU @ 2.70GHz, 192GB DDR4, Fedora 27, Linux Kernel 5.0.0-rc6, **4x** Intel® Alderstream 503GB SSD, SPDK commit 41b7f1ca2189, SPDK bdevperf, runtime = 60s, Data collected at Intel Storage Lab 09/12/2019

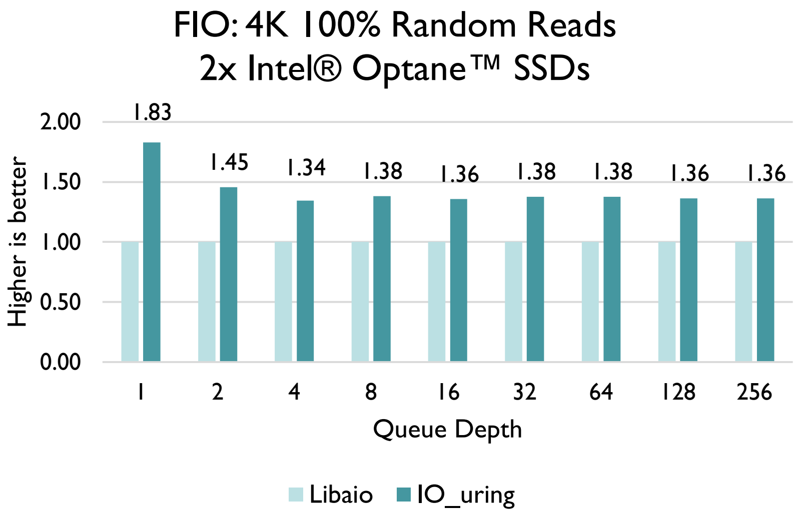
Performance configuration for slide 14 data: SuperMicro SYS-2029U-TN24R4T, Intel(R) Xeon(R) Platinum 8270 CPU @ 2.70GHz, 384GB DDR4, Ubuntu 18.04 LTS, Linux Kernel 5.2.0, **4x** Intel® Optane™ DC SSD P4800X 375GB SSD, fio-3.14-6-g97134, t/fio app used with varied batching sizes, Data collected at Intel Storage Lab 07/17/2019

Performance configuration for slide 15, 17 &18 data: SuperMicro SYS-2029U-TN24R4T, Intel(R) Xeon(R) Platinum 8270 CPU @ 2.70GHz, 384GB DDR4, Ubuntu 18.04 LTS, Linux Kernel 5.2.0, **4x** Intel® Optane™ DC SSD P4800X 375GB SSD, SPDK commit c223ba3b0f, fio-3.14-6-g97134, runtime = 60s, Data collected at Intel Storage Lab 09/6/2019

Performance configuration for slide 25 data: SuperMicro SYS-2029U-TN24R4T, Intel(R) Xeon(R) Platinum 8270 CPU @ 2.70GHz, 384GB DDR4, Ubuntu 18.04 LTS, Linux Kernel 5.2.0, **2x** Intel® Optane™ DC SSD P4800X 375GB SSD, 2x Intel® SSD DC P4610 fio-3.14-6-g97134, runtime = 300s, Data collected at Intel Storage Lab 07/17/2019

Relative IOPS Performance: Single Core: IO_Uring vs. Libaio





- Up to 10-15% improvement with io_uring on Intel® SSD DC P4610 at lower queue depths

- io_uring performs up to 1.8x better at lower queue depths on Intel® Optane™ SSDs