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

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Acknowledgements: John Kariuki, Jens Axboe
Agenda

- Existing Linux IO interfaces & their challenges
- IO_uring - the new efficient IO interface
- Introduction to Liburing library
- Performance of IO_uring on Non-volatile media
- 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
  - `aio_read, aio_write, async io (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://github.com/spdk/spdk.git

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™ SSD

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

For test configuration details please see slide # 15

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For more complete information about performance and benchmark results, visit www.intel.com/benchmarks.
IO_uring: The new IO interface

- Designed with low latency devices in mind
- Efficient in terms of per I/O overhead
- 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
- Easy to use
- Supports both block and file I/O
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](http://git.kernel.dk/cgit/liburing)
## I/O Interfaces comparisons

<table>
<thead>
<tr>
<th>SW Overhead</th>
<th>Synchronous I/O</th>
<th>Libaio</th>
<th>IO_uring</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Calls</td>
<td>At least 1 per I/O</td>
<td>At least 2 per I/O</td>
<td>At least 1 per batch, zero when using SQ submission thread. Batching reduces per I/O overhead</td>
</tr>
<tr>
<td>Memory Copy</td>
<td>Yes</td>
<td>Yes – SQE/CQE</td>
<td>Zero-copy. Shared SQ &amp; CQ</td>
</tr>
<tr>
<td>Context Switches</td>
<td>Yes</td>
<td>Yes</td>
<td>Minimal context switching</td>
</tr>
<tr>
<td>Interrupts</td>
<td>Interrupt driven</td>
<td>Interrupt driven</td>
<td>Supports both Interrupts and polling I/O</td>
</tr>
<tr>
<td>Blocking I/O</td>
<td>Synchronous</td>
<td>Asynchronous</td>
<td>Asynchronous</td>
</tr>
<tr>
<td>Buffered I/O</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
IO_uring: Single Core Max IOPS

- 4x Intel® Optane™ SSDs used to avoid I/O bottleneck
- IO Submission and completion batch sizes were increased from 1 to 32
- IOPS increases with increased submission and completion batch size from 1 to 8
- Max single core IOPS at 1.6M per core using IO_uring
- Libaio maxes out at ~600K per core
Measuring per I/O Latencies: Libaio vs. IO_uring

- Using overhead test app within SPDK. Measures software overhead of I/O submission and completion
- Runs a random read, queue depth = 1 I/O to a single device
- **Submission Latency**: Captures TSC before and after the I/O submission
- **Completion Latency**: Captures TSC before and after the I/O completion check

IO_uring (without fixedbufs) submission overhead reduces by 50% and completion overhead by 70% compared to libaio

Fixedbufs skips the entire mapping of pages, which improves submission latency

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For test configuration details please see slide # 16

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Santa Clara, CA
August 2019
Relative IOPS Performance:
Single Core: IO_Uring vs. Libaio

FIO: 4K 100% Random Reads
2x Intel® SSD DC P4610

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

FIO: 4K 100% Random Reads
2x Intel® Optane™ SSDs

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

For test configuration details please see slide # 16

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IO_uring is the latest high performance I/O interface in the Linux Kernel (available since 5.1 release)

- Helps improve performance for low-latency media
- Eliminates limitations of current Linux kernel async I/O interfaces
- Up to 1.8x better in IOPS per core and 70% better in latency than libaio for a single thread
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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™ 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 10 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™ 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 11 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, 1x Intel® Optane™ 375GB SSD, SPDK overhead tool used, runtime = 300s, Data collected at Intel Storage Lab 07/17/2019

Performance configuration for slide 12 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® 375GB SSD, 2x Intel® SSD DC P4610 fio-3.14-6-g97134, runtime = 300s, Data collected at Intel Storage Lab 07/17/2019
DEVS="nvme0n1 "

for dev in $DEVS; do
  echo "Prep /dev/$dev"
  SYSFS=/sys/block/$dev/queue
  echo 0 > $SYSFS/iostats
  echo 0 > $SYSFS/rq_affinity
  echo 2 > $SYSFS/nomerges
  echo 0 > $SYSFS/io_poll_delay
done