Accelerating NVMe I/Os in Virtual Machine via SPDK vhost* Solution

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Outline

• Background
• SPDK vhost solution
• Experiments
• Conclusion
NVMe & virtualization

• NVMe specification enables highly optimized drives (e.g., NVMe SSD)
  – For example, multiple I/O queues allows lockless submission from CPU cores in parallel
• However, even the best kernel mode drivers have non-trivial software overhead
  – Long I/O stack in kernel with resource contention
• Virtualization adds additional overhead
  – Long I/O stack in both guest OS kernel and host OS kernel
  – Context switch overhead (e.g., VM_EXIT caused by I/O interrupt in guest OS)
What is in QEMU’s solution?

- The solution in QEMU to virtualize NVMe device:
  - Virtio virtualization
  - NVMe controller virtualization
  - Hardware assisted virtualization

- Virtio virtualization
  - Virtio SCSI/block Controllers

- NVMe controller virtualization
  - QEMU emulated NVMe Device (file based NVMe backend)
  - QEMU NVMe Block Driver based on VFIO (exclusive access by QEMU)
What is in QEMU’s solution?

- Paravirtualized driver specification
- Common mechanisms and layouts for device discovery, I/O queues, etc.
- virtio device types include:
  - virtio-net
  - virtio-blk
  - virtio-scsi
  - virtio-gpu
  - virtio-rng
  - virtio-crypto
Accelerate virtio via vhost target

- Separate process for I/O processing
- vhost protocol for communicating guest VM parameters
  - memory
  - number of virtqueues
  - virtqueue locations

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**Guest VM**
(Linux*, Windows*, FreeBSD*, etc.)

- virtio front-end drivers

**Hypervisor (i.e. QEMU/KVM)**

- virtio back-end drivers
  - Device emulation
  - vhost

**vhost target**
(kernel or userspace)

- vhost
SPDK vhost solution
What is SPDK?

**Storage Performance Development Kit**

**Intel® Platform Storage Reference Architecture**
- Optimized for *Intel platform* characteristics
- Open source building blocks (BSD licensed)
- Available via github.com/spdk or spdk.io

**Scalable and Efficient Software Ingredients**
- User space, lockless, polled-mode components
- Up to millions of IOPS per core
- Designed for Intel Optane™ technology latencies
Combine virtio and NVMe to inform a uniform SPDK vhost solution

QEMU
Guest VM
Virtio Controller
virtio
vhost
eventfd
UNIX domain socket

SPDK vhost
virtio
dpdk vhost
vhost
eventfd
UNIX domain socket

QEMU
Guest VM
NVMe Controller
vhost

SPDK vhost
NVMe
dpdk vhost

virtqueue
Shared Guest VM Memory
Host Memory

virtqueue
Shared Guest VM Memory
Host Memory

UNIX domain socket

eventfd
Virtio VS NVMe

Both Use Ring Data Structures for IO
Virtio-SCSI and NVMe protocol format comparison

(16 * 3 + SCSI_Req + SCSI_Rsp + Data) Bytes

(NVMe_Req + Data + NVMe_Rsp) Bytes
## Comparison of known solutions

<table>
<thead>
<tr>
<th>Solution Usage</th>
<th>QEMU Emulated NVMe device</th>
<th>QEMU VFIO Based solution</th>
<th>QEMU PCI-Passthrough SR-IOV</th>
<th>SPDK Vhost-SCSI</th>
<th>SPDK Vhost-BLK</th>
<th>SPDK Vhost-NVMe</th>
<th>Mediated-NVMe VFIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guest OS Interface</td>
<td>NVMe</td>
<td>NVMe</td>
<td>NVMe</td>
<td>Virtio SCSI</td>
<td>Virtio BLK</td>
<td>NVMe</td>
<td>NVMe</td>
</tr>
<tr>
<td>Backend Device sharing</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>*Depends on implementation *</td>
</tr>
<tr>
<td>Live Migration support</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>No, Feature is WIP</td>
<td>*Depends on implementation *</td>
</tr>
<tr>
<td>VFIO dependency</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Can use UIO or VFIO</td>
<td>Can use UIO or VFIO</td>
<td>Can use UIO or VFIO</td>
<td>Y</td>
</tr>
<tr>
<td>QEMU Support</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>No, Upstream is WIP</td>
<td>Y</td>
</tr>
</tbody>
</table>
SPDK vhost NVMe implementation details
Vhost NVMe implementation details

QEMU
Guest VM
NVMe Controller

Admin Queue
Submit A New Request
IRQ Injection
Get CQE

Vhost
Shared Guest VM Memory

Kernel
kvm

UNIX Domain Socket
Pick up the New Request
Post CQE

SPDK Vhost-NVMe
NVMe

NVMe IO Queue Poller

BDEV
NS1
NS2
...
NS
BDEV
Create io queue

Guest: Create IO Queue

SPDK: Start to Create IO Queue

<table>
<thead>
<tr>
<th>QSIZE</th>
<th>QID</th>
<th>CQID</th>
<th>QPRIO</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PRP1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Guest: Submit to Admin, Write DB

QEMU: Pick up Admin Command

QEMU: Send via Domain Socket

SPDK: Memory Translation

SPDK: Both Guest and SPDK see same IO Queue now
New feature to address guest NVMe performance issue

- MMIO Writes happened, which will cause VM_EXIT

NVMe 1.3 New Feature: Optional Admin Command support for Doorbell Buffer Config, only used for emulated NVMe controllers, Guest can update shadow doorbell buffer instead of submission queue’s doorbell registers
# Shadow doorbell buffer

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00h</td>
<td>03h</td>
<td>Submission Queue 0 Tail Doorbell or Eventidx (Admin)</td>
</tr>
<tr>
<td>04h</td>
<td>07h</td>
<td>Completion Queue 0 Head Doorbell or Eventidx (Admin)</td>
</tr>
<tr>
<td>08h</td>
<td>0Bh</td>
<td>Submission Queue 1 Tail Doorbell or Eventidx</td>
</tr>
<tr>
<td>0Ch</td>
<td>0Fh</td>
<td>Completion Queue 1 Head Doorbell or Eventidx</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRP1</td>
<td>Shadow doorbell memory address, updated by Guest NVMe Driver</td>
</tr>
<tr>
<td>PRP2</td>
<td>Eventidx memory address, updated by SPDK vhost target</td>
</tr>
</tbody>
</table>
Experiments
1 VM with 1 NVMe SSD

IOPS (K)

CPU Utilization (%)

KVM Events

System Configuration: 2 * Intel Xeon E5 2699v4 @ 2.2GHz; 128GB, 2667 DDR4, 6 memory Channels; SSD: Intel Optane™ P4800X, FW: E2010324, 375GiB; Bios: HT disabled, Turbo disabled; OS: Fedora 25, kernel 4.16.0. 1 VM, VM config: 4 vcpu 4GB memory, 4 IO queues; VM OS: Fedora 27, kernel 4.16.5-200, blk-mq enabled; Software: QEMU-2.12.0 with SPDK Vhost-NVMe driver patch, IO distribution: 1 vhost-cores for SPDK, FIO 3.3, io depth=32, numjobs=4, direct=1, block size=4k, total tested data size=400GiB
8 VMs with 4 NVMe SSDs

- Linux kernel NVMe driver will poll completion queue when submitting a new request, which can help to decrease interrupt numbers and vm_exit events.

System Configuration: 2 * Intel Xeon E5 2699v4 @ 2.2GHz; 256GB, 2667 DDR4, 6 memory Channels; SSD: Intel DC P4510, FW: VDV101 10, 2TiB; BIOS: HT disabled, Turbo disabled; Host OS: CentOS 7, kernel 4.16.7. 8 VMs, VM config: 4 vcpu 4GB memory, 4 IO queues; Guest OS: Fedora 27, kernel 4.16.5-200, blk-mq enabled; Software: QEMU-2.12.0 with SPDK Vhost-NVMe driver patch, IO distribution: 2 vhost-cores for SPDK, FIO 3.3, io depth=128, numjobs=4, direct=1, block size=4k, runtime=300s, ramp_time=10s; SSDs well preconditioned with 2 hours randwrites before randread tests.
Conclusion
Conclusion

• Conclusion
  – In this presentation, we introduce SPDK vhost solution (i.e., SCSI/Blk/NVMe) to accelerate NVMe I/Os in virtual machines

• Future work
  – VM live migration support for the whole SPDK vhost solution (i.e., vhost SCSI/BLK/NVMe)
  – Upstream QEMU vhost driver.

• Promotion
  – Welcome to evaluate & use SPDK vhost target!
  – Welcome to contribute to SPDK community!
Q & A