Accelerating NVMe I/Os in Virtual Machines via SPDK vhost

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Agenda

• Background
• SPDK vhost solution
• Experiments
• Conclusion
Background
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)
Background: What is in QEMU

- 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

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

virtio front-end drivers

Hypervisor (i.e. QEMU/KVM)

virtio back-end drivers

Device emulation

vhost
devices

vhost target
(kernel or userspace)

• Separate process for I/O processing

• vhost protocol for communicating guest VM parameters
  • memory
  • number of virtqueues
  • virtqueue locations
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](https://github.com/spdk) or [spdk.io](http://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
**SPDK architecture**

- **Storage Protocols**
  - NVMe-oF
  - vhost-NVMe
  - iSCSI
  - vhost-scsi
  - vhost-blk
  - Linux nbd

- **NVMe Devices**
  - NVMe-oF Initiator
  - NVMe* PCIe Driver
  - Intel® QuickData Technology Driver

- **Block Device Abstraction (BDEV)**
  - Logical Volumes
  - snapshots
  - clones
  - GPT
  - DPDK Encryption
  - QoS
  - BlobFS
  - Blobstore

- **Storage Services**
  - NVMe
  - Linux AIO
  - Ceph RBD
  - PMDK blk
  - Virtio SCSI
  - Virtio Blk
  - iSCSI initiator

- **Integration**
  - Cinder
  - VPP TCP/IP
  - RocksDB
  - Ceph
  - QEMU

- **Drivers**
  - NVMe-oF Initiator
  - NVMe PCIe Driver
  - Intel® QuickData Technology Driver

- **Core**
  - Application Framework

**Release Dates**
- 18.01 Release
- 18.04 Release
- 18.07 Release
Combine virtio and NVMe to inform a uniform SPDK vhost solution.
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
SPDK vhost architecture

- QEMU
  - Vhost SCSI Driver
  - Vhost BLK Driver
  - Vhost NVMe Driver

- Guest 1
  - Virtio SCSI Controller

- Guest 2
  - Virtio BLK Controller

- Guest 3
  - NVMe Controller

- Kernel
  - kvm

- SPDK vhost Target
  - SCSI
  - BLK
  - NVMe
  - BDEV

QEMU Released
Separate Patch for QEMU
## Comparison of known solutions

<table>
<thead>
<tr>
<th>Solution Usage</th>
<th>QEMU Emulated NVMe device</th>
<th>QEMU VFIO Based solution</th>
<th>SPDK Vhost-SCSI</th>
<th>SPDK Vhost-BLK</th>
<th>SPDK Vhost-NVMe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guest OS driver Interface</td>
<td>NVMe</td>
<td>NVMe</td>
<td>Virtio SCSI</td>
<td>Virtio BLK</td>
<td>NVMe</td>
</tr>
<tr>
<td>Backend Device sharing</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Application Transparent support</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N (e.g., Command set is very small)</td>
<td>Y</td>
</tr>
<tr>
<td>Live Migration support</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>VFIO dependency</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>QEMU Change</td>
<td>No modification</td>
<td>Upstream is done</td>
<td>Upstream is done</td>
<td>Upstream is done</td>
<td>Upstream is in process</td>
</tr>
</tbody>
</table>
SPDK vhost NVMe implementation details
vhost NVMe implementation details

QEMU
Guest VM
NVMe Controller

SPDK Vhost-NVMe
NVMe

NVMe IO Queue Poller

Kernel
kvm

Admin Queue
IRQ Injection
Submit A New Request
Get CQE
Pick up the New Request
UNIX Domain Socket
Post CQE

Shared Guest VM Memory

s
q
c
q

s
q
c
q
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>PRP1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Guest: Create IO Queue

SPDK: Start to Create IO Queue

Guest: Submit to Admin, Write DB

QEMU: Pick up Admin Command

SPDK: Memory Translation

QEMU: Send via Domain Socket

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

Submit a new IO

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

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: VDV10110, 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=60s; SSDs well preconditioned with 2 hours randwrites before randread tests.
Conclusion
Conclusion & Future work

- **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!