Spool: Reliable Virtualized NVMe Storage Systems in Public Cloud Infrastructure

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2 Design of Spool
3 Spool key ideas
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Introduction

<table>
<thead>
<tr>
<th>Type</th>
<th>Performance</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDD</td>
<td>LOW PERFORMANCE</td>
<td>500 IOPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 ms LATENCY</td>
</tr>
<tr>
<td>SATA NAND SSD</td>
<td>AFFORDABLE PERFORMANCE</td>
<td>25 K IOPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 us LATENCY</td>
</tr>
<tr>
<td>NVMe NAND SSD</td>
<td>HIGH PERFORMANCE</td>
<td>400 K IOPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 us LATENCY</td>
</tr>
<tr>
<td>NVMe V-NAND SSD</td>
<td>EXTREME PERFORMANCE</td>
<td>1,500 K IOPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 us LATENCY</td>
</tr>
</tbody>
</table>

With the development of storage hardware, **software has become the performance bottleneck.**
Introduction

The local NVMe SSD-based instance storage provided for:
- Amazon EC2 I3 series
- Azure Lsv2 series
- Alibaba ECS I2 series

The local NVMe SSD-based instance storage optimized for:
- low latency
- high throughput
- high IOPS
- low cost
Introduction

High reliability is the most important and challenging problem:
- restarting the virtualization system
- removing the failed device
- performing the upgrade
Spool is proposed based on the SPDK NVMe driver but focuses on the reliability of the virtualized storage system.
Motivation

Unnecessary Data Loss: reset device controller
- For Azure, a device failure results in the entire machine being taken offline for repair.
- For SPDK, the administrator directly replaces the failed device through hot-plug.
- Only 6% of the hardware failures are due to real media errors.

The current failure recovery method results in significant unnecessary data loss.
Motivation

Poor Availability
- VM live migration is too costly.
- The downtime for SPDK restart is up to 1,200 ms.

The long downtime hurts the availability of the I/O virtualization system.
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Spool is comprised of:

- **A cross-process journal**: records each I/O request and its status to ensure data consistency.
- **A fast restart component**: records the runtime data structures of the current Spool process to reduce the downtime.
- **A failure recovery component**: diagnoses the device failure type online to minimize unnecessary disk replacement.
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The I/O requests are processed in a *producer-consumer* model:

1. The guest driver places the head index of descriptor chain into the next ring entry of the available ring, and *avail_idx* of the available ring is increased.
2. The backend running in the host obtains several head indexes of the pending I/O requests in the available ring, increases *last_idx* of the available ring and submits the I/O requests to hardware driver.
3. Once a request is completed, the backend places the head index of the completed request into the used ring and notifies the guest.
Reliable Cross-Process Journal

Reliable problem:
- The backend obtains two I/O requests, IO1 and IO2.
- Then, the last_idx is incremented from IO1 to IO3 in the available ring.
- If the storage virtualization system restarts at this moment, the last available index will be lost.

Spool persists:
- last_idx
- the head index of each request
- the states of each request: INFLIGHT, DONE, or NONE.
Reliable Cross-Process Journal

The challenge to ensure the consistency of the journal is to:
- guarantee that instructions to increase $last_idx$ and change the request’s status are executed in an atomic manner.

A multiple-instruction transaction model
- In T0, we make a copy of the variable to be modified.
- In T1, the transaction will be in the START state, and the variables are modified.
- After all the variables modified completely, the transaction will be in the FINISHED state in T2.

<table>
<thead>
<tr>
<th>T0: Init Phase</th>
<th>T1: Instrs Execution</th>
<th>T2: Valid Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory</td>
<td>Memory</td>
<td>Memory</td>
</tr>
<tr>
<td>State</td>
<td>State</td>
<td>State</td>
</tr>
<tr>
<td>Valid Data</td>
<td>Valid Data</td>
<td>Valid Data</td>
</tr>
<tr>
<td></td>
<td>last_avail_idx++</td>
<td>last_avail_idx++</td>
</tr>
<tr>
<td></td>
<td>last_req_head=head</td>
<td>last_req_head=head</td>
</tr>
<tr>
<td></td>
<td>req[head]=INFLIGHT</td>
<td>req[head]=INFLIGHT</td>
</tr>
</tbody>
</table>

Valid Data State

Write memory barrier

Valid
Invalid
Reliable Cross-Process Journal

An auxiliary data structure:

- It is a valuable trick to efficiently maintain journal consistency to eliminate the overhead of making a copy in T0.
- The state, last available index, and head index of the related request are padding to 64 bits and a union memory block with a 64-bit value.
- The three records are updated within one instruction.

```c
union atomic_aux {
    struct {
        uint8_t pad0;
        uint8_t state;
        uint16_t last_avail_idx;
        uint16_t last_req_head;
        uint16_t pad1;
    };
    uint64_t val;
};
```
Reliable Cross-Process Journal

Algorithm 1 Algorithm of cross-process journal

1. poll head1 from the available ring;
2. aux.state = START;
3. aux.last_idx = journal->last_idx+1;
4. aux.last_req_head = head1;
5. *(volatile uint64_t *)&journal->val = *(volatile uint64_t *)&aux.val;
6. req[head1] = INFLIGHT;
7. journal->state = FINISHED;
8. submit I/O request to driver;
9. poll head2 completion;
10. journal->used_idx++;
11. req[head2] = DONE;
12. put head2 to the used ring, may goto 10 or 13;
13. update used_index of the used vring with used_idx of journal;
14. req[head2] = NONE;

Every step Spool takes in algorithm 1 is likely to restart for upgrade.
Reliable Cross-Process Journal

The recovery algorithm:
- The new Spool process before the restart only needs to check the state and decide whether to redo the transactions.
- The states of IO request is repaired based on used index of vring and the last used index in the journal.

Algorithm 2 Algorithm for recovering I/O requests

1: if (state == START) {
2:     req[last_get_req_head] = INFLIGHT;
3:     state = FINISHED;
4: }
5: jstate = (last_used_idx == used_idx) ? NONE : INFLIGHT
6: change all requests with done status to jstate;
7: 
8: last_used_idx = used_idx;
9: submit all requests marked as INFLIGHT;
Start stage 1: Init EAL
- Obtaining memory layout information: 70.9% of the total time.
- The runtime configurations and memory layout information can be reused.

Start stage 2: Probe device
- Resetting the controller of NVMe devices: 90% of the total time.
- The controller information can be reused.
Optimizing Spool Restart

Reusing Stable Configurations
- Global runtime configurations.
- Memory layout information.

Skipping Controller
- NVMe device controller-related information.
- Gracefully terminate: SIGTERM and SIGINT signals.
Hardware Fault Diagnosis and Processing

Handling Hardware Failures
- A device failures or hot-remove cause process to crash.
- A SIGBUS handler is registered.

Failure Model
- Based on S.M.A.R.T. diagnosis
- Hardware media error: hot-plug a new device.
- Other hardware errors: reset the controller.
Experimental configuration

Table 1: Experimental configuration

<table>
<thead>
<tr>
<th></th>
<th>Host configuration</th>
<th>Guest OS configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU &amp; Memory</td>
<td>2x E5-2682v4 @2.5GHz; 128GB DDR4 Memory</td>
<td>4 vCPU; 8 GB</td>
</tr>
<tr>
<td>NVMe devices</td>
<td>2 Samsung PM963 3.84TB SSDs</td>
<td>CentOS 7 (kernel version 3.10.327)</td>
</tr>
<tr>
<td>OS info</td>
<td>CentOS 7 (kernel version 3.10.327)</td>
<td>CentOS 7 (kernel version 3.10.327)</td>
</tr>
</tbody>
</table>
Experimental configuration

Table 2: FIO test cases

<table>
<thead>
<tr>
<th>Tested metrics</th>
<th>Test cases</th>
<th>FIO Configuration (bs, rw, iodepth, numjobs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>Read</td>
<td>(128K, read, 128, 1)</td>
</tr>
<tr>
<td></td>
<td>Write</td>
<td>(128K, write, 128, 1)</td>
</tr>
<tr>
<td>IOPS</td>
<td>Randread</td>
<td>(4K, randread, 32, 4)</td>
</tr>
<tr>
<td></td>
<td>Mixread</td>
<td>(4K, randread 70%, 32, 4)</td>
</tr>
<tr>
<td></td>
<td>Mixwrite</td>
<td>(4K, randwrite 30%, 32, 4)</td>
</tr>
<tr>
<td></td>
<td>Randwrite</td>
<td>(4K, randwrite, 32, 4)</td>
</tr>
<tr>
<td>Average Latency</td>
<td>Randread</td>
<td>(4K, randread, 1, 1)</td>
</tr>
<tr>
<td></td>
<td>Randwrite</td>
<td>(4K, randwrite, 1, 1)</td>
</tr>
<tr>
<td></td>
<td>Read</td>
<td>(4K, read, 1, 1)</td>
</tr>
<tr>
<td></td>
<td>Write</td>
<td>(4K, write, 1, 1)</td>
</tr>
</tbody>
</table>

Performance: Bandwidth, IOPS, Average Latency
Reliability of Handling Hardware Failure

- SSD2 is hot-removed and hot-plugged.
- The storage service for VM2 is back online automatically.
- The storage service for VM1 is not affected.

Figure 12: Handling hardware failure with Spool.
Reliability of Handling Random Upgrades

- The file contents is verified with FIO on a Guest VM.
- Spool can guarantee data consistency during upgrades.

Figure 13: Data consistency at live upgrade with Spool.
Reducing Restart Time

Spool reduces the total restart time from 1,218 ms to 115 ms.
I/O Performance of Spool

Case 1: Single VM Performance

Figure 15: Average data access latency and IOPS of an NVMe SSD when it is used by a single VM.

- Spool achieves similar performance to SPDK.
I/O Performance of Spool

Case 2: Scaling to Multiple VMs

- Spool improves the IOPS of Randread by 13% compared with SPDK vhost-blk.
- Spool reduces the average data access latency of Randread by 54% compared with SPDK vhost-blk.

Figure 16: Average data access latency and IOPS of an NVMe SSD when it is shared by multiple VMs.
Spool increases the average data access latency no more than 3%.

And Spool reduces the IOPS by less than 0.76%

Figure 17: Overhead of the cross-process journal.
Deployment on an In-production Cloud

The maximum IOPS of a single disk is 50% higher.
The maximum IOPS of a largest specification instance is 51% higher.

Figure 18: Maximum read IOPS compared with AWS and Azure.
Thanks for listening!

Question?
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