SPDK Schedulers
Realizing Power Savings in Polled Mode Applications
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Introductions

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SPDK Overview
SPDK Overview

- **Storage Performance Development Kit**
  - Framework for building high-performance storage applications
  - Set of drivers and libraries
  - Includes fully functional storage target applications
  - Userspace, polled-mode programming model
  - Open-source community
  - BSD licensed
  - https://spdk.io

- **Block Storage Protocols**
  - **Networking:** NVMe-oF (RDMA, TCP, FC), iSCSI
  - **Virtualization:** vhost-scsi, vhost-blk, NVMe vfio-user

- **Block Storage Services**
  - **Partitioning:** Logical Volumes, GPT
  - **Caching:** OCF
  - **Host FTL:** ZNS
  - **Pooling:** RAID-0
  - **Transforms:** Crypto, Compression

- **Block Storage Providers**
  - NVMe, io_uring, Linux AIO, virtio, iSCSI, Ceph RBD

- **Drivers**
  - NVMe (PCIe, RDMA, TCP), virtio (scsi, blk), idxd, ioat
SPDK Threading Model
SPDK Threading Model

- **spdk_reactor**
  - One spdk_reactor per CPU core
  - Pinned POSIX thread
  - Created by SPDK application framework

- **spdk_thread**
  - Lightweight “thread” abstraction
  - By default, one spdk_thread per CPU core
    - Created by top-level block storage protocol library (nvmf, vhost, iscsi)
  - spdk_thread_poll() used by application framework to “run” an spdk_thread
spdk_thread_poll()

- spdk_poller
  - Libraries register spdk_pollers to poll on something
    - NVMe qpair
    - epoll fd (group of TCP sockets or rbd eventfds)
    - RDMA completion queue
  - One call to spdk_thread_poll() runs every spdk_poller once
    - Except for timed pollers
- spdk_thread_send_msg()
  - Used for inter-thread communication
Saving Power When Idle
All of this polling!

- Polled mode ideal for best performance and efficiency when CPU cores are busy
- But how can we save CPU cycles when we are not as busy?
Interrupt Mode

- SPDK does have some limited interrupt mode support
  - Restricted to very small subset of SPDK libraries (not including nvme driver or nvmf target)
  - Supporting libraries register fds with spdk_thread
  - spdk_reactor waits on epoll fd containing fds from all spdk_threads on that reactor
- Overly complex to implement efficiently
  - Avoid nested epoll fd groups
  - *Every* library must be modified to support interrupts
umonitor/umwait

- Newer x86 instructions to allow unprivileged monitor/mwait
- umwait – enables CPU to enter low-power state
  - Exits low-power state on observed write to memory range specified by umonitor
- Works well for one thread polling one HW queue
  - i.e. DPDK packet processing and userspace Ethernet PMDs
- Not suitable when polling many HW queues from one thread
  - Or when polling kernel TCP sockets!
Move spdk_threads?

- Would allow putting a CPU core to sleep!
  - While still ensuring the spdk_thread is continually polled (just on a new core)
- Supported by SPDK threading model
  - Since all resources allocated by an spdk_poller are spdk_thread local
SPDK Scheduler Framework
Scheduling Phases

- Reactors are never halted
- 1) `gather_metrics()` collects info on core and threads status

```
struct spdk_scheduler_core_info {
    /* stats over a lifetime of a core */
    uint64_t total_idle_tsc;
    uint64_t total_busy_tsc;
    /* stats during the last scheduling period */
    uint64_t current_idle_tsc;
    uint64_t current_busy_tsc;
    uint32_t lcore;
    uint32_t threads_count;
    bool interrupt_mode;
    struct spdk_scheduler_thread_info *thread_infos;
};
struct spdk_scheduler_thread_info {
    uint32_t lcore;
    uint64_t thread_id;
    /* stats over a lifetime of a thread */
    struct spdk_thread_stats total_stats;
    /* stats during the last scheduling period */
    struct spdk_thread_stats current_stats;
};
```
Balancing Threads

- 2) balance()
  - Change thread’s core assignment
  - Put a core to sleep
  - Modify core frequency via governor

Plug your own!

```c
struct spdk_scheduler {
    const char *name;

    /**
     * This function is called to initialize a scheduler.
     * return 0 on success or non-zero on failure.
     */
    int (*init)(void);

    /**
     * This function is called to deinitialize a scheduler.
     */
    void (*deinit)(void);

    /**
     * Function to balance threads across cores by modifying
     * the value of their lcore field.
     */
    void (*balance)(struct spdk_scheduler_core_info *core_info, uint32_t count);

    TAILQ_ENTRY(spdk_scheduler) link;
};

SPDK_SCHEDULER_REGISTER(scheduler_dynamic);

$ ./scripts/rpc.py framework_set_scheduler dynamic -p 1000000
```
SPDK Governors

- Use of governors by scheduler is optional
- Dynamic scheduler uses dpdk_governor
  - rte_power library
- Plug your own!

```c
SPDK_GOVERNOR_REGISTER(dpdk_governor);
rc = spdk_governor_set("dpdk_governor");
```

```c
struct spdk_governor {
    const char *name;
    uint32_t (*get_core_curr_freq)(uint32_t lcore_id);
    int (*core_freq_up)(uint32_t lcore_id);
    int (*core_freq_down)(uint32_t lcore_id);
    int (*set_core_freq_max)(uint32_t lcore_id);
    int (*set_core_freq_min)(uint32_t lcore_id);
    int (*get_core_capabilities)(uint32_t lcore_id, struct spdk_governor_capabilities *capabilities);
    int (*init)(void);
    void (*deinit)(void);
    TAILQ_ENTRY(spdk_governor) link;
};
```
Scheduler Actions

- **3a) update_core_mode()**
  - Puts a core into sleep

- **3b) threads_reschedule()**
  - Marks spdk_thread for move
Dynamic Scheduler

- Implementation of a scheduler
  \$ ./scripts/rpc.py framework_set_scheduler dynamic -p 1000000

- Prioritizes performance over power saving
  - Eager spdk_thread expansion

- Consolidates spdk_threads on minimal set of cores

- Puts unused cores to sleep

- Reduces CPU frequency of the main core on low use
Performance Data
Test Setup

- **SPDK NVMe-oF TCP Target**
  - 30 CPU cores assigned for the whole application

- **Two SPDK NVMe-oF TCP Initiators, each:**
  - 4 CPU cores
  - 8 NVMe-oF subsystems

- **FIO 4k block size randread workload**
  - Increasing Queue Depth
  - Increasing # of TCP connections with ‘numjobs’
Dynamic vs Static Scheduler

### NVMe-oF TCP Target CPU usage scaling for 16 connections

- **16 NVMe-oF subsystems**
- **1 connection each**

See configuration details – slide 20
NVMe-oF Poll Group

- spdk_poller polls an epoll fd
  - Group multiple TCP sockets
  - Round robin assignment of NVMe-oF qpairs

- No guarantees on balance across spdk_threads
  - Mix of active and idle qpairs
  - Qpairs can disconnect

- Initiator spreads load across qpairs
### Cost of NVMe-oF TCP Poll Groups

#### NVMe-oF TCP Target CPU usage scaling for 64 connections

<table>
<thead>
<tr>
<th>Queue depth</th>
<th># CPU utilized</th>
<th># CPU Dynamic</th>
<th># CPU Static</th>
<th>IOPS (k) Dynamic</th>
<th>IOPS (k) Static</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>8</td>
<td>21.9</td>
<td>34.0</td>
<td>854.1</td>
<td>880.7</td>
</tr>
<tr>
<td>32</td>
<td>32</td>
<td>32.2</td>
<td>34.1</td>
<td>1997.3</td>
<td>2043.3</td>
</tr>
<tr>
<td>64</td>
<td>64</td>
<td>34.5</td>
<td>35.1</td>
<td>3240.7</td>
<td>3276.5</td>
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<tr>
<td>128</td>
<td>128</td>
<td>34.3</td>
<td>33.8</td>
<td>5001.1</td>
<td>5000.7</td>
</tr>
</tbody>
</table>

- **16 NVMe-oF subsystems**
- **4 connections each**

See configuration details – slide 20
Summary and Next Steps
Summary

- Poll mode applications require special handling to save power and CPU cycles when idle
- SPDK event framework allows moving idle spdk_threads to put cores to sleep thus saving power
- Plugable scheduler framework is provided to define when spdk_threads should be moved
- Dynamic scheduler consolidates spdk_threads on minimal set of cores and puts remaining cores to sleep
Next steps

- Further improve the logic dynamic scheduler for spdk_thread placement
  - Give tweakable values to the user
- Address the cost of multiple poll groups on single core
- Scale CPU frequency of all cores
- Prioritize cores
  - Based on NUMA, hyperthreading and high frequency cores
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