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SDC 23

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Understanding Applications Through NVMe Driver Tracing Using BPF

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Agenda

- BPF and the NVMe Driver
- Application Analysis: MLPerf™ Storage

BPF and the NVMe Driver

BPF Overview

- Originally "Berkeley Packet Filter"
  - Developed to analyze network traffic
- Integrated with kernel
  - Executes sandbox programs in kernel
    - Used to trace, profile and monitor
  - Utilizes a just-in-time compiler
  - Verification Engine to protect kernel space
  - Various features supported in different kernel versions
    - Kernel 3.18 – eBPF VM
    - Kernel 5.5 – BPF Trampoline support
- BPF stack (Kernel) is limited to 512 bytes
  - Use maps to increase memory availability

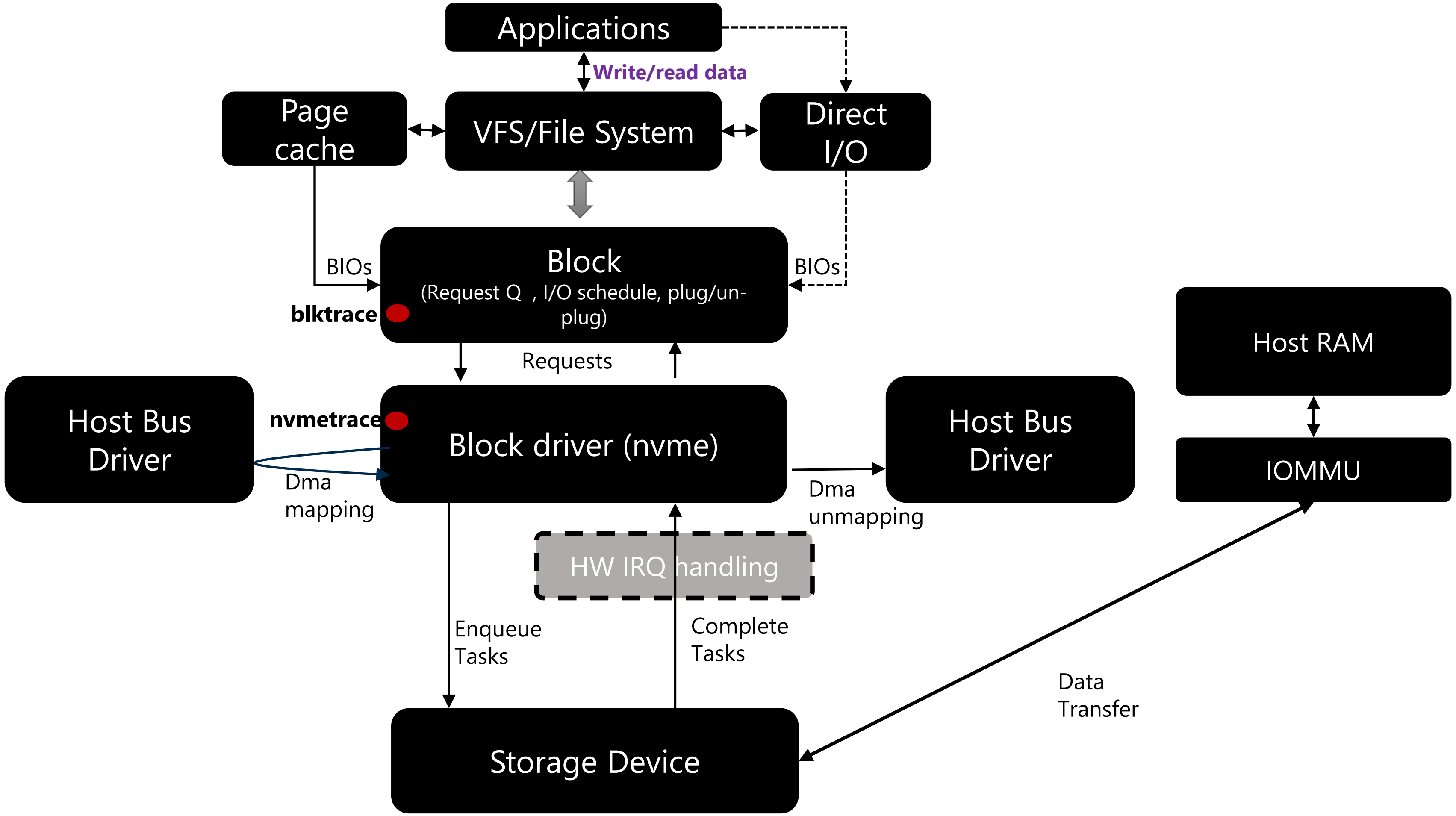
Methods of Tracing Kernel/Drivers

- Tracepoints
  - Stable interface
    - Managed by developers over multiple kernel versions
  - Limited to the data provided by tracepoint.
- Kprobes (Kernel Probes – kprobe/kretprobe)
  - Can attach/register probe to virtually any instruction.
    - Attachment to none kernel methods/functions requires debug kernel.
  - Can access data not directly provided.
  - Unstable interface
    - Kernel Functions are not stable across versions
- BPF Trampoline (kfunc/kretfunc and fentry/fexit)
  - Interface is similar to kprobes
  - Reduced overhead from kprobes
  - Doesn’t cause events to be missed due to interruption
  - Requires kernel support (Added in mainline kernel 5.5)

Need

- Original Multiple Tools
  - Blktrace
    - Used to analyze read/write pattern that was going to the device at the block layer
    - Requires post processing to get necessary output
  - Nvmelat
    - Bpftrace based tool, to give latency histogram of transactions at the driver layer
    - Could miss some transactions
- New Tool
  - Data processing done in line
  - Collects data for every transaction

Linux Storage Stack



NVMeTrace

- Collections information on every transaction in the nvme driver.
  - Starting LBA
  - Transaction Size/Length
  - Start Time/Completion Time/Latency
  - Process ID/Name
  - Device
  - Queue ID
  - Transaction Type
    - Read, write, flush, admin…
- Developed using libbpf
- Kernel version specific (sometimes)

Why Libbpf?

- Bpftrace
  - High level scripting language
  - Helpful to build tools quickly
  - Built on bcc and libbpf
  - Limited control over implementation
- Libbpf
  - More difficult entry point
  - More detailed control over implementation
    - Kernel space handlers
    - User space processing and output
  - CO-RE (Compile Once – Run Everywhere)
    - Can be done, might be difficult to implement depending on tool requirements

Code Flow

- Kernel Space
  - Memory Maps
    - Store data in program while it’s being processed.
    - Use Per CPU memory maps to avoid locking of map.
  - Ring Buffer
    - Used to transfer processed data to user space.
  - Three handlers tracing functions in the NVMe driver
    - nvme_setup_discard
      - Handles parsing multiple discards sent as single DSM command
    - nvme_submit_cmd
      - Handles submission of transactions to the NVMe device queue
      - Collect information about the transaction and store in a memory map
    - nvme_complete_rq
      - Handles completion of transactions, called when interrupt is activated.
      - Get completion time of transaction
      - Calculate latency
      - Put processed data on ring buffer
- User Space
  - Loads BPF application
  - Verification is done by the JIT compiler/BPF VM
  - Handles data passed through from kernel space

Request/Command Structure

- Request
  - Structure containing data from block layer provided to NVMe Driver
- nvme_iod
  - Structure containg Nvme I/O data.
  - Exists immediately after request in memory
  - Contains nvme_request, nvme_command, nvme_queue
- Pointers for all structures are not passed into each traced function
  - Limits direct access and reusability of code across kernel versions
  - Tool needs access to request and nvme_command in all functions
- Getting data from nvme_iod and request requires moving around memory
  - Jumping between structures in memory requires knowledge of the specific structures
    - Size, members, relative memory locations
  - Function interfaces and structures are not stable across kernel version
    - Kernel versions could require recompile, or even rewrite of handler logic

nvme_setup_discard Handler

- Loops in BPF are hard
  - Must have a defined end
  - JIT compiler does a basic check
  - Loop helper exists in newer kernel versions – bpf_loop
- Discards are sent through Data Set Management (DSM) command
  - Up to 256 discards per DSM command
  - Need to loop through individual

```
SEC("fentry/nvme_setup_discard")
int BPF_PROG(do_nvme_setup_discard, struct nvme_ns *ns, struct request *req, struct nvme_command *cmnd)
{
  int temp_index;
  struct bio *_bio = BPF_CORE_READ(req, bio);

  // max ranges = 256 for discard DSM command.
  for (int index = 0; index < 256; index++) {
    // Can't use index directly because verifier thinks it can be changed when used in bpf_map_lookup_elem
    temp_index = index;
    struct discard_data *temp_discard_data = bpf_map_lookup_elem(&discard_heap, &temp_index);
    if (temp_discard_data) {
      if (_bio == NULL) {
        temp_discard_data->slba = 0;
        temp_discard_data->length_bytes = 0;
        temp_discard_data->length_lbas = 0;
        break;
      }
      temp_discard_data->slba = BPF_CORE_READ(_bio, bi_iter.bi_sector) >> (BPF_CORE_READ(ns, lba_shift) - 9);
      temp_discard_data->length_bytes = BPF_CORE_READ(_bio, bi_iter.bi_size);
      temp_discard_data->length_lbas = temp_discard_data->length_bytes >> BPF_CORE_READ(ns, lba_shift);
      _bio = BPF_CORE_READ(_bio, bi_next);
    } else {
      break;
    }
  }
  return 0;
}
```


nvme_submit_cmd Handler

- Generate pointers to necessary memory locations for structures
- Check if memory is available on the heap
- Start collecting available data for the event
- Check if it's a non-admin command
  - Length = 1 (No device name)
- Stores collected information in event_map for use in nvme_complete_rq handler

```
SEC("fentry/nvme_submit_cmd")
int BPF_PROG(do_nvme_submit_cmd, struct nvme_queue *nvmeq, struct nvme_command *cmd, bool write_sq)
{
  struct nvme_iod *iod = container_of(cmd, struct nvme_iod, cmd);
  struct request *req = blk_mq_rq_from_pdu(iod);
  __u64 req_address = (__u64)req;
  int index = 0;

  struct event *temp_event = bpf_map_lookup_elem(&heap, &index);

  if (temp_event) {
    int length;

    temp_event->qid = BPF_CORE_READ(nvmeq, qid);
    temp_event->pid = bpf_get_current_pid_tgid() >> 32;
    bpf_get_current_comm(temp_event->process_name, sizeof(temp_event->process_name));
    temp_event->opcode = BPF_CORE_READ(cmd, common.opcode);

    length = bpf_probe_read_str(temp_event->device_name, sizeof(temp_event->device_name), BPF_CORE_READ(req, rq_disk, disk_name));
    if (length > 1) {
      if (temp_event->opcode == nvme_cmd_read || temp_event->opcode == nvme_cmd_write) {
        __u32 size = 511;

        temp_event->slba = BPF_CORE_READ(cmd, rw.slba);
        temp_event->length_bytes = BPF_CORE_READ(req, __data_len);
        temp_event->length_lbas = BPF_CORE_READ(cmd, rw.length) + 1;

      } else if (temp_event->opcode == nvme_cmd_dsm) {
        // slba, length_bytes, and length_lbas get handled with nvme_setup_discard
        // Setting to 0 until set at completion
        temp_event->slba = 0;
        temp_event->length_bytes = 0;
        temp_event->length_lbas = 0;
      } else {
        temp_event->slba = 0;
        temp_event->length_bytes = 0;
        temp_event->length_lbas = 0;
      }
    } else { //Admin Command
      temp_event->slba = 0;
      temp_event->length_bytes = 0;
      temp_event->length_lbas = 0;
    }

    temp_event->start_time_ns = bpf_ktime_get_ns();
    bpf_map_update_elem(&event_map, &req_address, temp_event, BPF_ANY);
  }
  return 0;
```


nvme_complete_rq Handler

- Gets matching information from request in event_map
- Reserves space on the ring buffer
- Calculates latency
- Writes all collected data to ring buffer for user space processing.

```
SEC("fentry/nvme_complete_rq")
int BPF_PROG(do_nvme_complete_rq, struct request *req)
{
  __u64 req_address = (__u64)req;
  struct event *info = bpf_map_lookup_elem(&event_map, &req_address);

  if (info) {

    struct event *e;
    e = bpf_ringbuf_reserve(&ring_buffer, sizeof(*e), 0); //This is allocating too slow
    if (!e) {
      bpf_printk("BUFFER FULL!\n");
      return 0;
    }

    e->start_time_ns = info->start_time_ns;
    e->end_time_ns = bpf_ktime_get_ns();
    e->latency_ns = e->end_time_ns - e->start_time_ns;
    e->qid = info->qid;
    e->pid = info->pid;
    bpf_probe_read_str(e->process_name, sizeof(e->process_name), info->process_name);
    bpf_probe_read_str(e->device_name, sizeof(e->device_name), info->device_name);
    e->opcode = info->opcode;
    e->slba = info->slba;
    e->length = info->length;

    bpf_map_delete_elem(&event_map, &req_address);

    bpf_ringbuf_submit(e, 0);
  }
  return 0;
}
```


Example Output

```
start_time_ns,end_time_ns,latency_ns,process_name,pid,device,qid,slba,length_bytes,length_lbas,opcode
945661828630244,945661828679823,49579,systemd-udevd,823,nvme2n1,18,0,4096,8,2
945661828720722,945661828744932,24210,systemd-udevd,823,nvme2n1,18,8,4096,8,2
945661828762102,945661828780561,18459,systemd-udevd,823,nvme2n1,18,24,4096,8,2
945661833805074,945661833822884,17810,systemd-udevd,823,nvme2n1,18,0,4096,8,2
945661833841224,945661833856614,15390,systemd-udevd,823,nvme2n1,18,8,4096,8,2
945661833869263,945661833884423,15160,systemd-udevd,823,nvme2n1,18,24,4096,8,2
945661838342307,945661838359766,17459,systemd-udevd,823,nvme2n1,18,0,4096,8,2
945661838394956,945661838431165,36209,systemd-udevd,823,nvme2n1,41,8,4096,8,2
945661838451645,945661838466984,15339,systemd-udevd,823,nvme2n1,41,24,4096,8,2
945661839510777,945661839552986,42209,systemd-udevd,55562,nvme2n1,31,30005842432,4096,8,2
945661839579855,945661839596465,16610,systemd-udevd,55562,nvme2n1,31,30005842592,4096,8,2
945661839609995,945661839625125,15130,systemd-udevd,55562,nvme2n1,31,0,4096,8,2
```


BPF Helpers

- bpf_ktime_get_ns()
  - Get current kernel timestamp
- bpf_get_current_comm()
  - Gets process name of process that triggered event being traced
- bpf_get_current_pid_tgit()
  - Gets PID of process that triggered event being traced
- BPF_CORE_READ()
  - Reads memory space of structures
  - Can read arbitrarily deep through structures with pointers.
- bpf_probe_read_kernel()
  - bpf_core_read
  - Read arbitrary memory location
- bpf_probe_read_str()
  - bpf_core_read_str
  - Reads string value and stores it in another point in memory

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BPF CO-RE

- CO-RE
  - Compile Once – Run Everywhere
    - Compile once and execute on multiple kernel versions
- Helper functions and methodology that help develop portable applications
- BTF
  - BPF Type Format
  - Debug information to describe all kernel/driver type information
  - Used by BPF Verifier
    - Finds matching structures and gets offsets for structure members
    - Enables ability to not have to fully define a structure to access a member of that structure
  - Build Kernel with CONFIG_DEBUG_INFO_BTF=y

https://nakryiko.com/posts/bpf-core-reference-guide/

Application Analysis

MLPerf™ Storage

MLPerf™

- How do we size storage for AI training?
  - MLCommons produces many AI workload benchmarks
    - Training, Inference, Tiny, HPC, etc
  - Training benchmark has been scaled to nearly 4 thousand accelerators
  - The performance of storage has been optimized out of the Training benchmark
  - Can't be used for measuring storage workload
- Options:
  - De-optimize the training process
  - Develop a new process

- De-optimizing
  - Limit memory to the system to prevent filesystem caching
  - Some datasets are very small, and it is impossible to find a memory capacity that allows the models to train properly without caching the entire dataset

- Develop a new process
  - Must do IO in the same way as the real AI training process
  - Must reduce hardware requirements for testing
    - (few storage vendors have hundreds of GPU systems for load testing)
  - Must provide larger datasets to limit effect of filesystem caching

MLPerf™ Storage Benchmark

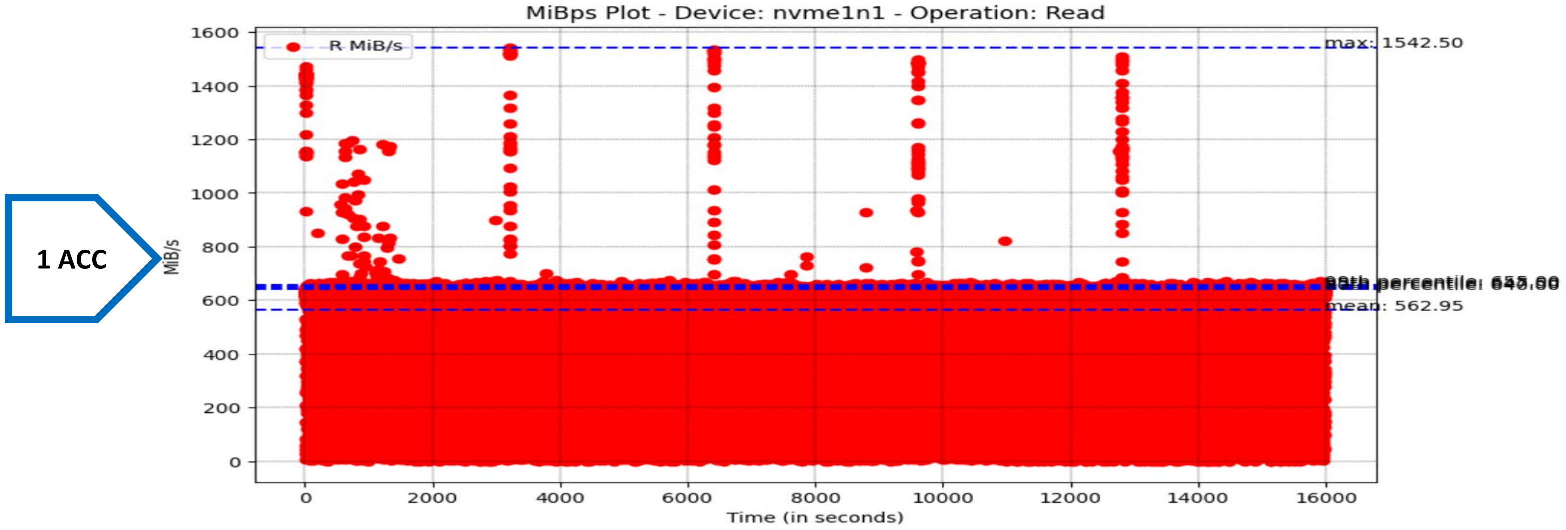
- Using the tool DLIO from Argonne Leadership Computing Facility (ALCF)
  - Uses the same data loaders as the real workload (pytorch, tensorflow, etc) to move data from storage to CPU memory
  - Implements a sleep in the execution loop for each batch
    - Sleep time is computed from running the real workload
  - A sleep time and batch size effectively defines an accelerator
    - How much data per batch and how long to spend on forward & backward passes
  - Scale up/out testing performed by adding clients running DLIO and using MPIO for multiple emulated accelerators per client

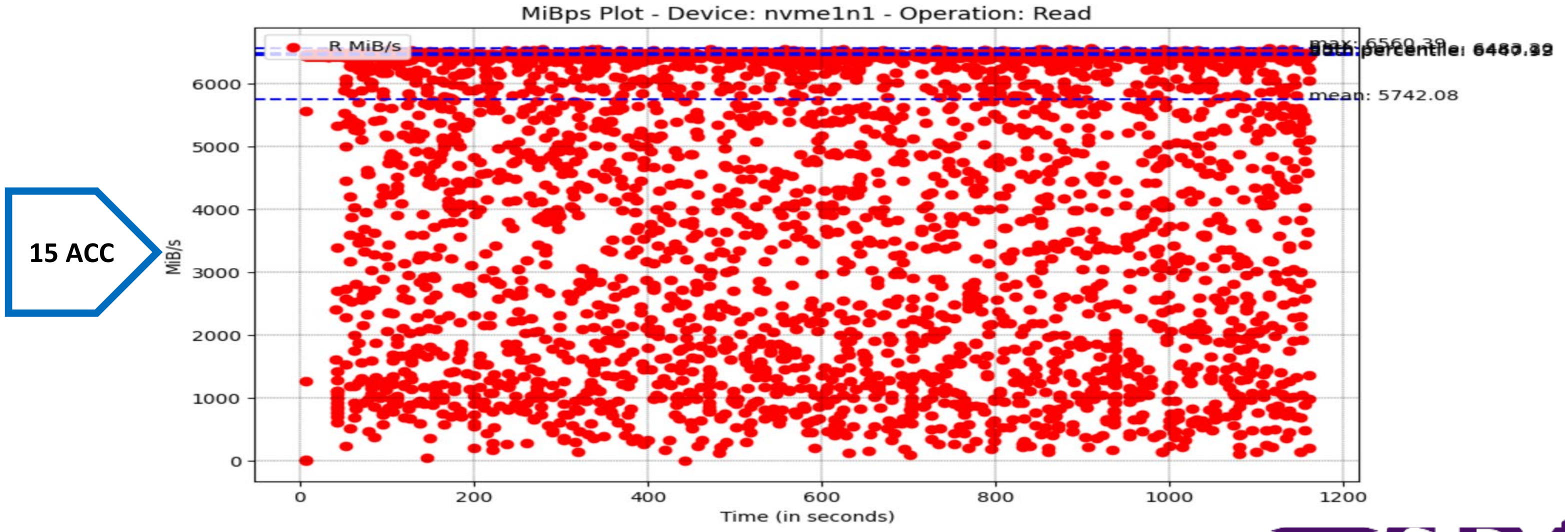
- MLPerf™ Storage
  - Defines a set of configurations to represent results submitted to MLPerf™ Training
  - Version 0.5:
    - BERT & Unet3D (NLP and 3D medial imaging)
  - Allows scale out and scale up testing without requiring GPUs
  - Reported metrics are:
    - Samples per Second
    - Number of supported accelerators
  - Requires maintaining a minimum Accelerator Utilization for a passed test
  - Still in early development
  - Get involved!
    - https://mlcommons.org/en/groups/research-storage/

Unet3D

I/O throughput versus time

- For a single Accelerator (top plot)
  - Data transferred in 1 second intervals ranges from 0 to 600 MB with peaks to 1,600 MB
  - The peaks correspond to the start of an epoch where the prefetch buffer is filled before starting compute
- For 15 accelerators (bottom plot)
  - Near the drive's limit (17 accelerators)
  - Workload continues to have bursty behavior with some 1 second intervals showing 0 MB transferred
- While the system does hit the maximum throughput of the device, **the low QD and idle times result in an average throughput that is 15 – 20% less than max supported**
  - Traditional tools will not show the peak throughput as measured here

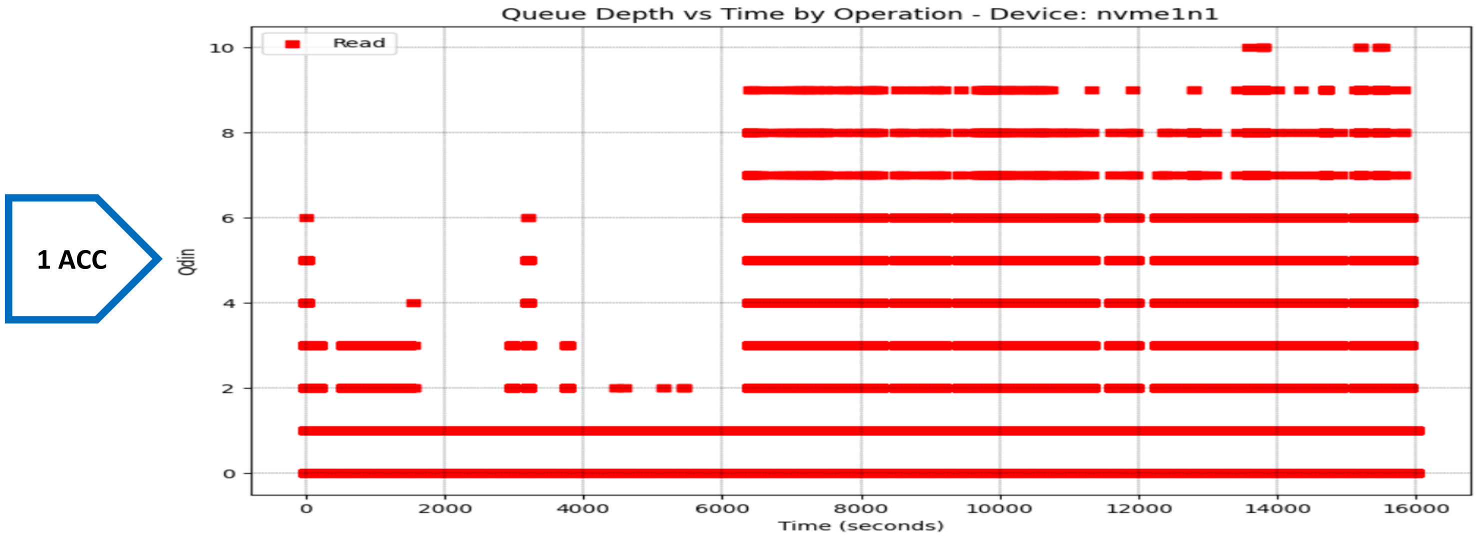




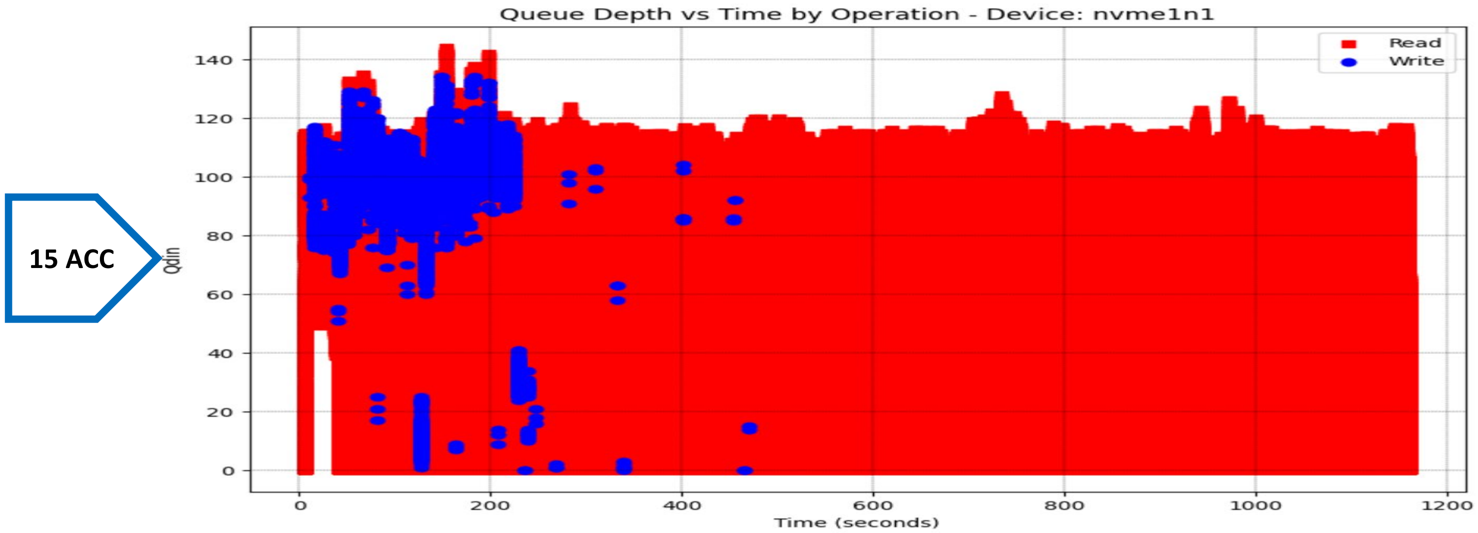
Unet3D

Queue depth versus time

- 1 accelerator (top plot):
  - Over time, queue depth remains low (less than 10)
  - After initial ramp, QD remains constant even during epoch starts which showed higher MB per second



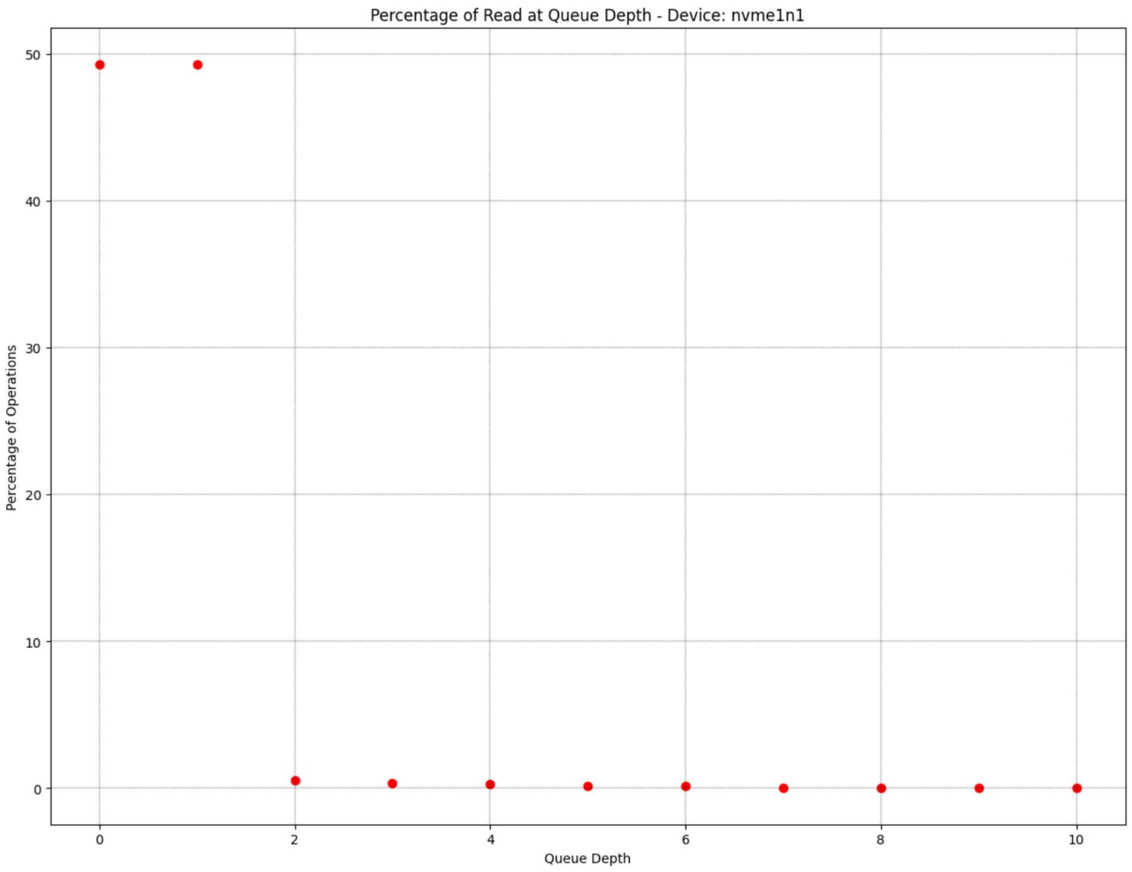
- 15 accelerators (bottom plot):
  - Queue depth peaks at 145 early then stabilized at 120 and below
  - This heavily loaded system still has low Queue Depth operations



Unet3D
Percent of I/Os by queue depth for 1 accelerator

- For 1 accelerator:
  - Less than 1% of IOs are at Queue Depths 2-5
  - Nearly 50% of IOs were inserted as the only IO in the queue
  - Nearly 50% were inserted as the second IO in the queue (QD1)

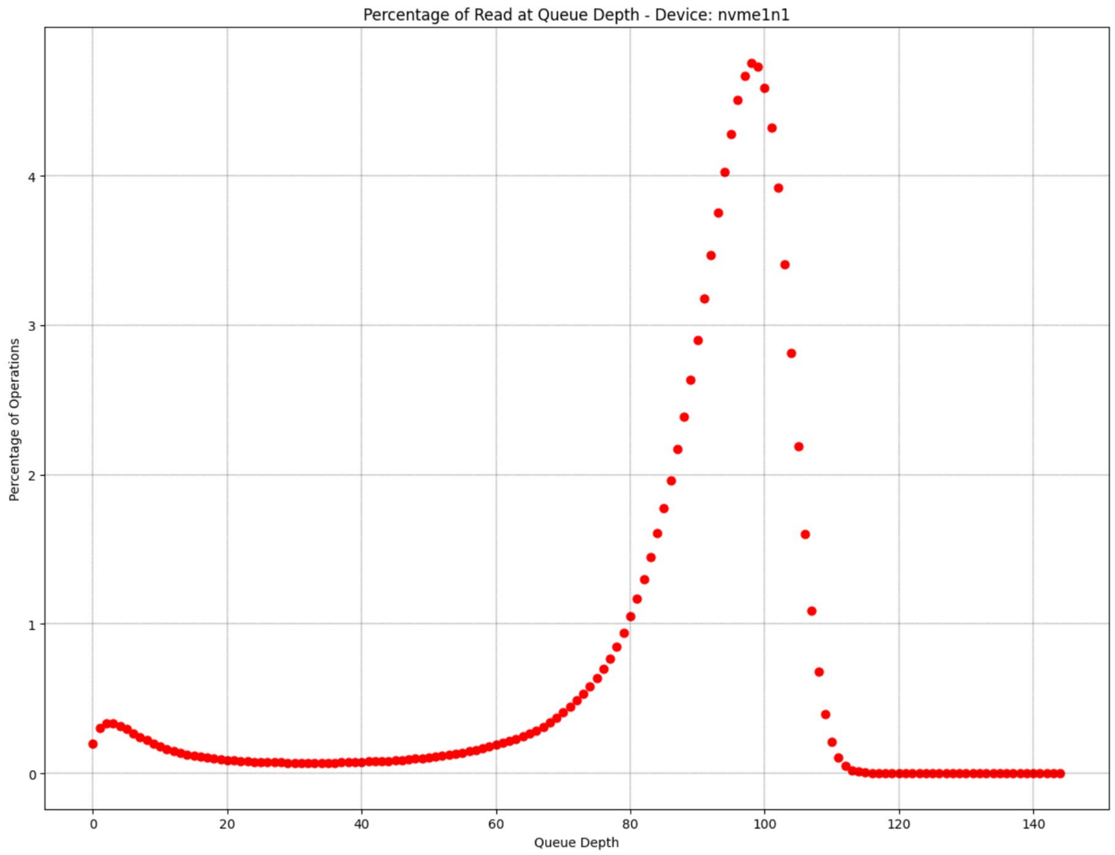
- Note: The specific transfer size is dependent on the device, block settings, and filesystem settings but we consistently see the max available size (512KB – 1280KB)



Unet3D

Percent of I/Os by queue depth for 15 accelerator

- For 15 accelerators:
  - We see a distribution of Queue Depths
  - The bump at low QDs is important
  - A not-insignificant number of IOs are inserted at very low Queue Depths (less than 5)
  - This behavior introduces idle time in workloads that were expected to be constantly high throughput



How device settings can affect I/O pattern

- Maximum Data Transfer Size – MDTS
  - Controller Setting
  - Sets maximum transfer size drive will accept
    - /sys/block/nvmeXnY/queue/max_hw_sectors_kb (Value in KiB)
  - Can be adjusted down
    - "echo <value_kb> > /sys/block/nvmeXnY/queue/max_sectors_kb"
    - max_sectors_kb – Working limit on OS
- Namespace Optimal Write Size – NOWS
  - Namespace setting – Cannot be adjust in OS
  - Hint for applications & file systems – not enforced by drive

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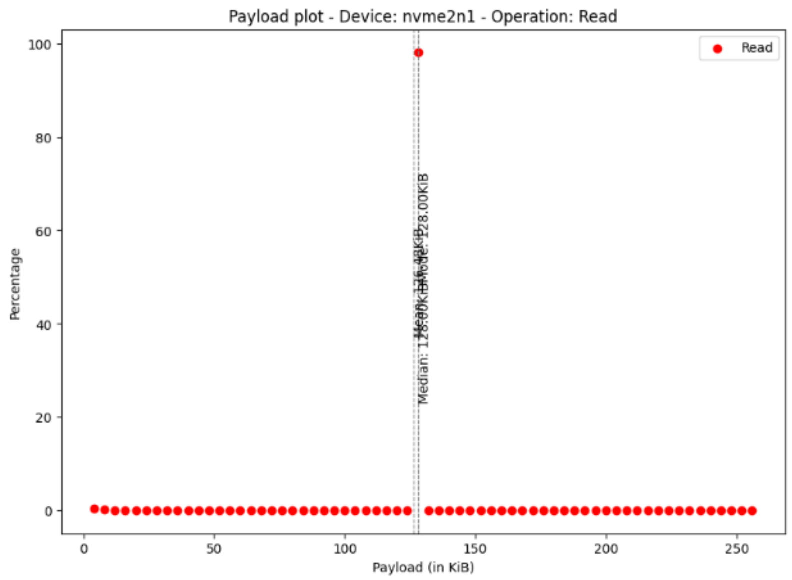
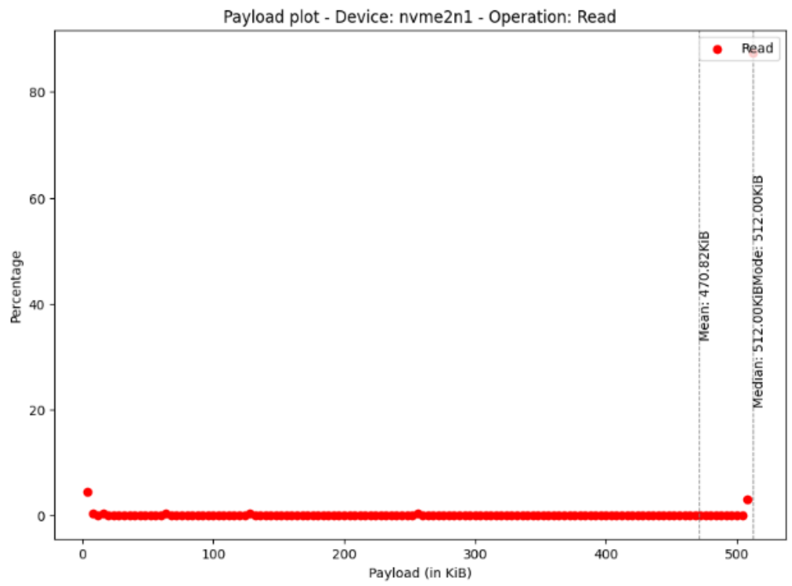
Unet3D

I/O Blocksize Pattern 16 Accelerators – XFS Filesystem

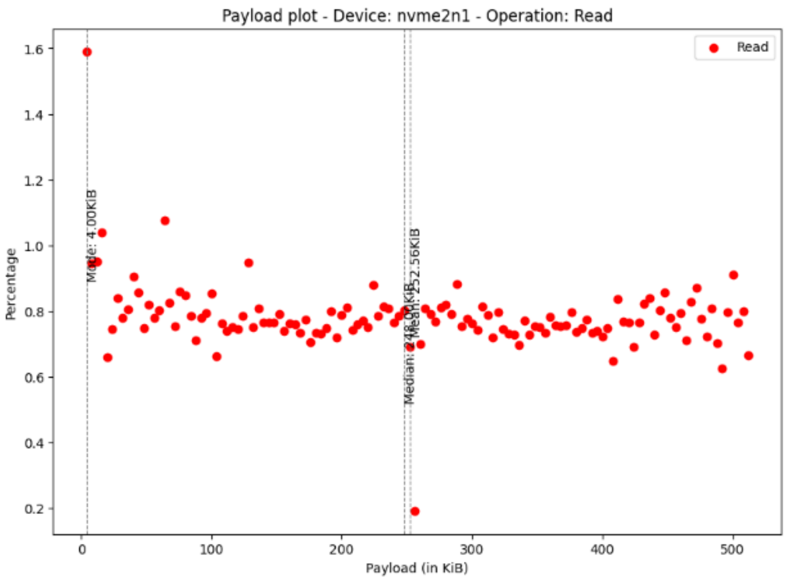
MDTS: 4MiB / NOWS: 4KiB



MDTS: 4MiB / NOWS: 256KiB



MDTS: 512KiB / NOWS: 256KiB



Future Improvements

- Trace of files accessed
- Trace application processes
- Analysis Improvements

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Reference Links

- libbpf - https://github.com/libbpf/libbpf
- libbpf-bootstrap - https://github.com/libbpf/libbpf-bootstrap
- BPF Performance Tools (Brendan Gregg) - https://www.brendangregg.com/bpf-performance-tools-book.html
- MLPerf™ Storage - https://mlcommons.org/en/groups/research-storage/

