OpenCSD, simple and intuitive computational storage emulation with QEMU and eBPF

Corné Lukken & Animesh Trivedi

fosdem@dantalion.nl

`https://github.com/Dantali0n/OpenCSD`

Who am I

Corne Lukken - Dantali0n

Parallel & Distributed Systems

Academia

- Bachelor Software Engineering (AUAS)
- Master Computer Science (VU / UvA)

Experience

- Health Technology @ AUAS
- Openstack @ CERN
- Computational Storage @ VU
- SCADA @ ASTRON

Why do we need it

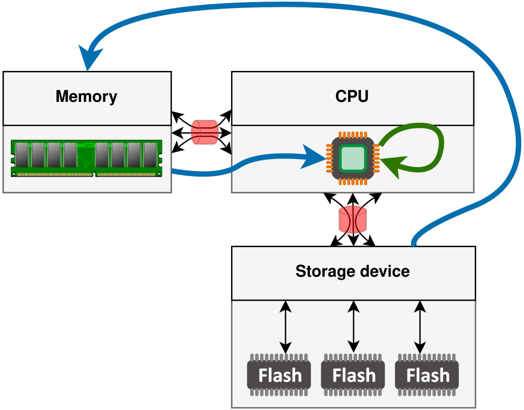
Why do we need it

Von Neumann architecture

Memory bottlenecks

Interconnect bottlenecks

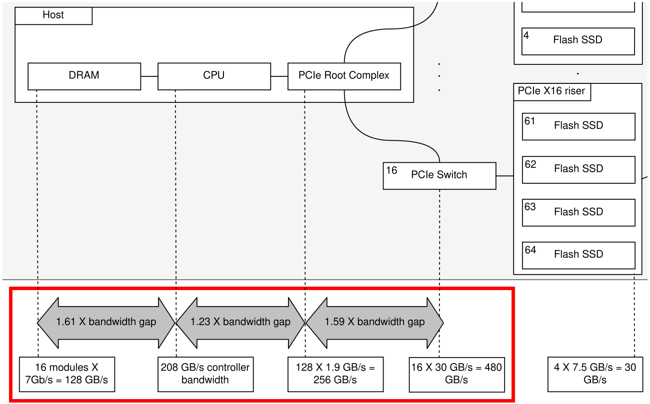
Energy efficiency



Why do we need it

4.5x bandwidth gap with 64 SSD storage server (2021)

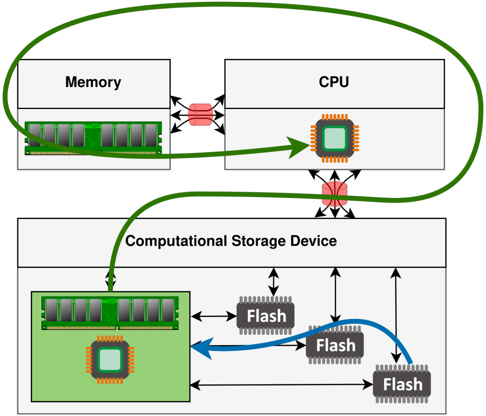
Solution: prevent moving data from flash SSD to host



[1] https://www.kernel.org/doc/html/latest/driver-api/pci/p2pdma.html

What is Computational Storage

- Fit compute & memory on storage device
- User submits programs to run on device (*kernels*)
- Only return results from user programs
- Reduce data movement
- Improve energy efficiency
- Specialized hardware (ASIC / FPGA)



State of Current Prototypes (September 2022)

Impediments:

1. API between host and device
2. Keep filesystem synchronized
3. Stick to existing interfaces

Shortlist:

BlockNDP (2020) [2]

Metal FS (2020) [3]

INSIDER (July 2019) [4]

---

[2] https://doi.org/10.1145/3429357.3430519

[3] https://doi.org/10.1145/3342195.3387557

[4] https://www.usenix.org/conference/atc19/presentation/ruan

OpenCSD & FluffleFS

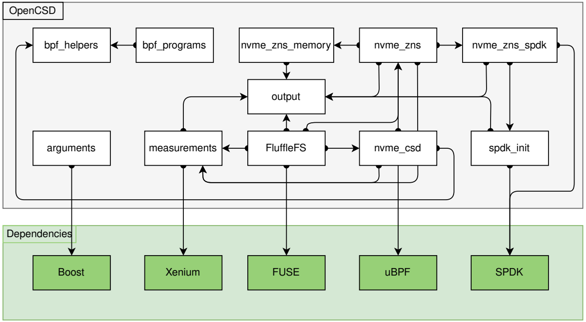
Entirely runs in user-space

Using pre-existing system calls

Concurrent access to same file

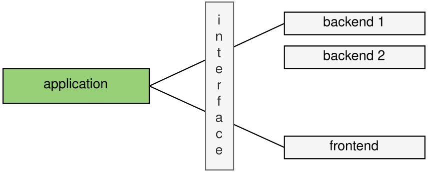
Built using existing open-source libraries

Use and experiment without any additional hardware

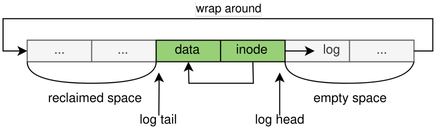


Design

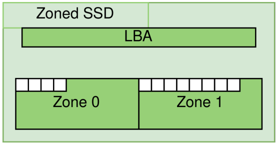
Modules & Interfaces



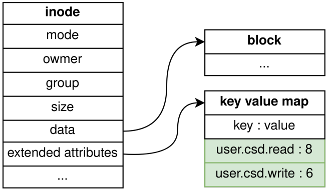
Log-Structured Filesystem (LFS) [6]



Zoned Namespaces (ZNS)



Extended Attributes (xattr)

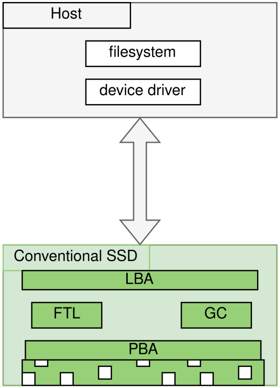


[6] The design and implementation of a Log-structured File System

Design: Zoned NameSpaces (ZNS) 1/2

Conventional SSDs

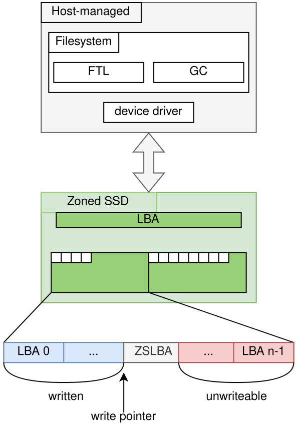
- The (traditional) block interface
- Linear writes
- Large erase units
- Flash Translation Layer (FTL)
- Logical vs Physical Block Address (LBA / PBA)



Design: Zoned NameSpaces (ZNS) [7] 2/2

Zoned Namespaces SSDs

- Fit interface to nand flash behavior
- Devide erase units in zones
- Require each zone is linearly written
- Perfect match for LFS filesystems
- Host operating system manages FTL



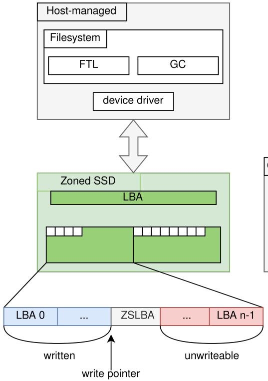
[7] NVM Express Zoned Namespace Command Set Specification 1.1b - https://nvmexpress.org/developers/nvme-command-set-specifications/

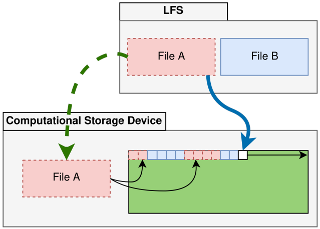
Design: ZNS + LFS

Synchronizing host & device filesystem

- Ensure file immutable for kernels
- No host communication during kernel execution
- Unblock regular access
- Check & understand kernel behavior

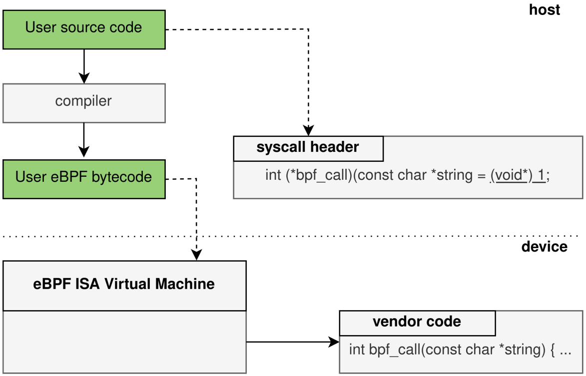
Snapshot consistency model





Design: Architecture Independent Kernels

- Define system calls in ABI header
- Leave implementation to VM (vendor)
- Compile once use everywhere
- eBPF ISA trivial to implement in VM
- Pre-existing FOSS eBPF VMs (uBPF)



Shannon Entropy Demo - Background

Quantify randomness, distribution of possible values

- High value, very random, typically between 0/1
- Normalize for bytes
- Used in background / filesystem compression
- Store count in 256 bins (array), histogram

$$H(x) = -\sum_{i=1}^{n} p(x_i) log_b p(x_i)$$

Shannon Entropy Demo - Kernel

eBPF very small stack size

Get heap pointer, manually offset

System calls provided by eBPF

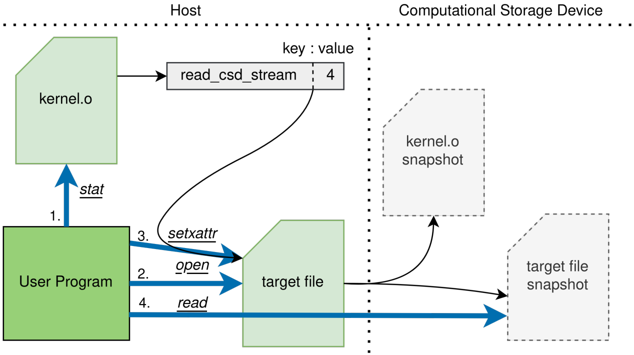
Helper functions & data structures provided by filesystem

Can we make user programs agnostic to filesystem?

```
void *buffer;
bpf_get_mem_info(&buffer, &buffer_size);

uint32_t *bins = (uint32_t*)(buffer + sector_size);
for(uint16_t i = 0; i < 256; i++) {
    bins[i] = 0;
}

while(buffer_offset < data_limit) {
    lba_to_position(*cur_data_lba, zone_size, &zone, &sector);
    bpf_read(zone, sector, 0, sector_size, buffer);

    for(uint64_t j = 0; j < bytes_per_it; j++) {
        bins[*(byte_buf + j)] += 1;
    }

    buffer_offset = buffer_offset + sector_size;
    next_data_lba(&cur_data_lba);
}

bpf_return_data(bins, sizeof(uint32_t) * 256)
```

Operating Principle Details

- Step by step system calls
- Stream vs Event kernels
- When to take snapshots?
  - Upon *setxattr*
- Isolate by filehandle, pid, inode?
  - By pid



Shannon Entropy Demo - Execution

How to submit I/O requests to execute kernels?

- Stride requests (FUSE page limit)
- Inode from kernel file as value for extended attribute Key
- Different keys for different types of offloading
- Return data from *os.pread* less then request size.

```python
read_stride = 524288
fd = os.open("test/test", os.O_RDWR)
# Determine the size of the file
fsize = os.stat("test/test").st_size
# Get the inode number for the BPF kernel
kern_ino = os.stat("test/bpf_flfs_read_entropy.o").st_ino
# Enable the BPF kernel on the open file for read operations
xattr.setxattr("test/test", "user.process.csd_read_stream",
               bytes(f"{kern_ino}", "utf-8"))
...
# Accumulate data for each strided request into the bins
final_bins = [0] * 256
for i in range(0, steps):
    data = struct.unpack('<256i', os.pread(
        fd, read_stride, i * read_stride))
    for j in range(0, 256):
        final_bins[j] += data[j]
```

Limitations and Considerations

Filesystem (FluffleFS) is **solely** proof of concept!

eBPF endian conversions and datastructure layouts

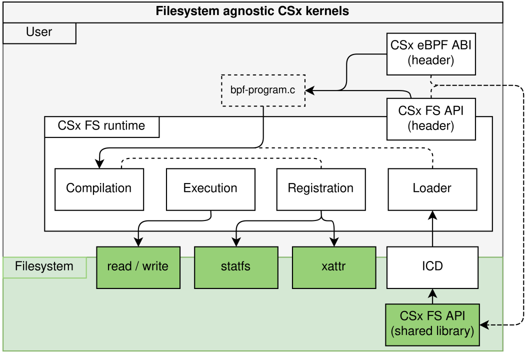
No floating point in eBPF

Kernel performance not representative of microcontrollers

Only, *read stream* kernel fully supported

Problematic *event* kernel performance

Filesystem agnostic kernels



Further Reading

Try it today! `https://github.com/Dantali0n/OpenCSD`

- OpenCSD: Log-Structured Filesystem enabled Computational Storage Device platform - https://tinyurl.com/opencsd-thesis
- ZCSD: a Computational Storage Device over Zoned Namespaces (ZNS) SSDs - https://arxiv.org/abs/2112.00142
- Past, Present and Future of Computational Storage: A Survey - https://arxiv.org/abs/2112.09691