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zonefs: Mapping the POSIX File System Interface to Zoned Block Device Accesses

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2020 Linux Storage and Filesystems Conference, VAULT'20

Damien presenting at LSF/MM

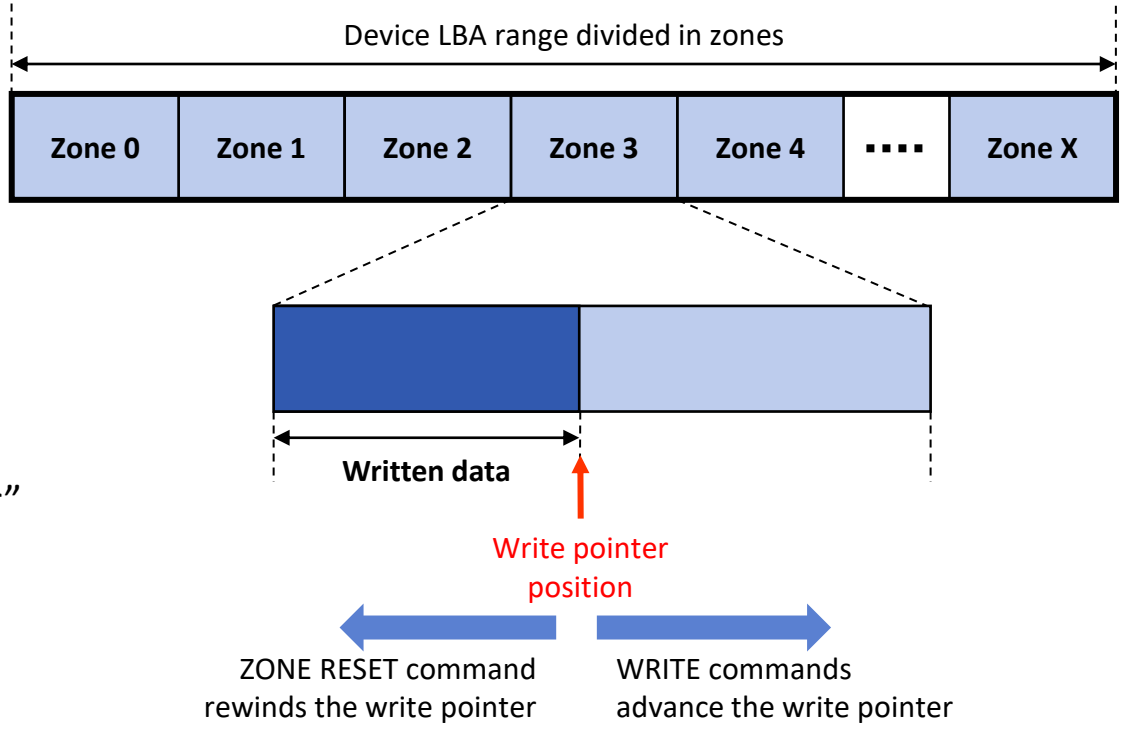
Outline

- Background
  - Zoned block devices principles
  - Linux support
- zonefs
  - Overview
  - File tree, format options and mount options
  - File operations mapping to zoned block device commands
  - I/O error handling
- Example use
  - LevelDB prototype implementation
- Future work and conclusion

Zoned Block Devices

Random reads but sequential writes

- Commonly found today in the form of SMR hard-disks (Shingled Magnetic Recording)
  - Interface defined by the ZBC (SCSI) and ZAC (ATA) standards
- LBA range divided into zones of different types
  - Optional conventional zones
    - Accept random writes
  - Sequential write required zones
    - Writes must be issued sequentially starting from the “write pointer”
    - Zones must be reset before rewriting
      - “rewind” write pointer to beginning of the zone
- NVMe Zoned Namespace defines a similar interface for NVMe SSDs
  - But no conventional zones



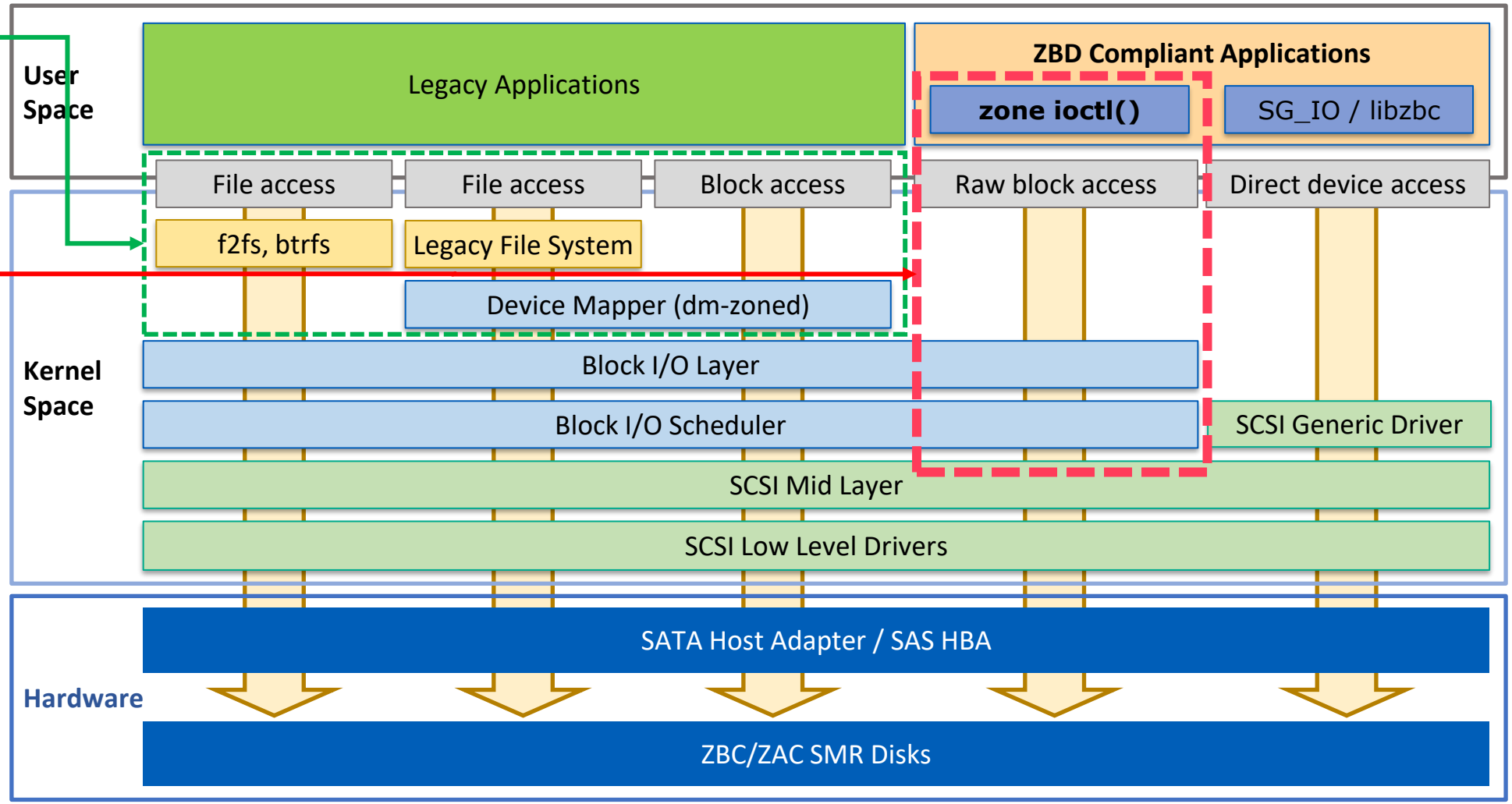
Linux Kernel Zoned Block Device Support

Since kernel version 4.10

Advanced support:
- **POSIX defined behavior**

Minimal support:
- Device sequential write constraint exposed to users
- Zone management API (ioctl) and write ordering guarantees

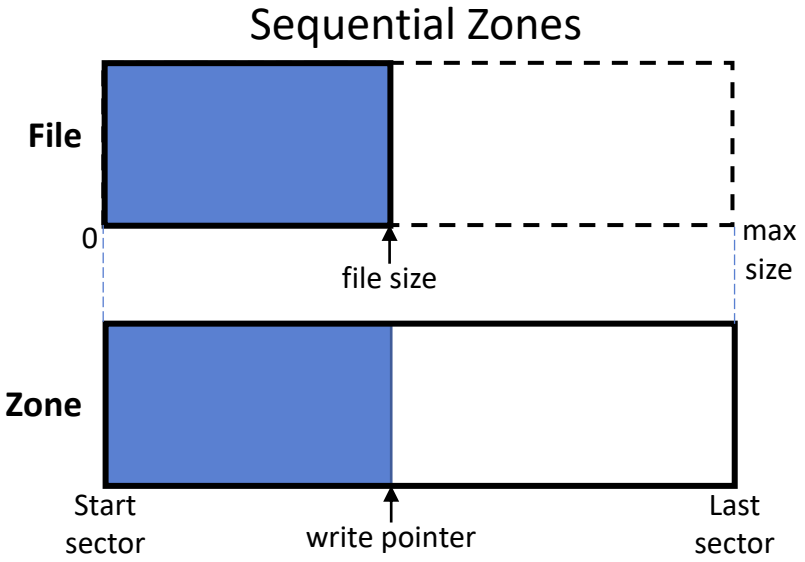
Zonefs goal
Simplify raw block device zone access and management

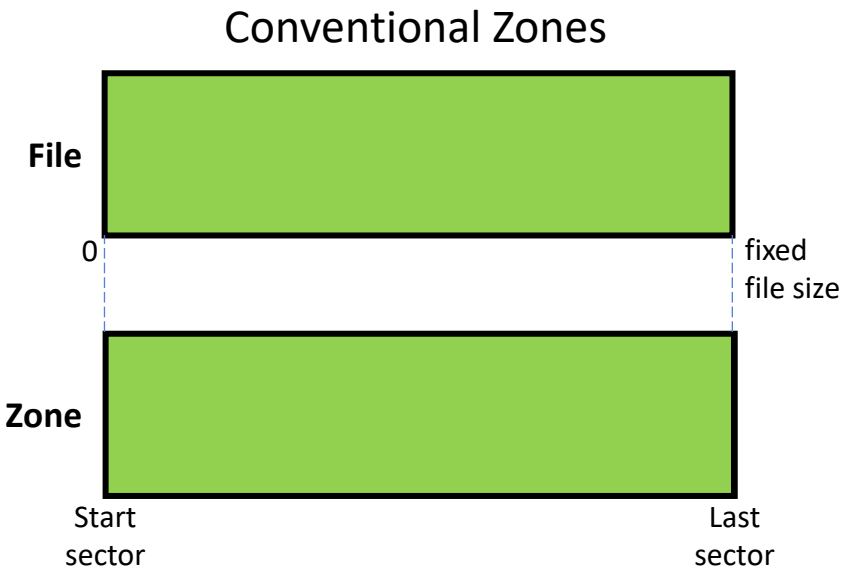


Zonefs: Overview

Expose each zone as a file

- Device zones are exposed as regular files
  - File size determined from its zone type and its zone write pointer position
- Zone information obtained from the device is used as inode metadata
  - On-disk metadata reduced to a static superblock (first zone)
    - No journaling needed
- File I/O block mapping implemented using iomap
  - No buffer-heads, static block mapping per file
- Immutable file names
  - Zone number per sub-group type
- File attributes control
  - Per zone UID, GID, access permissions



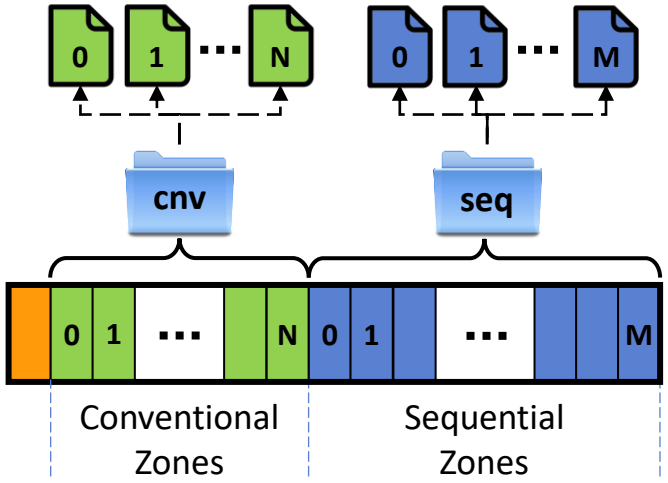


Zonefs: File Tree

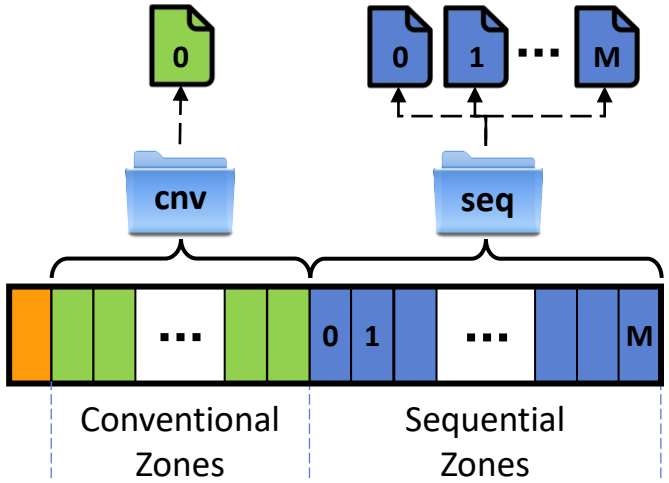
First zone used for the static superblock

- Files are grouped per zone type in different sub-directories
  - "cnv" for conventional zones
  - "seq" for sequential write required or preferred zones
- Contiguous conventional zones can be aggregated into a single file

No zone aggregation (default)



Aggregated conventional zones



Zonefs: Format and Mount Options

First zone used for the static superblock

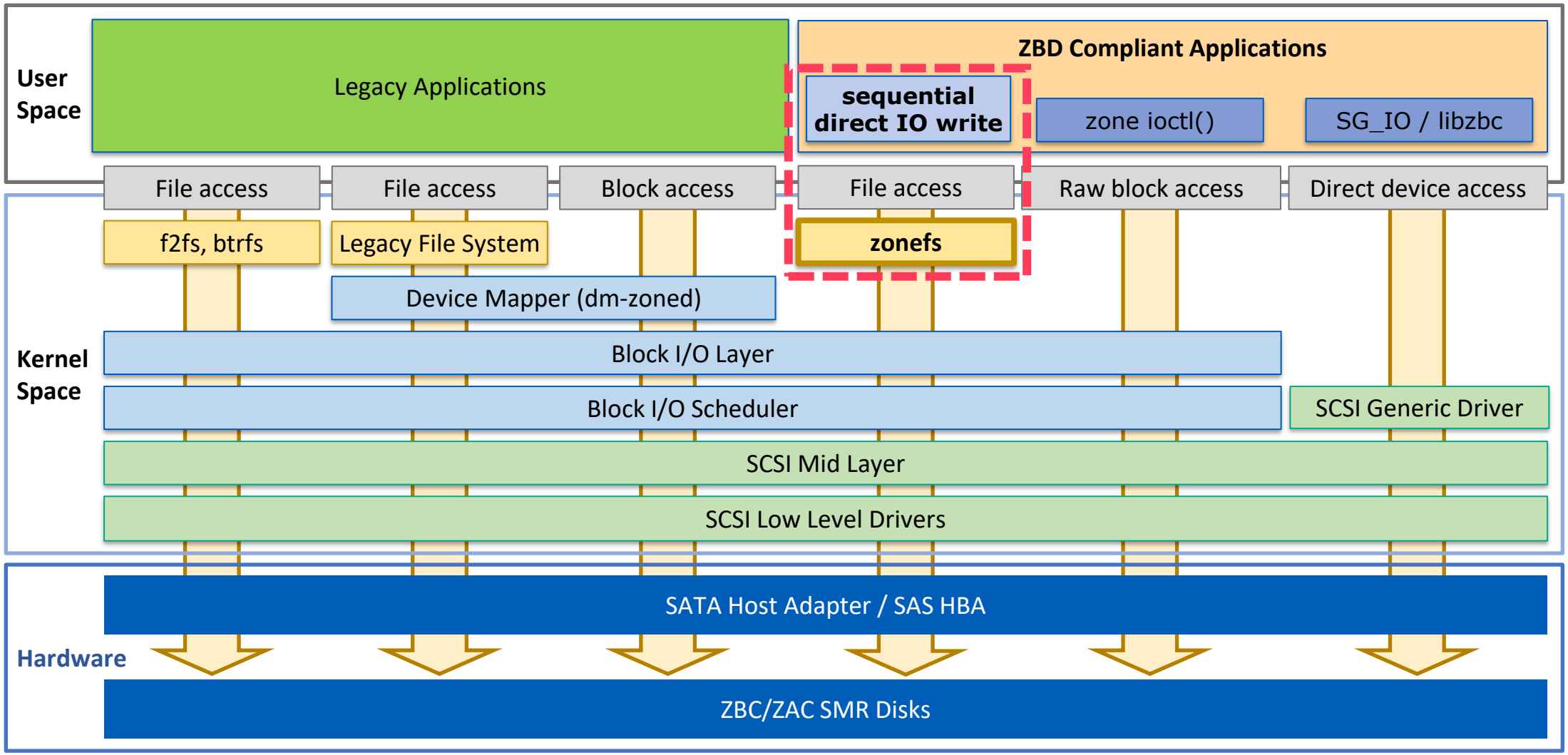
- Format options
  - File attributes: default UID, GID and access permissions
  - Conventional zones aggregation: on/off
- Mount options
  - Define behavior on IO error and zone condition changes
    - Handle unexpected change to a sequential zone write pointer
      - E.g. If a large write operation partially fails
    - Handle device transition of “bad” zones to OFFLINE or READONLY state
  - Defined behaviors:
    - remount-ro: File system remounted read-only
    - zone-ro: affected zone goes read-only
    - zone-offline: affected zone assumed to be offline
      - No accesses possible
    - repair: use zone write pointer to fix the file size and continue

zonefs error handling options

error=xxx mount option	Device zone condition	Post error recovery state				
		File size	Access permissions			
			File		Device zone	
			Read	Write	Read	Write
remount-ro (default)	Good Read-only Offline	Fixed Fixed 0	Yes Yes No	No No No	Yes Yes No	Yes No No
zone-ro	Good Read-only Offline	Fixed Fixed 0	Yes Yes No	No No No	Yes Yes No	Yes No No
zone-offline	Good Read-only Offline	0 0 0	No No No	No No No	Yes Yes No	Yes No No
repair	Good Read-only Offline	Fixed Fixed 0	Yes Yes No	Yes No No	Yes Yes No	Yes No No

Zonefs is *NOT* a Regular POSIX Filesystem

Requires ZBD compliant applications



Example: 15TB SMR Disk

524 conventional zones and 55356 sequential zones

- First conventional zone used for the super block

```
# mkzonefs -f /dev/sdi
/dev/sdi: 29297213440 512-byte sectors (13970 GiB)
  Host-managed device
  55880 zones of 524288 512-byte sectors (256 MiB)
  524 conventional zones, 55356 sequential zones
  0 read-only zones, 0 offline zones
Format:
  55879 usable zones
  Aggregate conventional zones: disabled
  File UID: 0
  File GID: 0
  File access permissions: 640
  FS UUID: 67730d07-34c3-472c-9fde-22d3c705f231
Resetting sequential zones
Writing super block
# mount –t zonefs /dev/sdi /mnt
# ls -l /mnt
total 0
dr-xr-xr-x 2 root root   523 Feb 17 10:40 cnv
dr-xr-xr-x 2 root root 55356 Feb 17 10:40 seq
```

Number of files

Conventional zone file size is fixed to the zone size

```
# ls -lv /mnt/cnv
total 137101312
-rw-r----- 1 root root 268435456 Feb 17 10:43 0
-rw-r----- 1 root root 268435456 Feb 17 10:43 1
-rw-r----- 1 root root 268435456 Feb 17 10:43 2
...
-rw-r----- 1 root root 268435456 Feb 17 10:43 521
-rw-r----- 1 root root 268435456 Feb 17 10:43 522
```

Sequential zone file size indicate the amount of written data

```
# ls -lv /mnt/seq
total 14511243264
-rw-r----- 1 root root        0 Feb 17 10:43 0
-rw-r----- 1 root root  1048576 Feb 17 10:45 1
-rw-r----- 1 root root        0 Feb 17 10:43 2
-rw-r----- 1 root root 268435456 Feb 17 10:45 3
-rw-r----- 1 root root        0 Feb 17 10:43 4
...
-rw-r----- 1 root root        0 Feb 17 10:43 55354
-rw-r----- 1 root root        0 Feb 17 10:43 55355
```

Example: 15TB SMR Disk

524 conventional zones and 55356 sequential zones

- With aggregated conventional zones

```
# mkzonefs -f -o aggr_cnv /dev/sdi
/dev/sdi: 29297213440 512-byte sectors (13970 GiB)
  Host-managed device
  55880 zones of 524288 512-byte sectors (256 MiB)
  524 conventional zones, 55356 sequential zones
  0 read-only zones, 0 offline zones
Format:
  55879 usable zones
  Aggregate conventional zones: enabled
  File UID: 0
  File GID: 0
  File access permissions: 640
  FS UUID: af10a4cd-8732-4400-bb2c-61889a12a35e
Resetting sequential zones
Writing super block
# mount –t zonefs /dev/sdi /mnt
# ls -l /mnt
total 0
dr-xr-xr-x 2 root root     1 Feb 17 10:51 cnv
dr-xr-xr-x 2 root root 55356 Feb 17 10:51 seq
```

All conventional zones aggregated into a single file

The file size is the total size of all aggreagted zones

```
# ls -lv /mnt/cnv/
total 137101312
-rw-r----- 1 root root 140391743488 Feb 17 10:51 0
```

Aggregated zone file can be used as a regular file, as a disk through loopback, etc

```
# mkfs.ext4 /mnt/cnv/0
.. .
# mount -o loop /mnt/cnv/0 /data
# ls -la /data
total 24
drwxr-xr-x   3 root root  4096 Feb 17 10:54 .
dr-xr-xr-x. 22 root root  4096 Feb 17 10:55 ..
drwx------   2 root root 16384 Feb 17 10:54 lost+found
```

File Operations: Discovery

How many zones and zones information

- Raw block device case
  - BLKNRZONES and BLKREPORTZONE ioctl()
  - struct blk_zone contains all information for a zone
    - Zone type, write pointer, start sector, size

- Zonefs case
  - stat()/fstat()
    - Zone group directory size indicates the number of zones
    - Zone write pointer: file size (stat.st_size)
    - Zone size: file blocks (stat.st_blocks << 9)
      - Maximum file size

```
/* How many zones ? */
fd = open("/dev/sdX", O_RDONLY);
ioctl(fd, BLKGETNRZONES, &nr_zones);

/* Zones information */
rep = malloc(sizeof(struct blk_zone_report)
        + sizeof(struct blk_zone) * nr_zones);
ioctl(fd, BLKREPORTZONE, &rep);

for (i = 0; i < nr_zones; i++) {
                wp = rep.zones[i].wp;
                ...
}
```

```
/* How many zones ? */
stat("/mnt/seq", &stat);
nr_zones = stat.st_size;

/* Zones information */
for (i = 0; i < nr_zones; i++) {
                sprint(filename, "/mnt/seq/%d", i);
                stat(filename, &stat);
                ...
}
```

File Operations: Sequential Writes

O_APPEND and zone isolation

- Raw block device case
  - pwrite()
  - Write offset allows reaching any zone
    - A bug can corrupt another zone

```
/* Write zone i */
fd = open("/dev/sdX", O_RDWR | O_DIRECT);

while (ofst < rep.zones[i].length << 9) {
                pwrite(fd, buf, size, ofst);
                ofst += size;
                ...
}
```

- Zonefs case
  - Regular write() with O_APPEND or pwrite()
  - Write operation limited to the open zone file
    - Cannot corrupt another zone

```
/* Write zone i */
sprint(filename, "/mnt/seq/%d", i);
fd = open(filename, O_RDWR | O_DIRECT | O_APPEND);

while (stat.st_blocks) {
                write(fd, buf, size);
                stat.st_blocks -= size >> 9;
                ...
}
```

File Operations: Zone Management

Zone reset and zone finish

- Raw block device case
  - BLKRESETZONE and BLKFINISHZONE ioctl()
- Zonefs case
  - truncate()/ftruncate() to 0 for zone reset
  - truncate()/ftruncate() to maximum file size for zone finish

```
fd = open("/dev/sdX", O_RDWR);

/* Reset zone i */
range.sector = rep.zones[i].start;
range.nr_sectors = rep.zones[i].length;
ioctl(fd, BLKRESETZONE, &range);

/* Finish zone i */
range.sector = rep.zones[i].start;
range.nr_sectors = rep.zones[i].length;
ioctl(fd, BLKFINISHZONE, &range);
```

```
sprint(filename, "/mnt/seq/%d", i);

/* Reset zone i */
truncate(filename, 0);

/* Finish zone i */
truncate(filename, stat.st_blocks << 9);
```

Use Case Example: LevelDB

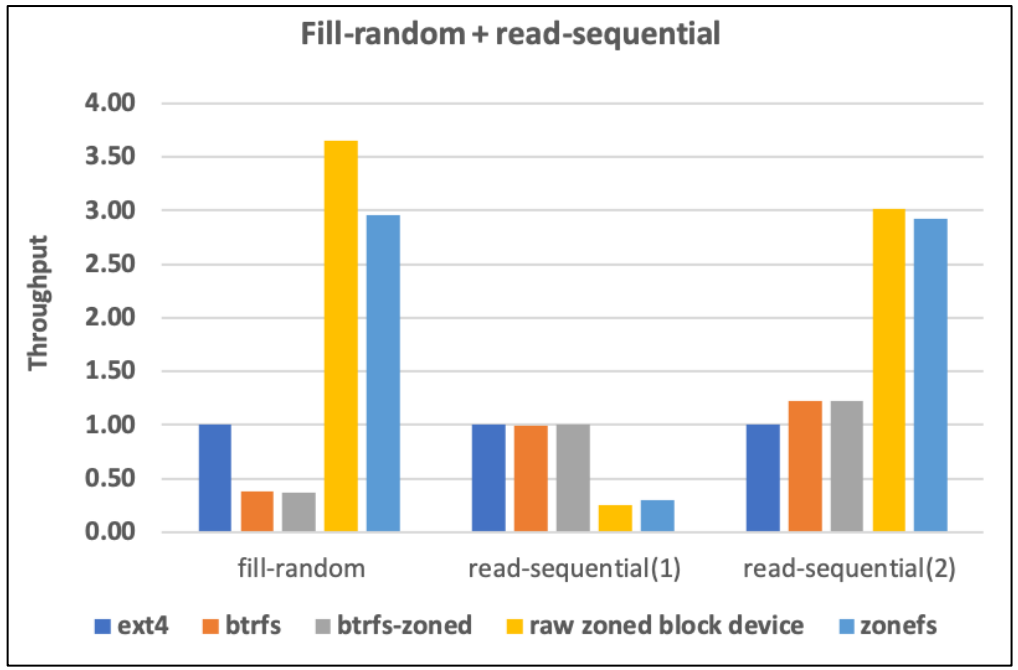
Use zone files to store SSTables

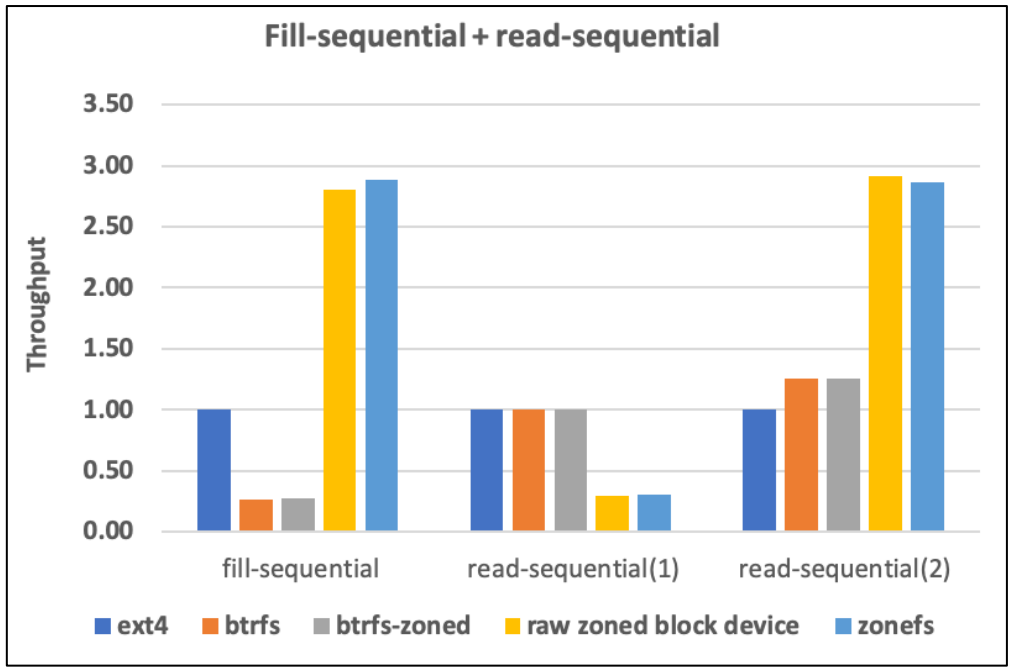
- Modified LevelDB implementation to use zone files for storing SSTable files
  - Use direct IO writes to zones
    - Similar modification to also add raw zoned block device support
  - Buffered and mmap reads of SSTables
- Experiment: Regular NVMe SSD vs prototype NVMe ZNS drive
  - Regular SSD: ext4 (baseline) and btrfs
  - Prototype ZNS drive: btrfs-zoned (on-going work), raw block device and zonefs
  - 16B keys and 4KB values
  - Execute db-bench with the sequences:
    - fillrandom, readseq, readseq
    - fillseq, readseq, readseq
- Results normalized to the Regular NVMe SSD + ext4 baseline case
  - All results are averaged over of 5 runs

Use Case Example: LevelDB

Random and sequential write operations followed by read operations

- 2.5 to 3 times better throughput for ingest (random and sequential)
  - File system journaling overhead avoided
- Direct IO write operations result in lower first-time read performance
  - No data in page cache after writes
  - But up to 3x throughput for second read with warm cache





Current Status

Initial release included with upstream kernel

- Initial pull accepted for Linux 5.6-rc1
  - Selection under “File systems” menu
  - Requires *CONFIG_BLK_DEV_ZONED* selection
    - Zoned block device support in “Enable the block layer” menu
- Userspace tool available on github
  - https://github.com/damien-lemoal/zonefs-tools
  - Provides the format utility *mkzonefs* (*mkfs.zonefs*)
- xfstests support not planned
  - Too few common test cases with regular POSIX file systems
  - A special test suite is provided with zonefs-tools

Future Work

Extend file operation mapping to zone operations

- Better handling of *IOCB_NOWAIT* for asunchronous I/Os
  - Currently silently ignored since it can cause IO reordering if enabled
- Continue integration of zone management commands
  - Zone explicit open/close with file (inode) open()/close()
    - Can improve performance for ZNS SSDs (control of active resources)
  - Integrate NVMe ZNS “zone append” command use
    - For asynchronous write operations specifying RWF_APPEND and/or files opened with O_APPEND
- Read-after-write performance improvements
  - Explore new “*RWF_CACHED*” flag: *O_SYNC* like behavior while retaining direct-IO alignement constraint
    - Warm up page cache on direct writes for page aligned writes
- Continue exploring different use cases to identify potential areas of improvement
  - RocksDB on-going
  - Clearly separate application problems vs zonefs performance limitations
    - For now, read-after-write problem is the most obvious

Questions ?

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