Disk I/O Scheduling in Hadoop YARN Cluster (Draft)

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1. Motivation

Resource sharing and isolation techniques in Hadoop YARN have been studied and implemented for resources such as CPUs and memory. Individual tasks (or containers) can be limited on the number of CPU cores and the amount of memory they are allowed to use. However, YARN doesn't support I/O resource management and isolation. Co-located tasks might compete for I/O resources and interfere with each other. This document focuses on disk I/O resource scheduling, and provides a solution for I/O resource scheduling and isolation.

Setting up a feasible disk I/O resource scheduling mechanism is desirable. Individual tasks have diverse disk I/O requests. Scheduling two disk I/O-intensive tasks together on a node with insufficient resources will lead to interference among these tasks. Additionally, without isolating disk I/O resources, it is hard for YARN to deliver a stable performance for I/O-intensive tasks. For example, scheduling an I/O-intensive task in a I/O-light node may run faster than in a I/O-heavy node.

In this document, we propose fair sharing mechanism for disk I/O management. Each task can specify its own disk I/O requirement, and the scheduler can guarantee the amount of I/O resource assigned to each task. This way, we can alleviate the I/O resource competition and make sure some higher priority tasks (with higher I/O resource request) wouldn't be blocked by

lower priority tasks (with lower I/O resource request). In this document, we only achieve disk read isolation, and write operation cannot be supported right now (more discussion in Section 4.2).

2. Design

This section mainly discusses the design of disk I/O scheduling, including: (1) How to describe the disk I/O resource? (2) How does the scheduler factor in disk I/O resource? (3) How does each NodeManager enforce the disk I/O resource usages for each local task?

2.1 Disk I/O Resource Description

For disk I/O resource description, here we introduce an additional resource dimension `vdisks` (virtual disks) to existing dimensions (CPU and memory). Each task can specify its own disk I/O resource request via `vdisks` according to their I/O request. A larger `vdisks` value translates to higher disk I/O bandwidth. The default `vdisks` value is set to 1, which means I/O-light. Note that `vdisks` doesn't expose the heterogeneity among disks on a node, which is out of scope for this work.

2.2 Scheduler-Side

The major change in the scheduler-side is to include `vdisks` to the Dominant Resource Fairness (DRF) policy. Currently, the DRF in scheduler supports cpu and memory. We also introduce configurations for users to specify which resources should be included into the DRF.

2.3 Enforcement by NodeManager

In summary, we would like to provide proportional disk I/O fair sharing. The available disk I/O resource is shared among all tasks in a proportional way (the `vdisks` value). We use Cgroups to implement this solution. Here we first illustrate functions provided by Cgroups and then discuss the implementation details.

Cgroups provides a subsystem called `blkio`, which offers two policies for controlling access to disk I/O:

- Proportional weight division: implemented in the Completely Fair Queuing I/O scheduler, this policy allows you to set weights to specific cgroups. This means that each cgroup has a set percentage (depending on the weight of the cgroup) of all I/O operations reserved..
- I/O throttling (Upper limit): this policy is used to set an upper limit for the number of I/O operations performed by a specific device. This means that a device can have a limited rate of read or write operations.

We use the proportional weight division policy to provide a weighted fair sharing among all containers. If a container specifies its disk I/O request as `p`, we can set the weight for that container to `p` directly.

3. Implementation

3.1 Disk I/O Resource Description

Summary: Add the disk I/O dimension (`vdisks`) to the resource request.

Add field `vdisks` to `ResourceProto` in `yarn_protos.proto`.

```
message ResourceProto {
  optional int32 memory = 1;
  optional int32 virtual_cores = 2;
+ optional int32 vdisks = 3;
}
```

Add field `vdisks` to `org.apache.hadoop.yarn.api.records.Resource`.

```
+ public abstract int getVdisks();
+ public abstract void setVdisks(int vdisks);
```

Add the following configurations to `org.apache.hadoop.yarn.conf.YarnConfiguration`.

```
+ /** Number of virtual disk I/O resources which can be allocated for containers. */
+ public static final String NM_VDISKS = NM_PREFIX + "resource.vdisks";

+ /** Minimum request grantable by the RM scheduler. */
+ public static final String RM_SCHEDULER_MINIMUM_ALLOCATION_VDISKS =
YARN_PREFIX + "scheduler.minimum-allocation-vdisks";
+ public static final String DEFAULT_RM_SCHEDULER_MINIMUM_ALLOCATION_VDISKS =
0;

+ /** Maximum request grantable by the RM scheduler. */
+ public static final String RM_SCHEDULER_MAXIMUM_ALLOCATION_VDISKS =
YARN_PREFIX + "scheduler.maximum-allocation-vdisks";
+ public static final String DEFAULT_RM_SCHEDULER_MAXIMUM_ALLOCATION_VDISKS =
20;
```

3.2 Scheduler-side Changes

Summary: The major changes in the scheduler-side includes (both for FairScheduler and CapacityScheduler):

- Configure whether the scheduler does disk I/O scheduling. If disabled, the scheduler only works on memory and vcores.

- Add `vdisks` to DRF policy, and configure which resources are included when calculating DRF.

```
+ /** Enable vdisks scheduling or not. */
+ protected static final String VDISKS_SCHEDULING_ENABLED = CONF_PREFIX +
"vdisks-scheduling-enabled";
+ protected static final boolean DEFAULT_VDISKS_SCHEDULING_ENABLED = false;

+ /** Enable memory/vcores/vdisks in DRF or not. */
+ protected static final String DRF_MEMORY_ENABLED = CONF_PREFIX +
"drf.memory.enabled";
+ protected static final boolean DEFAULT_DRF_MEMORY_ENABLED = true;
+ protected static final String DRF_VCORES_ENABLED = CONF_PREFIX +
"drf.vcores.enabled";
+ protected static final boolean DEFAULT_DRF_VCORES_ENABLED = true;
+ protected static final String DRF_VDISKS_ENABLED = CONF_PREFIX +
"drf.vdisks.enabled";
+ protected static final boolean DEFAULT_DRF_VDISKS_ENABLED = true;
```

3.3 NodeManager-side Enforcement

Summary: Add support for NodeManager to enforce the disk I/O resource usage for each task.

3.3.1 Prepare

Make changes to `org.apache.hadoop.yarn.server.nodemanager.util.CgroupsLCEResourcesHandler` to mount the Cgroups path to include `blkio`.

3.3.2 For Newly Launched Container

In general, for each newly launched container `C` with `vdisks` `p`, we create a new cgroup under the `blkio` subsystem. The cgroup's weight for all disk devices is set to `p`.

```
mkdir /sys/fs/cgroup/blkio/hadoop-yarn/C_ID
echo p > /sys/fs/cgroup/blkio/hadoop-yarn/C_ID/blkio.weight
```

And add `C`'s process to the cgroup's `tasks` file.

```
echo C_PID > /sys/fs/cgroup/hadoop-yarn/blkio/C_ID/tasks
```

Once the container finishes, remove the created cgroup.

4. Follow-up items

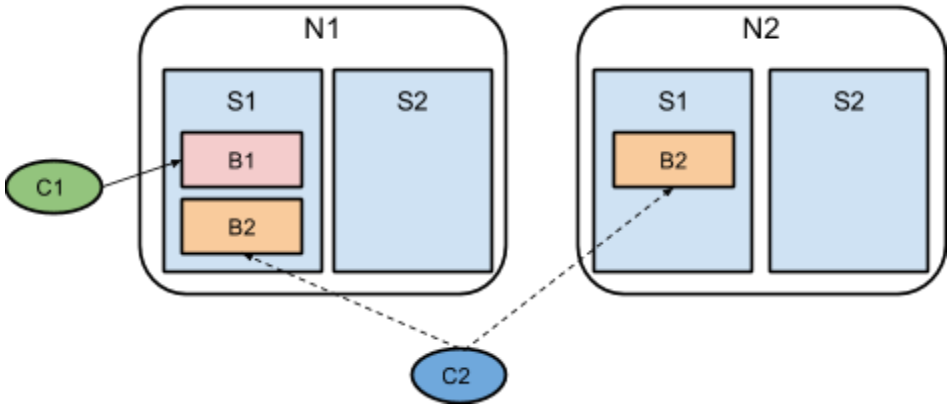
4.1 Spindle Locality

4.1.1 Motivation

In the previous discussed disk I/O scheduling solution, each NM achieves the fair sharing of disk I/O bandwidth across all local disks. Without considering the spindle locality information, disk contention may happen when one disk becomes fully loaded while other disks are idle.

Consider the following example that we have two node (`N1`, `N2`), each with two spindles (`S1`, `S2`). Each spindle offers 100 MB/s bandwidth, and the vdisks value for both `N1` and `N2` is 20, which means 1 vdisks represents 10 MB/s bandwidth. We have two containers (`C1`, `C2`), each requesting 10 vdisks. Assume `C1` has been assigned to `N1`, and reads data block `B1`; `C2` needs to read data block `B2`, and is waiting to be scheduled. Without considering the spindle-locality, the scheduler finds that both `N1` and `N2` have enough vdisks resources to satisfy `C2`'s request, and can assign `C2` to either one. However,

- If `C2` is assigned to `N1`, both `C1` and `C2` read data from `S1`, and each has a reading bandwidth of 50 MB/s.
- If `C2` is assigned to `N2`, both `C1` and `C2` has a reading bandwidth of 100 MB/s.



For the first condition, even worse, as `C1` and `C2` take all vdisks resources offered by `N1`, the scheduler will not schedule new container to `N1` even that the spindle `S2` is idle. This situation happens because the scheduler works on coarse datanode locality, without considering the spindle locality to eliminate disk contention.

4.1.2 Proposed solution

To avoid the aforementioned scenario, we'll introduce spindle-locality when disk I/O scheduling is enabled, to eliminate disk contention. Currently, HDFS exposes disk-location information for blocks in HDFS-3672, which allows clients to make scheduling decisions for better locality and load balancing, on a per-disk rather than coarse per-datanode basis. Through that API, each client can specify its own resource request with spindle-locality; and the scheduler can achieve

better disk I/O scheduling by considering the spindle-locality information contained in resource requests. Here we brieflydescribe the changes to NodeManager, Client, and Scheduler perspectives.

NodeManager: Each node manager specifies its own vdisks per spindle, i.e., `node1.spindle1.vdisks`=10, `node1.spindle2.vdisks`=10. The node manager can also only specify the total vdisks value, and we can retrieve the spindle number from the HDFS side (may need a new HDFS API).

Client: Each resource request specifies its spindle locality request, besides the existing node/rack locality information. For example, in MapReduce framework, the MRAppMaster can fetch the spindle locality information for each mapper's data block through the HDFS API, and attach these information with resource requests for map tasks.

Scheduler: firstly, the scheduler adds a new configuration field to specify the delay timeout for spindle locality. And a node `N` fulfills a container resource request `C` only if the following conditions hold: (1) `N` has enough available cpu/memory/vdisks resources that satisfy `C`'s request; and (2) `N` meets `C`'s spindle locality request, and that corresponding spindle has enough available vdisks; or `N` meets `C`'s node locality request and reach `C`'s spindle locality delay is timeout; or `N` meets `C`'s rack locality request and `C`'s node locality delay is timeout; or `C`'s any locality delay is timeout.

The scheduler also tracks the available vdisks resource for each spindle, which is updated once a container is assigned to a spindle. Here we only consider the container that achieves spindle-locality at the current node.

Back to the previous example, after assigning container `C1`, the available vdisks resources are listed as:

- `N1.S1.vdisks=0, N1.S2.vdisks=10`;
- `N2.S1.vdisks=10, N2.S2.vdisks=10`.

For container `C2`, it will be assigned to `N1` only if its spindle locality delay is timeout; otherwise, it will be assigned to `N2` as `N1`'s `S1` has no available vdisks.

4.2 Buffered Write Isolation

Currently, Cgroups' `blkio` subsystem can only support sync I/O queues, and cannot enforce buffered write traffic (buffered read is ok)[1], because all the buffered writes are system wide and not per group/process. The right way to solve this would be with support in the kernel for buffered-writes. Although we only support read I/O traffic enforcement in phase 1, it is still desirable for scenarios having lots of read-heavy BI workloads.

[1] https://www.kernel.org/doc/Documentation/cgroups/blkio-controller.txt

To solve the buffered write problem, one approach is to add a FUSE[2] wrapper that overlay on top of the local file system. Since the wrapper can see all I/O traffic, it can easily perform monitoring and rate limiting to enforce the sharing policy.

[2] http://fuse.sourceforge.net/.