Log-assisted Straggler-aware I/O Scheduler for High-End Computing

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Background and Motivation
Straggler: Some of OSSs take a much longer time in responding to I/O requests than other servers.

The occurrence of stragglers has significant affects on I/O performance of object storage systems.
Our previous work, two-choice randomized:
- Solves the straggler problem.
- For each I/O request, before making scheduling decision, probing strategy is used.
- Two random servers will be probed, the one with the minimum load will be selected.
- Suffer from expensive probing messages and communication overhead

In this study:
- Use client-side logs to assist straggler-aware I/O scheduling.
Overall Architecture
Proposed Architecture

Diagram showing the proposed architecture with Compute Nodes, File System Library, Applications, I/O Scheduler, Client-side Server Statistic Log, Network, Object storage server (OSS), Service Interface, Metadata Maintain Threads, Redirect Table, OSD-1, OSD-K, Local Storage Layer.
Proposed Architecture: Components

- **Client-side server statistic log**
  - Record current pending I/O requests and also server statistic
- **Metadata maintainer thread**
  - Runs in the background to move the redirected objects back to their default location when the file systems are idle.
- **Redirect Table**
  - Record the current location of chunk of data
Scheduling Model

- **Time Series:** all the queued I/O requests.
- **Time Window:** we schedule I/O in a fixed time interval, called time window.
- **Time Step:** each time window can contain multiple steps, each of them contains the I/O requests on the same object.
### Client-Side Server Statistics Log

<table>
<thead>
<tr>
<th>Object ID</th>
<th>Offset</th>
<th>Length</th>
<th>Load</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Obj}_1$</td>
<td>$\text{Off}_1$</td>
<td>$\text{Len}_1$</td>
<td>$\text{OSS}_1$</td>
<td>$P_1$</td>
</tr>
<tr>
<td>$\text{Obj}_2$</td>
<td>$\text{Off}_2$</td>
<td>$\text{Len}_2$</td>
<td>$\text{OSS}_2$</td>
<td>$P_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Obj}_n$</td>
<td>$\text{Off}_n$</td>
<td>$\text{Len}_n$</td>
<td>$\text{OSS}_M$</td>
<td>$P_M$</td>
</tr>
</tbody>
</table>

- **Object ID**: Identifies the object.
- **Offset**: The starting position of the object within the data structure.
- **Length**: The size of the object.
- **Load**: The load associated with the object.
- **Prob.**: The probability of accessing the object.

The table above represents the client-side server statistics log, which records the number of requests, object IDs, offsets, lengths, loads, and probabilities for each object accessed.
After scheduling I/O request of a single step, the server loads in the server statistic log is updated to:

\[ l = l' + \text{Len} \]

\( l \): Expected server load at the end of each step.
\( l' \): Server load from the previous step.
\( \text{Len} \): Length of scheduled I/O requests.

Update the probability of selecting server \( i \):

\[ p_i = p_i' \times e^{-l_i} \]

\( p_i' \): Indicates the current probability of selecting server \( i \).
Not only update the load of the selected server

It needs to update the probability of choosing another server to prepare for the next scheduling. The following equation shows how this is done:

$$p_j = p'_j + \frac{(p'_i - p'_i e^{-l_i})}{M-1}, j \neq i$$

$M$ : indicates the total number of storage servers.

$i$ : The server that is chosen to serve the current I/O request.

$j$ : refers to all other object storage servers.
Scheduling Algorithms
Based on the information stored in the server statistic log, we propose two scheduling algorithms.

These algorithms leverage the statistic log to develop an efficient straggler-aware I/O scheduler.

Firstly, Max Length - Min Load (MLML)
- select the server with lighter workloads with a higher probability.

Secondly, Two Random from Top Half (TRH)
- takes advantage of the random strategy in addition to server statistic log.
Proposed Algorithm: Max Length - Min Load
MLML

- It sorts the storage servers based on their probabilities from the highest to the lowest.
- Sort the I/O requests from the maximum length to the minimum one.
- These two sorted lists are processed sequentially, from the top to the bottom of lists then starting again from the top of the lists in a circular manner.
- The maximum length I/O request will be scheduled to the server with lighter load and the minimum length I/O request will be distributed to the server with heavier load.
Two sorted lists: `sortedServers` and `sortedRequests`.

- **Default_oss** describes the default location of requested objects (default RR strategy).
- **Target_oss** represents the storage server calculated based on this MLML scheduling algorithm.

If the target_oss and the default_oss are not the same server, we then need to consider whether it is worth of scheduling this request to the target oss as this might increase read overhead due to the redirection.
Algorithm 1 Max Length-Min Load algorithm (MLML)

1: procedure MLML(SERVERS, REQUESTS, THRESHOLD)
2:    sortedServers = sort(servers);
3:    sortedRequests = sort(requests);
4:    index=0;
5:    while need_schedule() do
6:        default_oss = requests[index mod M];
7:        target_oss = sortedRequests[index mod M];
8:        benefit = load(default_oss) - load(target_oss);
9:        if benefit ≤ threshold then
10:            return target_oss;
11:        else
12:            return default_oss;
13:        index++;

Example of MLML algorithm

<table>
<thead>
<tr>
<th>Selected OSS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ob 4 (len 1)</td>
<td>OSS 1</td>
</tr>
<tr>
<td>Ob 3 (len 2)</td>
<td>OSS 2</td>
</tr>
<tr>
<td>Ob 2 (len 3)</td>
<td>OSS 3</td>
</tr>
<tr>
<td>Ob 1 (len 4)</td>
<td>OSS 4</td>
</tr>
<tr>
<td>Ob 6 (len 5)</td>
<td>OSS 5</td>
</tr>
<tr>
<td>Ob 5 (len 6)</td>
<td>OSS 1</td>
</tr>
</tbody>
</table>
Proposed Algorithm: Two Random from Top Half (TRH)

- Two OSSs are randomly selected as potential targets and the one with the lighter load will be chosen.
- The sorted list of object storage servers is also used, same as in the MLML algorithm.
- For a given I/O request, two object storage servers will be randomly chosen from the top half of all object storage servers.
- The top half indicates M servers that have lighter loads.
- A threshold is used to decide whether choosing the calculated target_oss or the default_oss.
Proposed Algorithm: Two Random from Top Half (TRH)

Algorithm 2 Two Random from top Half (TRH) Algorithm

1: procedure TRH(SERVERS, REQUESTS, THRESHOLD)
2:   sortedServers = sort(servers);
3:   sortedRequests = sort(requests);
4:   index = 0;
5: while need_schedule() do
6:   default_oss = requests[index] mod M;
7:   ross_1 = random_oss();
8:   ross_2 = random_oss();
9:   target_oss = find_min_load(ross_1, ross_2);
10:  benefit = load(default_oss) - load(target_oss);
11:  if benefit ≤ threshold then
12:      return target_oss;
13:  else
14:      return default_oss;
15:  index++;

Example of TRH algorithm

<table>
<thead>
<tr>
<th>List of two Random OSSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ob 1</td>
</tr>
<tr>
<td>Ob 2</td>
</tr>
<tr>
<td>Ob 3</td>
</tr>
<tr>
<td>Ob 4</td>
</tr>
<tr>
<td>Ob 5</td>
</tr>
<tr>
<td>Ob 6</td>
</tr>
</tbody>
</table>
Evaluations
We use simulation to evaluate the proposed scheduling algorithms.

Synthetic workloads generated by simulating real-world applications.

Combining three different types of I/O requests:

- large I/O (each request is greater than \( O(10\text{MB}) \))
- medium I/O (each request is between 4MB and 10MB)
- Small I/O (each request is less than 4MB)

The simulation is run in an HEC cluster with 100 object storage servers and 200 compute nodes.
We issued 2,000 I/O requests in each run with various sizes for each request.

The total data written for all large I/O case can be between $O(20\text{GB})$ and $O(2\text{TB})$ depending on the size of each request.
Evaluation Results

X-axis: Storage servers
Y-axis: Load of each storage server (i.e., write data size in MB).

Load distribution with the RR scheduling algorithm

Load distribution with the log-assisted straggler-aware scheduling with the MLML algorithm
Evaluation Results

X-axis: Storage servers
Y-axis: Load of each storage server (i.e., write data size in MB).

Load distribution with the log-assisted straggler-aware scheduling with the TRH algorithm.
Evaluation Results

X-axis: Current Load of Storage servers (i.e., write data size in MB).
Y-axis: Maximum number of scheduled I/O requests.

Comparison of RR, MLML, and TRH scheduling algorithms.
A new log-assisted straggler-aware I/O scheduler is introduced.

A client-side server statistic log is introduced.

Two straggler-aware scheduling algorithms based on the proposed client-side server statistic log:
- Max Length - Min Load (MLML) algorithm
- Two Random from Top Half (TRH) algorithm.

The evaluations confirm that the log-assisted straggler-aware scheduling achieves a better load balance on storage servers while avoiding stragglers.
Questions