GreenHDFS: Towards An Energy-Conserving, Storage-Efficient, Hybrid Hadoop Compute Cluster

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ABSTRACT

Hadoop Distributed File System (HDFS) presents unique challenges to the existing energy-conservation techniques and makes it hard to scale-down servers. We propose an energy-conserving, hybrid, logical multi-zoned variant of HDFS for managing data-processing intensive, commodity Hadoop cluster. Green HDFS’s data-classification-driven data placement allows scale-down by guaranteeing substantially long periods (several days) of idleness in a subset of servers in the datacenter designated as the Cold Zone. These servers are then transitioned to high-energy-saving, inactive power modes. This is done without impacting the performance of the Hot Zone as studies have shown that the servers in the data-intensive compute clusters are under-utilized and, hence, opportunities exist for better consolidation of the workload on the Hot Zone. Analysis of the traces of a Yahoo! Hadoop cluster showed significant heterogeneity in the data’s access patterns which can be used to guide energy-aware data placement policies. The trace-driven simulation results with three-month-long real-life HDFS traces from a Hadoop cluster at Yahoo show a 26% energy consumption reduction by doing only Cold zone power management. Analytical cost model projects savings of $14.6 million in 3-year total cost of ownership (TCO) and simulation results extrapolate savings of $2.4 million annually when GreenHDFS technique is applied across all Hadoop clusters (amounting to 38000 servers) at Yahoo.

1. INTRODUCTION

Cloud computing is gaining rapid popularity. Data-intensive computing needs include advertising optimizations, user-interest predictions, mail anti-spam, data analytics and deriving search rankings. With the increase in the sheer volume of the data that needs to be processed, storage and server demands of computing workloads are on a rapid increase. Yahoo!’s datacenters already have 170 petabytes of data and deploy 38000 servers [4]. Over the lifetime of IT equipment, the operating energy cost is comparable to the initial equipment acquisition cost [9] and constitutes a significant part of the TCO of a datacenter [7]. Hence, energy-conservation of the extremely large-scale, commodity server farms has become a priority.

Server energy consumption costs can be cut down significantly by using low-power, high-energy-saving inactive power modes during idle periods of utilization\(^1\). However, inactive power modes cannot be used in an adhoc fashion as there are significant latencies associated with the power state transitions. Effective usage of inactive power modes mandates presence of significantly long periods of idleness in the system.

There is significant amount of research literature about datacenter energy management. A large number of these techniques aim to classify and place the computational load during periods of low activity. This can be relatively easy to accomplish when using simple data models, when servers are mostly stateless (e.g., serving data that resides on a shared NAS or SAN storage system). However, in complex data distribution models that have significant state, such techniques cannot manufacture enough idleness to make usage of inactive power modes feasible. One such example is the Hadoop compute cluster.

Given the massive bandwidth requirements and the sheer amount of the data that needs to be processed, data-intensive compute clusters such as those running Hadoop have moved away from NAS/SAN model to completely clustered, commodity storage that allows direct access path between the storage servers and the clients [10]. Hadoop’s data-intensive computing framework is built on a large-scale, highly resilient Hadoop distributed filesystem (HDFS) managed cluster-based storage [13]). HDFS distributes data chunks and replicas across the servers for higher performance, load-balancing and resiliency. With data distributed across all servers, any server may be participating in the reading, writing, or computation of a data-block at any time. Such a data placement complicates power-management and makes it hard to generate significant periods of idleness in the Hadoop clusters and renders usage of inactive power modes infeasible [15].

Recent research on increasing energy-efficiency in GFS and HDFS managed clusters [2, 15] propose maintaining a primary replica of the data on a small covering subset of nodes that are guaranteed to be on and which represent the lowest power setting. The remaining replicas are stored in larger set of secondary nodes. Performance is scaled up by increasing the number of secondary nodes. However, these solutions suffer from degraded write-performance and increased DFS code complexity [3]. These solutions also do not do any data differentiation and treat all the data in the system alike.

We take a different approach to generating significant periods of idleness in a Hadoop cluster. Instead of energy-efficient placement of computations or replicas, we use energy-

\(^1\)Some SATA disks consume only 0.9W in sleep state vs. 7.5W in idle state and 17W in active state
aware placement of data and focus on data-classification techniques to differentiate the data. A study of Yahoo!’s Hadoop cluster illustrated in Section 2 shows significant variation in the access patterns of the data stored in the cluster. We seek to utilize the heterogeneity in the data towards our energy-conserving data-classification-driven data placement. We proposed this approach in the context of cloud storage in our paper [12].

We propose GreenHDFS, an energy-conserving, self-adaptive, hybrid, logical multi-zone variant of HDFS. GreenHDFS trades performance and power by logically separating the Hadoop cluster into Hot and Cold zones. Zone’s temperature is defined by its power consumption and the performance requirements. Data’s temperature evolves based upon its availability/performance requirements. We use data-classification policies to place data onto a suitable temperature zone. Since computations exhibit high data locality in the Hadoop framework, the computations flow naturally to the data in the right temperature zones.

GreenHDFS technique results in a number of servers in the Cold zone with very low utilization and guaranteed periods of idleness. The CPU, DRAM and Disks on these servers can then be transitioned to inactive power modes resulting in substantial energy savings. Thus, GreenHDFS provides a mechanism to have an energy-proportional behavior in data centers built with non-energy-proportional components.

We argue that zoning in GreenHDFS will not affect the Hot zone’s performance adversely and the computational workload can be consolidated on the servers in the Hot zone without exceeding the CPU utilization above the provisioning guidelines. A study of 5000 Google compute servers, showed that most of the time is spent within the 10-50% CPU utilization range [5]. Hence, significant opportunities exist in workload consolidation. And, the compute capacity of the Cold zone can always be harnessed under peak load scenarios as discussed in Section 3.4.

The remainder of the paper is structured as follows. In section 2, we describe the data characteristics of a Yahoo! cluster. In Section 3, we discuss the design, and the conceptual basis of the policies in GreenHDFS. We focus on the major design primitive: an adaptive multi-zoned Hadoop cluster. In Section 4, we include simulation results demonstrating the effectiveness of our design in conserving energy in an enterprise Hadoop cluster at Yahoo!. Finally, we conclude.

2. ANALYSIS OF A YAHOO CLUSTER

We analyzed three months of HDFS logs in one of Yahoo!’s enterprise Hadoop clusters. The cluster had 2600 servers and hosted 34 million files, and the data set size was 5 Petabytes. We found existence of a significant amount of data in the system which either wasn’t accessed at all or rarely accessed after some amount of elapsed time. We introduced four file lifespan metrics to analyze the evolution and lifetime of the files in the cluster. FileLifeSpanCFR metric is defined as the file lifespan between the file creation and first file read access. This metric is used to understand the gap between a file’s creation and the start of a file’s hotness lifespan. FileLifeSpanCLR metric is defined as the file lifespan between the file creation and the last file read access. This metric is used to determine the Hotness profile of a file, i.e., the period of the time for which the file is actively accessed. FileLifeSpanBFR metric helps in determining the Coldness profile of a file, i.e., the period for which a file lies dormant in the system without getting accessed.

As shown in Figure 1, the FileLifeSpanCFR of 90.26% of data is less than 2 days. Thus, data is accessed soon after its creation. 89.61% of data has a FileLifeSpanCLR of less than 10 days. This indicates that majority of the data is hot for less than 10 days after its creation in the system. This clearly illustrates a news-server-like behavior for 89% of the data whereby the reads to the data are clustered around its creation and accesses die down after a short hot lifespan. 40% of the data in the cluster has a FileLifeSpanBFR of higher than 20 days. This indicates that 40% of the data lies untouched in a dormant state in the cluster for more than 20 days. We didn’t account for temporary data that is stored in the grid in this analysis. Had we accounted for the same, a higher percentage (60%) would be dormant for more than 20 days.

As shown in Figure 2(mid), in steady-state, almost 60% data was not accessed at all in a 20 day window. This cold data amounted to 70% of the files in the system as shown in the Figure 2(left). This cold data needs to exist in the system for regulatory compliance and historical trend analysis. This study indicates that there are tremendous opportunities to differentiate the data into different temperature classes in a Hadoop computer cluster.

3. GREENHDFS’S HYBRID MULTI-ZONE LAYOUT

We give an overview of GreenHDFS’s zones in this section and we only discuss the functionality and policies which are relevant to Hadoop cluster’s energy-management. The zone with the higher temperature is designated as the Hot zone. The zone with the lower temperature is designated as the Cold zone. High-level data placement policy decides the zone on which data will be placed initially based on per-zone data-classification policies illustrated below. The data transitions adaptively between the zones as its temperature changes in response to the energy-management policies covered in Section 3.3. GreenHDFS requires few changes to the HDFS code such as differentiating inactive servers from failed servers in the heartbeat handling mechanism and directing data accesses to the right zone. We have built a prototype which is out of the scope of this paper.

3.1 HotZone

Data Class: Consists of hot, popular data that is accessed very frequently. The popularity can be spatial or temporal. Hardware Class: consists of high performance, high power and hence higher cost CPUs. Data Chunking Policy: Uses a Chunk Server Placement policy that considers the problem of assigning n chunks f1, f2, \ldots, fn among m servers and aims to optimize the mean response time and the system throughput by minimizing the queuing delays on

\footnote{This is necessary as HDFS replicates the blocks residing on a server if it doesn’t receive a heartbeat from the server within a configured threshold of time.}
the servers’ disks in Hot zone. We assume $m \geq n$. Full description of the algorithm is beyond the scope of this paper. **Power Policy:** None, Hot zone has strict service level agreement (SLA) requirements and hence, performance is of the greatest importance. We trade-off power savings in interest of higher performance and servers in Hot zone will remain in the active mode at all times. **Zone Server Assignment:** Majority (70% +) of the servers in the cluster are assigned to the hot zone upfront. We are working on a dynamic server assignment policy which is self-adapts to the changes in the workload patterns similar to [8].

### 3.2 Cold zone

**Data Class:** consists of files with low spatial or temporal popularity with few to rare accesses. We trade-off performance for higher energy-conservation in this zone. **Hardware Class:** We propose using a larger number of disks per server in these zones compared to the Hot zone to accommodate the huge amount of cold data. This has two advantages: 1) fewer servers will need to be assigned to the Cold zone, hence, performance-critical Hot zones will get a higher share of servers. Higher number of hot servers is critical in a high-performance and high-availability distributed systems software which tends to spread data and computation. **Power Policy:** Aggressive, Performance and SLA requirements are not critical for Cold zone and we employ aggressive power management schemes and policies in Cold zone to transition servers to a very low power consuming, inactive power mode. **Zone Server Assignment:** On-Demand servers are powered-on and assigned to Cold zone on-demand. **Data Chunking Policy:** None, For optimal energy savings, it is important to increase the idle times of the servers and limit the wakeups of servers that have transitioned to the inactive-power-saving mode. Keeping this rationale in mind and recognizing the low performance needs and infrequence of data accesses to the Cold zone; this zone will not chunk the data. By not chunking the data, we ensure that future access to a particular data is limited to just one server hosting that data. **File Allocation Policy** tries to avoid powering-on a server and maximizes the use of the existing powered-on servers in its server allocation decisions in interest of maximizing the energy savings. We used In-order placement policy where a data structure maintains a sorted list of all the server IDs and the first few servers in the data structure are chosen as a target for data placement. These servers are kept powered-on and are filled completely to capacity before the next set of servers is chosen from the list. **Data Integrity** To ensure data integrity in the Cold zone, disks in the Cold zone are scrubbed from time to time. Every block on the disk is read and checked for agreement with its signature.

### 3.3 Energy-management Policies

Files are moved from the Hot zone to the Cold zone as their temperature changes over time. In this paper, we use age of a file, as defined by the last access to the file, as the

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4 We have added 1 day per month per server to the servers in the Cold zone, to account for a monthly scrub in our evaluation.
measure of temperature of the file. File Migration Policy monitors the age of the files and moves old files to the Cold Zone. The advantages of this policy are two-fold: 1) it leads to higher space-efficiency as space is freed up on the Hot zone for files which have higher SLA requirements by moving rarely accessed files out of the servers in these zones; furthermore, these files can be aggressively compressed on the lower storage capacity2) it leads to higher energy-efficiency as the concentration of the cold data on these servers allows for aggressive power management techniques illustrated earlier. Server Power Conservation Policy determines the servers which can be transitioned into a power saving standby/sleep mode in the Cold zone. We rely on Wake-on-LAN to wake the system upon arrival of a packet. Servers transition back to active power state upon receipt of data access, data migration or disk scrubbing events. All the components in the servers typically illustrate poor energy-proportionality and servers consume 50% peak power even when idle [5]. Thus, it is not sufficient to just scale-down one component in the system and we scale-down all the components (CPU, DRAM, Disks) in the system. File Reversal Policy: ensures that the QoS, bandwidth and response time of files which become popular again after a period of dormancy is not impacted. A once-again-popular file is moved back from the Cold zone to the Hot zone if the number of accesses to the file exceed a certain threshold.

3.4 Discussion

Based on our observation that a large amount of data in the cluster is cold, GreenHDFS will move this data to the Cold zone. The observation that the accesses to the data have a news-server-like access pattern, ensures that once a data is deemed cold (i.e., was not accessed in past n days), the probability of it being accessed again is lower. This will guarantee significant periods of idleness in the Cold zone and allow a large number of servers in the Cold zone to transition to inactive power modes. Hence, there can be a significant reduction in the energy costs of the cluster.

Given that the servers are under-utilized, the workload can be consolidated in the Hot zone servers. Furthermore, the boundary between the Hot and Cold zone is a logical boundary and in periods of peak utilization, the compute power of the Cold zone servers can still be harnessed. We also argue that the resulting power reduction courtesy of a percentage of always-sleeping servers could allow for provisioning more servers in the data center than a baseline case within the same power budget. [11] quotes in favor of our argument that - Maximizing usage of the available power budget is also important for existing facilities because it can let the computing infrastructure grow or enable upgrades without requiring the acquisition of new datacenter capacity, which can take years if it involves new construction. These additional servers can be provisioned to the Hot zone, allowing the Hot zone to offer similar availability, performance and bandwidth as the baseline case.

Finally, Oozie, which is used to manage and schedule Hadoop workflows, can be used to proactively power-on inactive servers since it knows upfront when/where a job needs to be launched [1]. Such proactive powering-on will help hide and amortize the wakeup latency of the power state transition. Also, given the batch-processing mode of the workloads, the wakeup penalty is of less concern. Still, we are taking several steps to mitigate the performance penalty of state transitions in our ongoing research.

4. EVALUATION RESULTS

We used a trace-driven simulator 5 to evaluate GreenHDFS and used HDFS traces generated by a Hadoop cluster at Yahoo! as an input to the simulator. We used models for the power levels of the disk, processor and the DRAM in the simulator 6. Table 1 lists the power values used in the Simulator. There were 34 million files in the trace file and the total size of the dataset was 5 PetaBytes.

All experiments and analysis were performed on the nodes of a development cluster at Yahoo. We used PIG extensively for the data analysis of the traces. We used a hybrid-model with storage-heavy servers (12, 1TB disks/server) in the Cold zone and normal (4, 1TB disks/server) servers in the Hot zone. Our comparisons were done with the baseline HDFS which doesn’t do any energy-management. The Simulator assumed 2600 servers to be consistent with the Hadoop cluster under consideration. For performance, load balancing and availability reasons, we provisioned 70% (i.e., 1820) servers to the Hot zone and 30% (i.e., 780 servers) to the Cold zone in the simulator.

<table>
<thead>
<tr>
<th>Server</th>
<th>Active Power (W)</th>
<th>Idle Power (W)</th>
<th>Sleep Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot server (2 CPU, 8 DRAM DIMM, 4 HDD)</td>
<td>442.7</td>
<td>105.3</td>
<td>14.1</td>
</tr>
<tr>
<td>Cold server (2 CPU, 8 DRAM DIMM, 12 HDD)</td>
<td>578.7</td>
<td>165.3</td>
<td>21.3</td>
</tr>
</tbody>
</table>

Table 1: Power Number Used in Simulator

Energy-Conservation In this section, we show the energy savings made possible by GreenHDFS over three months in comparison to the baseline HDFS. The cost of electricity was assumed to be $0.063/Kwh [11]. Applying GreenHDFS to 2600 servers results in $41,607 energy savings in a three-month period which is 26% of the baseline energy costs. If GreenHDFS technique is applied to all of the Yahoo! Hadoop clusters (amounting to 38000 servers), $2,432,417 can be saved in the energy costs annually. And, these results are with power management only in Cold zone. Energy saving from off-power servers will be further compounded in the cooling system of a real datacenter. For every Watt of power consumed by the compute infrastructure, a modern data center expends another one-half to one Watt to power the cooling infrastructure [18].

Cold Zone Reliability Consideration We analyzed the frequency distribution of the power transitions incurred by the servers in the Cold zones. As shown in Figure 3, the maximum number of power state transitions incurred by a server in a three-month simulation run was 70 times. Frequently starting and stopping disks is suspected to affect disk longevity. Given the very small number of transitions incurred by a server in the Cold zone in a year, there is no risk of exceeding the start/stop cycles 7 during the typical 5 year service life time of the disks.

5The GreenHDFS simulator was implemented in Java and MySQL distribution 5.1.41 and executed using Java 2 SDK, version 1.6.0-17.
6Information was extracted from the datasheet of Seagate Barracuda 7200.7 which is a SATA hard drive, and a Quad core Intel Xeon X5490 processor. This is an approximation of the cluster hardware.

Most of the SATA disks can tolerate 50,000 start/stop cycles.
Analytical Cost Model Projections We changed the homogeneous Analytical Cost Model used in [11] to allow heterogeneity 8 in the power consumption rate and in the costs of the servers in the hybrid model. In the hybrid model with 4, 1TB disks server (lower cost) in the Hot zone and 12, 1TB disks server (higher cost) in the Cold zone, the 3-year TCO with no energy management is $15.1 million for 2600 servers. In our simulation run, on average only 198 servers were awake in the Cold zone out of the assigned 780 servers. Taking the sleeping servers into consideration, the Analytical Cost Model shows savings of $1 million in the 3-year TCO for 2600 servers in the hybrid model while giving an extra 6.8 Petabytes of storage. 3-yr TCO saving will amount to $14.6 million by applying GreenHDFS technique across all the hadoop clusters (around 38000 servers overall).

5. CONCLUSION AND FUTURE WORK

We presented GreenHDFS, an energy-conserving, hybrid, logical multi-zoned variant of Hadoop’s compute cluster. We rely on data classification driven data placement to realize guaranteed, substantially long periods of idleness in a subset of servers designated as the Cold zone in the Hadoop cluster. These long periods of idleness allow us to use aggressive inactive power modes in all components (CPU, disks, DRAM) of this subset of servers projecting significant energy cost savings. We argue that the multi-zone data center layout won’t have an adverse impact on the performance of the Hot zone as there are ample opportunities for workload consolidation given the low utilization (10-50%) in compute servers [5]. Simulation results show that GreenHDFS is capable of achieving 26% savings in the energy costs of a Hadoop cluster in a three-month simulation run. Analytical cost model projects a savings of $14.6 million in 3-year TCO and simulation results extrapolate a savings of $2.4 million annually when GreenHDFS technique is applied across all Hadoop clusters (amounting to 38000 servers) at Yahoo. We are working on optimizations to enhance the energy-efficiency by using low-cost processors, amortizing the power transition penalties, reducing replication by exploring RAID alternatives and compression mechanisms to make the Cold zone more energy- and storage-efficient.

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7. REFERENCES