**Improving MapReduce Performance in Heterogeneous Network Environments and Resource Utilization**

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*Abstract*— In MapReduce, map and reduce tasks are assigned to map and reduce slots hosted by worker nodes. Usually the numbers of map and reduce slots are carefully chosen to gain optimal resource usage. We found resource utilization is inefficient when there are no enough tasks to fill all task slots because the resources “reserved” for idle slots are just wasted. We propose resource stealing which enables running tasks to steal the unutilized resources and return them when new tasks are assigned. It exploits the opportunistic use of the otherwise wasted resources to improve overall resource utilization and reduce job execution time. Besides, our practical use of Hadoop shows current mechanism adopted to trigger speculative execution creates many unnecessary speculative tasks that are killed soon after creation as the speculated tasks complete earlier. To alleviate the issue, we propose Benefit Aware Speculative Execution which predicts the benefit of launching new speculative tasks and greatly eliminates nonbeneficial runs of speculative tasks. At last, MapReduce is mainly optimized for homogeneous environments and its inefficiency in heterogeneous network environments are witnessed by our experiments. We investigate network heterogeneity aware scheduling of map and reduce tasks. Overall, the goal is to enhance Hadoop to cope with drastic network heterogeneity and improve resource utilization.

Keywords- heterogeneity, MapReduce, Hadoop, resource utilization

# Introduction

Several frameworks, such as Google File System (GFS) /MapReduce [1- 2], Hadoop[3] and Cosmos/Dryad [4] have been proposed to run data-intensive applications. Their support of data locality aware scheduling dramatically reduces data movement. They have been used in large scale to run both commercial applications [2, 5] and scientific applications [6-7]. Hadoop is an open source implementation of GFS and MapReduce. Hadoop Distributed File System (HDFS), which is modeled after GFS, is a distributed file system designed and optimized for write-once-read-many accesses of large files. Files are partitioned into equally-sized chunks. MapReduce is designed for data parallel applications that can be expressed with primitive *map* and *reduce* operations. Each map task applies user-implemented map operation to the data contained in one chunk.

Modern cluster servers are usually equipped with multi-core processors, so that multiple job tasks can run on a single node concurrently without incurring severe resource contention. The concurrency on each node needs to be carefully tuned so that resource usage is optimized. If the number of concurrent tasks is far less than the optimal setting, resource utilization is low and some resources are wasted. Otherwise, if the number of concurrent tasks is far more than the optimal setting, resource contention becomes high and degrades the efficiency drastically. The optimal setting depends on not only hardware configuration but also application workload. Rather than guess the optimal setting automatically, Hadoop gives users the freedom to control concurrency. Each worker node has a number of map and reduce slots which can be configured by users on a per-node basis. Nodes with heterogeneous hardware and processing capabilities can be configured accordingly. Each slot can host one task and each task can only be scheduled to one slot. One disadvantage of this mechanism is that hard partitioned slots cannot fully explore the processing capability of resources. When all slots are not used, the corresponding resources of idle slots are just wasted. To improve resource utilization, we propose *resource stealing* which dynamically expands and shrinks the usable resource set of running tasks.

Hadoop tackles fault-tolerance by speculatively launching duplicate tasks for the tasks deemed to be stragglers. Whenever a task completes, all other duplicate tasks are immediately terminated. Therefore the failure of nodes and tasks does not bring down the overall job execution or the whole system. Progress rates of tasks are used to identify outliers in Hadoop, which has been found by us to be insufficient because some slowly progressing tasks that are close to completion are speculated unnecessarily. We propose Benefit Aware Speculative Execution which only launches speculative tasks if they are expected to complete earlier than the speculated tasks.

Heterogeneity is inevitable for organizations that own various generations of IT resources purchased over different time frames. Cloud bursting allows organizations to dynamically scale out their infrastructures by integrating their own dedicated resources and rented resources provided by third-party providers (e.g. Amazon, Rackspace), which results in heterogeneity apparently. Hadoop does not perform well in heterogeneous environments [5, 8]. In our study, we propose network heterogeneity aware scheduling algorithms to improve the performance of Hadoop in heterogeneous network environments.

# Related work

Work stealing enables idle processors to steal computational work from other processors, which yields better load balancing and higher resource utilization [21]. MapReduce adopts a different model and supports finer control over tasks running on each node. We take a “reverse” approach in the sense that running tasks steal available resources (e.g. CPU cores, memory, network) reserved for prospective tasks. Cycle stealing harnesses the available workstations by supplying them with work and receiving produced results [22]. While our proposed resource stealing shares similar motivations, it is applied to the resources located on the same node and cross-node load balancing is enforced by central Hadoop scheduler.

Speculative execution has been applied to various areas. Branch predictors predict which branch a conditional jump will go to and speculatively execute the instructions before the evaluation of branch condition completes [23]. For a critical task which many other tasks depend on directly or transitively, task duplication, which redundantly executes the task at multiple places, has been proposed to reduce communication cost [24]. In MapReduce, speculative execution is used for both fault tolerance and performance improvement [2]. To improve MapReduce in heterogeneous environments, Longest Approximate Time to End (LATE) chooses the tasks that hurt the response time most to speculate and schedules them to fast node [5]. In addition LATE caps the number of speculative tasks. Our proposed Benefit Aware Speculative Execution goes one step further by reducing the number of useless speculative tasks.

Prefetching and pre-shuffling are proposed in [12] to increase the data locality in Hadoop. Intra-block prefetching prefetches data that will be processed subsequently by running map tasks. Intra-block prefetching prefetches whole data chunks to nodes where map tasks are expected to run. They maximize the overlap between computation and data IO to reduce job execution time. Pre-shuffling reduces the amount of shuffled data by scheduling map tasks close to future reduce tasks which intermediate data will be shuffled to. Although the authors did not mention heterogeneity, prefetching can potentially be used to “smooth out” the variation in network bandwidth. Our study explicitly considers network heterogeneity.

# Our Approaches

## MapReduce Background

When a task tracker reports that it has available map slots, the scheduler needs to decide which waiting task will be scheduled there. Tasks with input data stored on the node are scheduled immediately.

## Resource Stealing

As we introduced in section I, in Hadoop each worker node comprises a user-configurable number of map and reduce slots to which tasks are assigned. You can imagine that a portion of underlying resources are reserved for each slot, and resource usage is optimal when all slots are used for each node. Whenever a task is scheduled and run, the corresponding share of resources is used. By default, each node has two map slots and two reduce slots. We found the default settings are too conservative and make Hadoop not able to fully utilize the resources in our clusters. So they are changed to fall between 1x – 2x the number of cores, which is a best practice recommended by Hadoop developers.

Even if map and reduce slots are configured optimally, the resource usage of the whole system is optimal only when all slots are used simultaneously. Usually clusters are neither idle nor fully loaded. According to the collected usage data of a thousand-node Google production cluster, CPU utilization is between 0% and 50% most of the time [25]. Applying this fact to Hadoop, we can conclude that a significant portion of slots are left idle during off-peak hours. We aim to solve the issue that how to utilize the available resources to accelerate the execution of tasks.

We propose *resource stealing* which is illustrated in Fig. 1. It shows how resource stealing can improve resource utilization compared to native Hadoop. In Fig. 1(a), node *N1* has four task slots among which two slots are occupied with running tasks and the other two sit idle. Vanilla Hadoop leaves idle slots unutilized unless there are new tasks to fill them. Fig. 1(b) shows how resource stealing can alleviate the issue. For each of tasks *T1* and *T2*, a new task is created dynamically so that the total number of tasks becomes equal to the number of slots. Those newly created tasks can utilize the resources “reserved” for idle slots *A3* and *A4*. Please note that slots *A3* and *A4* are still idle. Each original task and its newly created tasks process the input data concurrently. In Fig. 1(c), two new tasks *T3* and *T4* are scheduled to node *N1* by job tracker. To avoid severe resource contention, two running tasks are terminated, thereby handing back the stolen resources to the newly assigned tasks.

We call the portion of unutilized resources *residual resources*. The next issue we investigate is how to allocate residual resources to running tasks in the system. The allocation policies can range from simple to complex in their collection and use of system state information. The policies we came up with are summarized in Table I.

1. Resource Allocation Policies

|  |  |
| --- | --- |
| Strategy | Description |
| Even | Evenly allocate residual resource to tasks |
| First-Come-Most | The task that starts earliest is given residual resource. |
| Shortest-Time-Left-Most | The task that will complete soonest is given residual resource. |
| Longest-Time-Left-Most | The task that will complete latest is given residual resource. |
| Speculative-Task-Most | Speculative tasks are given residual resource. |

**Even**: This policy evenly allocates residual resources to running tasks. This policy is inherently stable because it does not rely on the collection or prediction of system state and thus not impacted by the information inaccuracy.

**First-Come-Most** (FCM): The tasks with earliest start time are given residual resources. This policy tries to enforce the order in which jobs are submitted to the system (in a FIFO manner).

**Shortest-Time-Left-Most** (STLM): The task that is expected to complete earliest is given residual resources. The motivation is to make way for long tasks by letting tasks that are close to completion complete as soon as possible.

**Longest-Time-Left-Most** (LTLM): The task that is expected to complete latest is given residual resources.

Policies STLM and LTLM require the prediction of remaining execution time of running tasks. We adopt the approach used in [5] which is shown in (1) and (2).





The policy Even is simple in the sense that it does not require system state information. The fact that this policy is extremely simple does not necessarily indicate it will perform significantly worse than other more sophisticated policies. To evaluate the effectiveness of these policies in real clusters is part of our future work.



(a) Native Hadoop scheduling



(b) Steal resources when there are idle slots



(c) Hand back resources when new tasks are assigned

1. Native Hadoop vs. Resource stealing

## Benefit Aware Speculative Execution

Speculative execution is adopted by Hadoop as a fault-tolerance mechanism. The job tracker keeps track of the progresses of all running tasks. Whenever a task is found to be unusually slow compared with peer tasks, a *speculative task* is created and launched by the job tracker to process the same input data. The tasks whose progress rates are one standard deviation lower than the mean of all tasks are deemed to straggler tasks. So Hadoop does not consider which of the speculated and speculative tasks will complete first. Consider the scenario where there are two running tasks *T1* and *T2*. *T1* progresses slow with rate 1 but its progress is 90%; *T2* progresses fast with rate 5 and its progress is 50%. With default policy, Hadoop will launch a speculative task *T1’* for *T1*. We assume *T1’* progresses with rate 5. By doing simple calculation, we can find that *T1* completes earlier than *T1’* although *T1* progresses much slower. The reason is *T1* is close completion when it is speculated.

We propose Benefit Aware Speculative Execution (BASE) to resolve the issue. The remaining execution time of running tasks is calculated using (1) and (2). The expected execution time of speculative tasks is estimated using historical information. If a speculative task *T’* is assigned to a node *N*, its estimated execution time is the harmonic mean of the duration of the completed tasks that belong to the same job and ran on node *N*. If the job does not have any task that completed on node *N*, the harmonic mean of all tasks of the job is used. Basically, we use the historical execution time of completed tasks to predict how long speculative tasks will run. We choose to adopt harmonic mean because the average of task progress rates is desired.

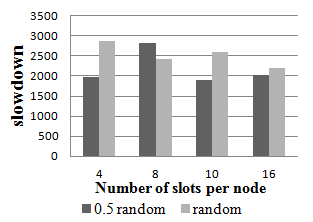
Part of our future work is to investigate the effectiveness of BASE by conducting intensive experiments on real clusters.

## Heterogeneity Aware Scheduling

As we discussed before, clusters are not always homogeneous, and there are situations where heterogeneity is inevitable. In hierarchical MapReduce [10], multiple local clusters, which are administrated under different domains and may even be geographically scattered, are unified to form a single MapReduce cluster that can offer more processing capability than any of the participating cluster. One consequence is the heterogeneity of network – inter-cluster bandwidth is usually dramatically different from intra-cluster bandwidth.

We took another approach to build a unified Hadoop cluster across multiple physical clusters by building virtual network overlay. ViNe [9] was used to create a virtual network environment that supports bi-directional communication between any pair of nodes. From the perspective of applications, ViNe is transparent and thus indistinguishable from physical networks in functionalities. However, bandwidth and latency among nodes still depend upon physical network topology. In our experiments, several FutureGrid clusters were connected using ViNe. Inter-cluster bandwidth is set to 1Mbps – 10Mbps while intra-cluster bandwidth is 100Mbps – 1Gbps. Apparently the network environment is drastically heterogeneous. We deployed Hadoop on top of ViNe without modification and conducted a series of tests to evaluate performance. The scenario where data locality is 100% was chosen as the reference case. Random scheduler was developed with the support of configurable *randomness*. Randomness 0.5 and 1 mean half of tasks and all tasks are randomly scheduled respectively. We ran an IO intensive application *linecount* which counts the number of lines contained in input data. The computation in *linecount* is trivial and data IO dominates the overall execution. The result is shown in Fig. 2. The performance degrades 2000 – 3000 times. The reason is that some tasks lost data locality and needed to fetch input data from nodes located in another cluster so that they greatly lag behind other data-local tasks.

To alleviate the performance degradation, we propose network heterogeneity aware scheduling algorithms. Firstly, network bandwidth between any pair of hosts is maintained and future network performance is estimated. Network Weather Service [15] fits this purpose which can collect real-time network bandwidth information without injecting overwhelming number of probing packets into network and forecast future performance.



1. Inefficiency in the face of heterogeneous network

Firstly, we define some useful symbols. If task *Ti* is assigned to node *Nj*, *DSi* denotes the size of input data of task *i*; *DTij* denotes the data transfer time; *PTij* is the computation time; *ETij* denotes the execution time; *ATj* denotes the time when node *Nj* will become available; and *CTij* denotes the wall-clock completion time. Their relationship is shown in (3), (4) and (5).







### Scheduling of Map Tasks

If there are available slots and none of waiting tasks can achieve data locality, we get into the dilemma of scheduling non-local tasks immediately or delaying the scheduling with the hope to achieve better data locality in the subsequent scheduling. Delay scheduling [13] is demonstrated to be able to improve data locality in a system where most of jobs are small. However, that approach has a couple of issues. Firstly, for systems with different workload (e.g. many large jobs), delay scheduling may not work well. Secondly, the length of delay interval is specified by users, and the optimal setting is difficult to find for heterogeneous environments and may change with the change of system state (e.g. peak hours vs. off-peak hours).

We propose a more adaptive approach which reacts to the change of real-time system state information. Given task *Ti* and node *Nj*, the expected completion time of *Ti* on *Nj* is calculated using (3), (4) and (5). The node that yields the earliest expected completion time for a task is called the *preferred node*, formulated in (6). If a task is scheduled to its preferred node immediately, smallest completion time is achieved. The set of tasks whose preferred node is *Nj* is called the *candidate task set* for *Nj* and denoted by *Cj*. If *Cj* contains multiple tasks, the scheduler needs to choose one of them. To find the optimal solution is NP-hard [17]. We propose two heuristics to find approximately good solutions. The first heuristic is to choose the task with minimum expected completion time among *Cj*, shown in (7). This heuristic changes the availability status by the least amount and is expected to yield high throughput measured by the number of tasks processed per time unit on average. However, long tasks may get starved and priority boosting can be used to avoid starvation. The second heuristic is to choose the task with maximum expected completion time among *Cj*, shown in (8). This heuristic schedules long running tasks early so that they will not slow down the overall job execution. Neither of the heuristics is expected to perform consistently better than the other. We will evaluate the relative merits of those two heuristics for different applications in the future.



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### Shuffling and Scheduling of Reduce Tasks

Each map tasks generates intermediate key/value pairs which are shuffled to reduce tasks. The only constraint of the shuffling process is that key/value pairs with identical keys must be sent to and processed by the same reduce task. This is needed to guarantee the correct semantics of MapReduce model. For each job, the distribution of intermediate key/value pairs among all nodes is formulated as a matrix shown in Fig. 3. Set {*K1, K2, …, Kn*} contains all unique keys generated by map tasks. Set {*N1, N2, …, Nm*} contains all nodes in the system. *Vij* is the number of key/value pairs that have key *Kj* and are generated by map tasks executed on node *Ni*. If no map task runs on node *Ni* or map tasks running on *Ni* do not generate key/value pairs with key being *Kj*, *Vij* is 0. To find the optimal way to schedule shuffling, we need to (i) choose the nodes where reduce tasks will run; (ii) figure out how to distribute intermediate data to reduce tasks. Ibrahim et al. proposed a heuristic algorithm to balance the amount of shuffled data and fair distribution of intermediate data on reduce nodes [19]. However, they implicitly assume that the network connection between map tasks and reduce tasks are homogeneous and thus only consider the size of shuffled data. Handling network heterogeneity is an integral part of our study.

We propose a simple heuristic, which will be refined in future work, to decide to which node a reduce task should be scheduled. Given a reduce task that needs to fetch map output from a set of nodes, we select the node which yields the minimum sum of data shuffling time and computation time. The execution of a reduce task cannot start until all data that are partitioned to it are fetched. So the slowest data fetching determines the overall shuffling time. Because pairwise bandwidth information is maintained for all nodes and the amount of shuffled data is known after intermediate output is generated, we can calculate the data shuffling time for all nodes where the reduce task under consideration can run. Computation time can be estimated based on historical data if possible. If no historical data is available, sample run or user hints are need to provide approximately accurate estimation. In heterogeneous environments, we expect this heuristic to substantially outperform native Hadoop scheduling which blindly schedules reduce tasks.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **K1** | **K2** | **K3** | **…** | **Kn** |
| **N1** | V11 | V12 | V13 | … | V1n |
| **N2** | V21 | … | … | … | … |
| **N3** | V31 | … | … | … | … |
| **…** | … | … | … | … | … |
| **Nm** | Vm1 | … | … | … | Vmn |

1. Key ditribution of intermediate data on map side

### Data Replication

According to a study [20], over 50% of data accesses take place 1 minute after its creation. During that short period, all replicas may not be fully created so that the data locality of subsequent MapReduce job execution will degrade. By default, HDFS maintains three replicas among which one replica is stored on the local rack and the other two are stored on a remote rack. This design reflects the philosophy “do not put all eggs in one basket” and thus has emphasis on data availability. Beyond these constraints, HDFS does not apply any optimization. One improvement we propose is that replicas should be quickly created by choosing the nodes with maximum interconnection throughput without violating the availability guarantee. In an environment with drastically heterogeneous network, full replication may take long time. Data availability can be violated temporarily by fully replicating data on nodes close to each other first and propagating it to remote rack in background asynchronously. This can increase the data locality of successively submitted MapReduce jobs. Whenever data copies on a remote rack are created, the excessive replicas on nearby nodes are removed. Also the order of replica propagation can be tuned to speed up replication process.

# Conclusion

[TO BE ADDED]

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