Job Scheduling in Cluster Computing: A Student Project

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Abstract

Cluster computing has become widespread by utilizing *COTS* (Commercial-Off-The-Shelf) PCs, a high-speed network, and Linux operating system. This simple configuration of multiprocessor system can provide an excellent environment for student projects in courses such as Operating Systems, Data Communication, Distributed Programming, just to name a few. In this paper we describe an ongoing project focused on job scheduling for a cluster of processors.

Job scheduling on distributed-memory parallel systems has always been a challenge. Traditional measurement factors such as job length to allocate the requested resources does not suffice. Other factors such as communication delays and synchronization overhead which are normally in the user domain, could turn out as key issues for multiprocessors' utilization. As a result, utilization of each processor in a distributed-memory parallel system may end up comparatively lower than a single processor system. Consequently, performance of the entire system may degenerate and user jobs risk waiting long in the queue before getting the requested number of processors. This project is divided into several phases. In each phase, one to three students investigate how to minimize waiting time of the jobs in the queue while allowing other projects have a scheduling policy that suits their experiment and research. This paper reports the results of the first group which focuses on variable partitioning scheme. When resources for the highest priority job are not available, then the lower priority jobs are allowed to acquire the available resources. This paper investigates and evaluates variable partitioning schemes for job scheduling on distributed-memory parallel systems.

1. Introduction

High Performance Computing (HPC) nowadays can easily be achieved with clusters of PCs connected through a high-speed switch on a high-speed network. Such a tool provides excellent opportunities to explore numerous projects for educational as well as research purposes in computer science. For this reason, we have installed a Beowulf Cluster[1, 2, 3, 4, 5] with 16 compute nodes in our computing lab in order to engage our students with exciting projects in courses such

as Operating Systems, Data Communication, Parallel Programming, Distributed Simulation, Algorithms, Data Base Management, and several others.

The Message-Passing Interface (MPI) library[4, 6] and a fairly simple resource manager transform the cluster into a distributed-memory parallel system. The job scheduler module of the parallel machine has a vital roll on the utilization of the distributed resources. This project aims at studying feasible approaches to job scheduling on the parallel system. Further, it targets improving the overall performance of our Beowulf system by modifying the existing scheduler. This paper reports the first phase of the project.

Scheduling of parallel applications on distributed-memory parallel system often occurs by granting each job the requested number of processors for its entire run time. This approach is referred to as variable partitioning which frequently utilizes non-preemptive batch scheduling[7]. That is, once a job acquires the requested number of compute nodes, it continues until the job completes or some error forces the system to abort the faulty job. Consequently, most parallel programs restrict their I/O bursts to the beginning and to the end of the program in order to avoid significant performance penalties.

Another scheduling approach is dynamic partitioning. This scheme suggests partial allocation of requested nodes for a parallel job. Even though this approach could help some jobs to start processing their task, the scheduling method is not widely used because of practical limitations. For example, consider a job where it needs all its requested nodes in order to start processing the parallel tasks. In this case, allocating fewer compute nodes than the requested numbers will clearly contributes to the system deficiencies since the allocated nodes are not going to be used until this job receives the rest of its requested nodes.

In this paper we focus on the variable partitioning schemes[8, 9, 10]. The simplest method is to prioritize waiting jobs based on a preset policy, such as the arrival time, the job length, and the estimated wall-clock time. When resources for the high priority job are not available or there are no more higher priority jobs in the queue, then the lower priority jobs are allowed to acquire the available computing nodes. This approach seems to have the advantage of better utilizing the system resources. However, a closer look reveals several pitfalls of this method. Examples include: jobs could starve; no guarantee can be made to the user as to when a job is likely to be executed; and the high priority jobs may risk to starve.

The project aims at investigating potential deficiencies and tries to provide alternative solutions for variable partitioning schemes. The goal is to improve our existing scheduler in our clustered-base parallel system. To overcome some of the drawbacks mentioned above, this paper selects approaches such as reservations for jobs and backfilling technique to increase system utilization.

The three scheduling algorithms in the framework of variable partitioning that we have focused on are *Non-FCFS*, *Aggressive Backfilling*, and *Conservative Backfilling*[8, 9]. In Sections 2, 3, and 4 we briefly describe each of these algorithms. In Section 5 we discuss the implementation issues. In Section 6 the simulation results are provided. Finally, the future work and the concluding remarks are presented in Sections 7 and 8 respectively.

2. Non-FCFS Scheduling Algorithm

One simple scheme in variable partitioning is to prioritize the jobs in the waiting queue based on a preset policy such as the requested number of processors or the estimated wall-clock time in addition to the arrival time. The resource manager then tries to allocate compute nodes to the waiting jobs in the order inserted in the queue. When resources for the job at the head of the line with the highest priority are not available then other jobs in the queue with the lower priority can obtain the available resources. This approach has three pitfalls; jobs can starve; no guarantee is made to the user as to when a job is likely to be executed; and there is no real priority since the high priority jobs can starve. However, most schedulers that use this simple approach employ a simple starvation prevention policy by enforcing an upper bound for waiting. These systems normally use two priority levels and a certain time limit, for example 12 or 24 hours, for a job to be in the Non-FCFS waiting queue. After this time limit the priority is increased and the FCFS policy is enforced. Another way to prevent the starvation would be to allow only a certain number of lower priority jobs to jump over a queued job. The OpenPBS Torque[2], which is incorporated in numerous clusters, employs such a policy. It is important to mention that starvation can be prevented at the cost of utilization.

Example of Job Scheduling Using Non-FCFS Scheduling Algorithm

Consider a system with 16 nodes and a 24 hour wait limit to prevent starvation. Table 1 provides an example of a set of jobs in the system and Figure 1 illustrates a snapshot of the scheduler.

Table 1: Status of current jobs in the system before 24 hours wait limit

Job ID	Nodes Needed	Time unit	Status
Job1	6	3	running
Job2	6	2	running
Job3	12	1	queued less than 24 hours
Job4	5	3	new arrival – jumps over Job3
Job5	4	2	new arrival – jumps over Job3

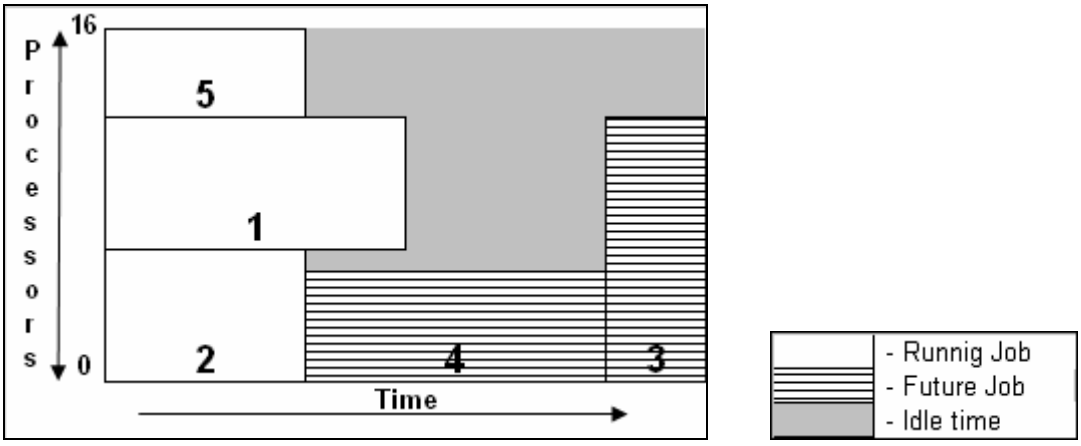


Figure 1: Non-FCFS without wait limit

Selection of the jobs for execution are based on the number of requested processors. When there is a tie between the requests, then the jobs' execution time is considered. As illustrated in Table 1, Job1 and Job2 are running. Job1 has 3 time units to complete and Job2 has 2 time units to finish its task. Job3 is queued because there are not enough nodes available. Assume that Job4 and Job5 have just arrived in the system. Job5 gets immediate allocation since there are 4 free nodes left idle in the system. When Job2 terminates, Job4 will be able to run. As illustrated, the two new jobs move ahead of the waiting job3 and acquire the resources. The fairness is poor in this scheme. Further, if more new small jobs arrive, then the large jobs will starve assuming there was no upper bound for waiting.

Now, consider the same example, but assume that Job3 has been queued in the system more than 24 hours, as illustrated in Table 2. Figure 2 demonstrates the snapshot of the system when waiting time exceeds the 24 hour limit.

Table 2: Status of current jobs in the system after 24 hours wait limit

Job ID	Nodes Needed	Time unit	Status
Job1	6	3	running
Job2	6	2	running
Job3	12	1	queued more than 24 hours
Job4	5	3	new arrival – queued
Job5	4	2	new arrival – queued

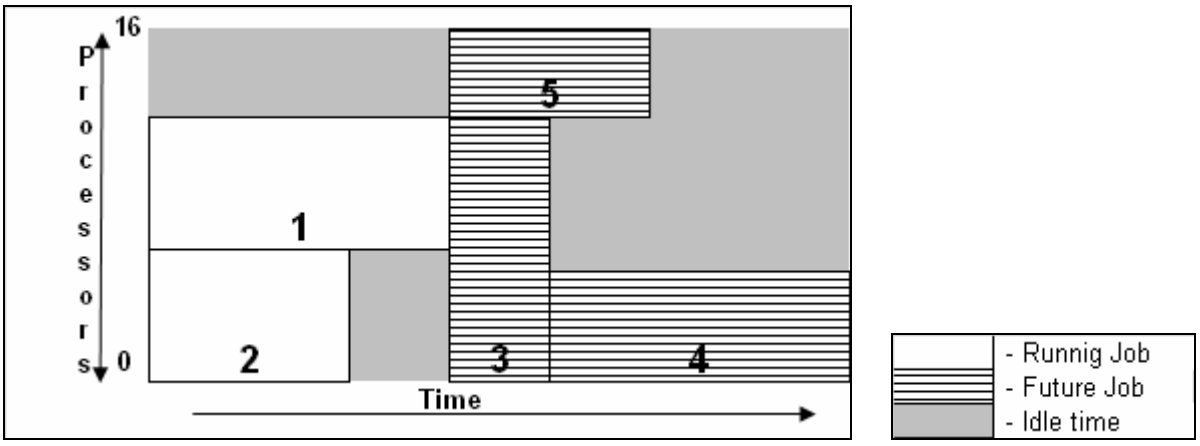


Figure 2: Illustration of waiting time limit on Non-FCFS

Figure 2 shows arrival of Job4 and Job5 in the system. Job3 has already been waiting for more than 24 hours exceeding the wait time limit. The scheduler inserts Job4 and Job5 after Job3 in the queue. Even though allocation of nodes for Job5 would not delay the execution of Job3, the scheduler just queues all the incoming jobs in the arriving order until the starved job (i.e. Job3) has acquired the requested resources. This simple technique would clearly lead to a low system utilization, however, it will prevent starvation.

3. Aggressive Backfilling Algorithm

This scheme requires the user to provide an estimated runtime in order to overcome the deficiency problem of Non-FCFS algorithm. With the additional information this algorithm makes a first reservation scheduled for the queued job. Then, it scans through the waiting queue to find a smaller job which can be run ahead of the reserved job without imposing any further delay for the reserved jobs. This algorithm solves the starvation problem as well as improving system utilization by using backfilling technique. That is, a job that does not risk to delay the reserved job is allowed to execute prior to the reserved job. The drawback of this technique is that it cannot make any guarantee about the response time of the user job at the time of job submission. Further, the user estimation may not be correct. Early terminations and exceeding the estimated runtime have to be dealt with. Early termination may not cause serious problems whereas exceeding the estimated runtime may generate numerous problems.

Another issue is how to handle high priority job arrival. If a new job has a higher priority than the reserved job in the queue, then the system has two choices: either preempt the existing reservation and reschedule for the new job, or make another reservation for the new job immediately after the current reservation without preempting it. There is no simple solution for this case. Choosing the former may result in starvation again as the higher priority jobs may continue to arrive. Choosing the latter approach is not fair for the high priority jobs as their requests could be delayed and hence risking not be scheduled on time.

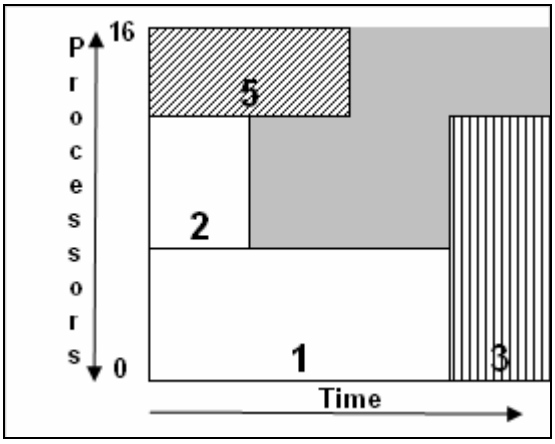
Example of Job Scheduling using Aggressive Backfilling Algorithm

Consider again the system of 16 nodes. Table 3 shows a set of jobs in the system ordered based on their arrival.

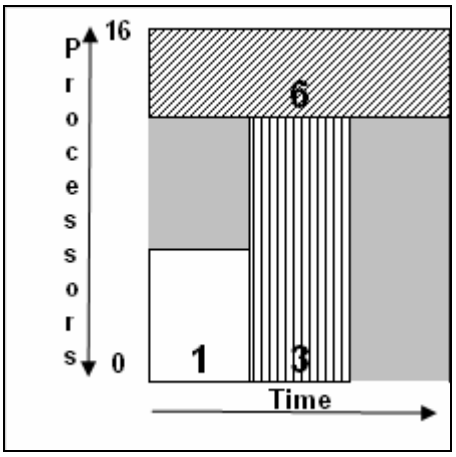
Table 3: Status of current jobs in the system for a backfilled queue

Job ID	Nodes Needed	Time unit	Status
Job1	6	3	running
Job2	6	1	running
Job3	12	1	queued
Job4	14	1	queued
Job5	4	2	new arrival – backfilled
Job6	4	3	new arrival – backfilled

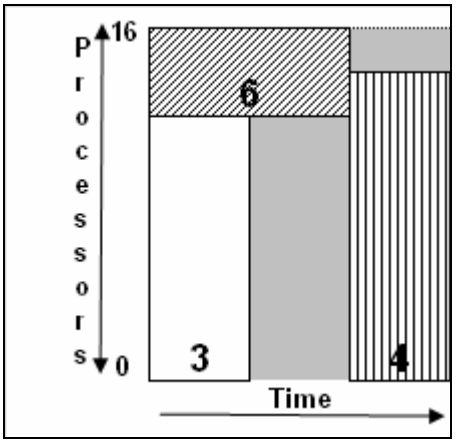
Job3 is the first queued job so it has a reservation in the system. Job4 is queued behind Job3. When Job5 and Job6 arrive, the system attempts to backfill the jobs. Job5 can be backfilled and scheduled immediately. Job6 is queued. This case is shown in Figure 3a for the system after arrival of Job4 and Job5. When Job2 has terminated, its 6 nodes become available for 2 time units before Job1 terminates. Since Job6 requires 3 time units the system cannot schedule it. Job6 is scheduled after the termination of Job5. This case is demonstrated in Figure 3b, after Job5 has terminated. At time 3, Job3 starts its execution. Now that Job3 has been removed from the ready queue, Job4 becomes the first job in the queue so the system makes a reservation for it. Figure 3c shows snapshot of the system after Job3 starts execution. Figure 3d illustrates the overall snapshot. This example also demonstrates that the queued jobs (except the first one)



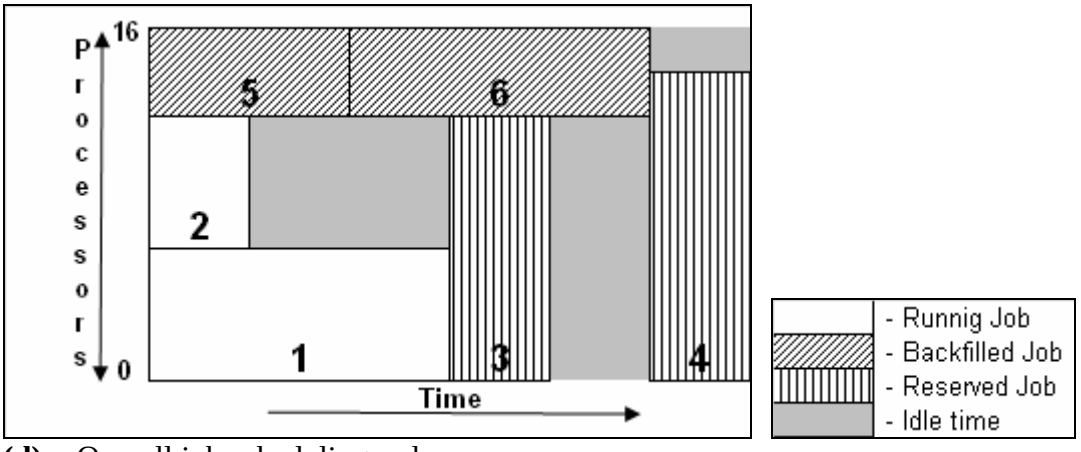
(a): System after the arrival of Job4 & Job5



(b): System after Job5 terminated



(c): System after Job3 starts execution



(d): Overall job scheduling order

Figure 3: Illustration of the Aggressive Backfilling algorithm based on their arrival

can be delayed because of backfilling. This is a drawback which needs to be further analyzed when such a scheme is used.

4. Conservative Backfilling Algorithm

In Aggressive Backfilling algorithm only one reservation is made for the job in front of the queue. This could delay unnecessarily execution of a job even though enough resources may exist to allocate for that job. The situation can be improved by allowing the scheduler to take a further step in backfilling. In Conservative Backfilling all jobs get their own reservations when they are submitted. Therefore this algorithm can guarantee execution time when a new job is submitted. However, the algorithm works only for the First-Come First-Served (FCFS) priority policy. As jobs arrive in the system, the scheduler makes reservation for them and provides a guaranteed execution time for each arriving job based on the estimated times provided by the users. When a job with higher priority arrives, the system cannot reshuffle its current reservations to provide the higher priority job a reservation ahead of the existing ones for the previous queued jobs. The reason is simple since any rearrangement would lead to not executing the existing jobs at their guaranteed times. A system using Conservative Backfilling with guaranteed execution time can only have FCFS priority.

Early job terminations lead to vacancies in the system. In order to make efficient use of these vacancies the algorithm must reschedule the existing reservations for queued jobs. However, keeping in mind that the reservations cannot be reshuffled as that may lead to not executing the jobs at their guaranteed times, we can only compress the existing reservation schedule so that it runs at an earlier time. This however may lead to an unfair scheduling.

Example of Job Scheduling Using Conservative Backfilling Algorithm

Table 4 shows a set of jobs in the system. As is the case for Conservative Backfilling, all jobs in Table 4 that are queued have a reservation. Job3 has its reservation after the termination of Job1. Job4 has its reservation after the termination of Job3. The system backfills Job5 as it does not delay the jobs that have reservation. Since Job6 cannot be backfilled, the system makes a reservation for Job6 after the termination of Job4. The snapshot of the system is illustrated in Figure 4.

Table 4: Status of current jobs for an improved backfilled queue

Job ID	Nodes Needed	Time unit	Status
Job1	6	3	running
Job2	6	1	running
Job3	12	1	queued
Job4	14	1	queued
Job5	4	2	new arrival – backfilled
Job6	4	3	new arrival – queued

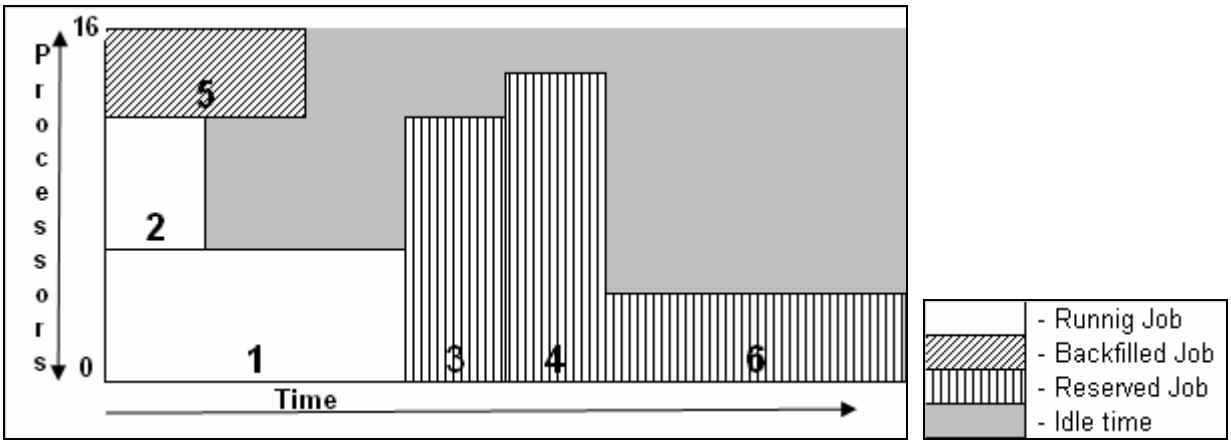


Figure 4: Snapshot of a Conservative Backfilling algorithm for jobs in Table 4

5. Implementation Issues

We have simulated the three algorithms discussed above. This section clarifies some issues related to the implementation. More details can be found in the project technical report[10].

In a simulation study, the quality of input data plays a vital role in determining the significance of the simulation results. To safeguard our simulation, we looked at some observations made by researchers in the field of distributed-memory parallel systems[8, 9]. These studies indicate small jobs (i.e. requiring few compute nodes) are more common than large ones (i.e. requiring large number of compute nodes). Further, jobs with short runtimes are more common than jobs with long runtimes. Based on these observations, we generated the input data for 16 compute nodes. The main characteristics of the input data are:

1. 30% small jobs: 1-5 nodes, 40% medium jobs: 6-10 nodes, 30% large jobs: 11-16 nodes.
2. 80% of jobs with simulated runtime between 90 seconds and 9 hours, 20% of jobs with simulated runtime between 9 hours and 12 hours. We use a minimum of 90 seconds runtime which also includes overhead of parallel execution.
3. A simulated runtime may be anywhere between 10% to 100% of the estimated runtime.

The input data is kept in a workload file and is transferred to the job profiles in the simulator. The supplied information for each job is: process-ID, number of requested nodes, estimated runtime in seconds, simulated runtime in seconds, and arrival time in seconds. The arrival time is used to order jobs in the ready queue prior to their scheduling or reservation of nodes.

For the Non-FCFS algorithm, a 24 hour limit is used to determine starved jobs in the system. The backfilling algorithms employ the first-fit technique. This method looks for the first queued job that can be used for backfilling. It would be interesting to investigate whether other methods such as best-fit could have any impact to the performance.

The simulator utilizes two queues: event queue and ready queue. The event queue keeps track of the arrivals and departures of jobs and generates events for the respective type. The simulation clock advances when the system processes an event. The ready queue on the other hand holds all arrival jobs for which their requested nodes are not yet granted. This queue is used by the

algorithms to schedule the jobs. Once a job arrives in the system, its profile will be moved from the event queue to the ready queue. When a job is scheduled, its profile will be moved back from the ready queue to the event queue. A departure event will remove the profile of the terminated job. Both queues are implemented as vectors.

6. Simulation Results

Table 5 summarizes results of the simulation. The workload file that was used for the input data was generated by using the specifications described in Section 5. To illustrate performance degradation caused by early job terminations (that is before their estimated times), we assume the simulated runtime of a job be the perfect estimation time. Table 6 summarize the results of the second simulation. All illustrated times in the tables are simulated times and are in seconds.

Table 5: Results of simulation for generated job mix

Algorithm Name	Average Execution Time (sec)	Average Wait Time	% System Utilization	Highest Response Time
Non-FCFS	308.37	101.04	85.49	296.36
Aggressive Backfilling	301.37	107.52	87.48	284.88
Conservative Backfilling	302.72	107.24	87.09	290.55

Table 6: Results of simulation for jobs submitting with prefect estimate

Algorithm Name	Average Execution Time (sec)	Average Wait Time	% System Utilization	Highest Response Time
Aggressive Backfilling	764.38	262.55	89.36	747.08
Conservative Backfilling	765.75	280.52	89.20	743.59

We also used a set of input data which has been used in a simulation carried out at Ames Laboratory[7]. For this set of data, the following two tables summarize the results of our simulation.

Table 7: Results for the simulation job mix available using different input data

Algorithm Name	Average Execution Time (sec)	Average Wait Time	% System Utilization	Highest Response Time
Non-FCFS	68.55	19.92	77.99	62.73
Aggressive Backfilling	65	20.08	82.25	59.18
Conservative Backfilling	65.17	20.14	82.04	59.35

Table 8: Results for the simulation job mix using different input data with prefect estimate

Algorithm Name	Average Execution Time (sec)	Average Wait Time	% System Utilization	Highest Response Time
Aggressive Backfilling	80.02	25.23	83.14	74.14
Conservative Backfilling	79.17	25.42	84.04	73.29

The results shown in Table 5 through Table 8 depict that for the Backfilling algorithms utilization is better than the Non-FCFS algorithm. Both Aggressive Backfilling and Conservative Backfilling have almost the same utilization. However, for both algorithms the average wait time is higher than the one from Non-FCFS. The highest response time (i.e. the job that waited the most in the system) is lowest in the Aggressive Backfilling algorithm.

If we consider the case when the arrival job has a perfect estimate, then the utilization becomes the same in both Aggressive Backfilling and Conservative Backfilling algorithms. With perfect estimated runtime, utilization increases marginally. For example, in the case of Conservative Backfilling, utilization increases by 2% from 87.09% to 89.20% (see Table 5 and Table 6).

The simulation results also indicate that more jobs are executed in their order of arrival for both Backfilling algorithms, but that is not the case with Non-FCFS where many jobs that arrived late could finish ahead of the jobs that arrived before them. This shows that the Aggressive Backfilling and the Conservative Backfilling algorithms follow the priority policy more closely than the Non-FCFS algorithm. Furthermore, the simulation results show that the Backfilling algorithms are able to distribute the wait time among the jobs more evenly instead of just making a few jobs wait indefinitely.

7. Future Work

For the next phases, we would like to expand the simulation using variable nodes and launch numerous actual jobs. These jobs could be managed by a mixture of simulated and experimental scheduler in order to provide us with better measured data to further study and analyzing them. We would like also to study additional scheduling algorithms and provide experimental models for students to use in courses such as Operation Systems.

One job scheduling that is of high research interest is dynamic partitioning. In this approach, a parallel job needs not always get its requested number of processors for its entire run time. Two such techniques method that are still widely under research are Dynamic Co-scheduling and Gang scheduling[11, 12]. Both of these approaches try to allocate more than one process to a node and time share that node between processes. The difference is that Gang scheduling is similar to round robin scheduling in which the system switches to a new sets of jobs after a fixed time quantum. Dynamic co-scheduling, on the other hand, uses message arrivals to trigger execution. The Dynamic co-scheduling can start a job even when all its requested nodes are not available. Simulation can be done on these two approaches to study their performance.

Utilization of compute nodes tends to decrease in very large parallel systems. In our future work, we can model workloads for very large systems and study performance of various scheduling algorithms on such systems.

Moab Workload Manager is a cluster scheduler that is compatible with the Torque; an OpenPBS based cluster resource manager[7]. The Moab scheduler has several configuration settings which can provide the administrator with a greater flexibility in changing the scheduling algorithm to suit some specific needs of the system. Moab scheduler can be configured to work as both an Aggressive Backfilling scheduler and a Conservative Backfilling scheduler. In future, we would like to install the Moab scheduler in Beowulf system and fine-tune it to suit our needs.

8. Concluding Remarks

The first phase of this project has provided significant insight on how the current work could continue in several directions. Our primary objectives are still valid. That is, providing exciting projects for students in a multiprocessors environment, as well as improving the current job scheduler for our Beowulf cluster. The preliminary results of this study confirm that cluster scheduling could furnish several interesting student projects for educational purposes, as well as providing several challenging topics in the cutting edge research.

Furthermore, our simulation results advocate that the Backfilling algorithms produce better utilization than Non-FCFS algorithm. The average wait time for a job, however, is higher in the Backfilling algorithms than the one in the Non-FCFS algorithm. This could be nonetheless a result of distributing the wait time among many jobs. Our future work will pursue to better answer this issue. The simulation also shows that the two Backfilling algorithms perform almost the same. Between the two, Aggressive Backfilling is less complex and more flexible when regarding input to set the priority policy. The Conservative Backfilling algorithm can be used in systems that would desire to have its scheduling policy set strictly based on FCFS. Conservative Backfilling will be able to give the users a guaranteed response time.

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