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Bi-objective workflow scheduling of the energy consumption and reliability in heterogeneous computing systems

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ABSTRACT

Recent studies focus primarily on low energy consumption or execution time for task scheduling with precedence constraints in heterogeneous computing systems. In most cases, system reliability is more important than other performance metrics. In addition, energy consumption and system reliability are two conflicting objectives. A novel bi-objective genetic algorithm (BOGA) to pursue low energy consumption and high system reliability for workflow scheduling is presented in this paper. The proposed BOGA offers users more flexibility when jobs are submitted to a data center. On the basis of real-world and randomly generated application graphs, numerous experiments are conducted to evaluate the performance of the proposed algorithm. In comparison with excellent algorithms such as multi-objective heterogeneous earliest finish time (MOHEFT) and multi-objective differential evolution (MODE), BOGA performs significantly better in terms of finding the spread of compromise solutions.

1. Introduction

Modern data centers consume a tremendous amount of power and produce a large amount of pollution. The Tianhe-2, a heterogeneous computing system, is one example, which is located at the National Supercomputer Center in Guangzhou (China). It is the worlds fastest supercomputer as of July 13, 2015. The power consumption of Tianhe-2 is 17,808 kW [1]. Assuming that the electricity charge is 1 yuan per kilowatt hour, the electricity cost of Tianhe-2 is approximately 156 million yuan (USD 25 million) per year. In addition, high energy consumption also has a negative effect on system reliability. High-performance heterogeneous computing systems attract the attention of many researchers, who have conducted numerous studies on different service quality of simple objectives based on heterogeneous computing systems; such objectives include minimum completion time, low energy consumption, minimum execution cost, and higher system reliability. Such studies are more challenging when the focus is on more than one objective. Dongarra et al. [9] presented bi-objective scheduling algorithms for optimizing makespan and reliability of heterogeneous systems. They constructed a task graph and transformed a heuristic that targets makespan minimization to a bi-criteria heuristic. Boeres et al. [5] developed an efficient weighted

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bi-objective scheduling algorithm for heterogeneous systems. This study also introduced a classification of the solutions provided by weighted bi-objective schedulers aimed at helping users to adjust the weighting function such that an appropriate solution can be matched in accordance with different needs.

To devise matching and scheduling algorithms that account for both makespan and failure probability and balance them in a parallel application, Doğan and Özgüner [8] explored the bi-objective scheduling algorithms for execution time-reliability trade-off in heterogeneous computing systems. For this purpose, the bi-objective dynamic level scheduling algorithm is presented by modifying an existing scheduling algorithm, the dynamic-level scheduling [24] algorithm. With respect to workflow scheduling in heterogeneous environment, Fard et al. [13] proposed a four-objective case study that comprises makespan, economic cost, energy consumption, and reliability based on ASKALON environment for grid and cloud computing. Jeannot et al. [17] explored the optimization of performance and reliability on heterogeneous parallel systems. For scheduling independent tasks, constrained minimum lambda tau was designed. For scheduling tasks with precedence constraints, a general Pareto front approximation was devised. On the basis of multi-objective swarm algorithms, Arsuaga-Ríos et al. [3] presented the multi-objective artificial bee colony and the multi-objective gravitational search algorithm in search of a bi-objective optimization for both execution time and cost. Durillo et al. [10] proposed a novel multi-objective heterogeneous earliest finish time (MOHEFT) list-based workflow scheduling algorithm, which is an extension of the heterogeneous earliest finish time (HEFT) [26] algorithm. In the beginning of the MOHEFT, high-quality initial populations are generated under the state-of-the-art HEFT strategy. The MOHEFT is capable of computing a set of tradeoff optimal solutions in terms of makespan and energy efficiency.

Bhuiyan et al. [4] devised excellent strategies in deploying wireless sensor networks with fault tolerance for structural health monitoring. Wang et al. [12] proposed a look-ahead genetic algorithm (LAGA) which utilizes reliability-driven reputation to optimize the makespan and the reliability of a workflow application. Xu et al. [31] presented a hybrid chemical reaction optimization scheme for task scheduling on heterogeneous computing systems. Zhang and Li [33] investigated the energy minimization problem for real-time software systems with task execution time following a statistical distribution. Huang et al. [16] presented novel heuristic speculative execution strategies in a cluster that runs Hadoop MapReduce. The non-dominated sorting genetic algorithm (NSGA-II) was presented by Deb et al. [28] in 2002. Zhang et al. [34] developed novel algorithms to maximize system reliability with energy constraint in heterogeneous systems. Xu et al. applied the conventional chemical reaction optimization framework in [30] and used a multiple priority queues genetic algorithm in [32] to address the DAG scheduling problem on heterogeneous computing systems. Given its relatively low time complexity and rapid convergence rate, NSGA-II is used widely in many fields, such as industry, transportation, and finance. In addition, Penmatsa and Chronopoulos designed a load-balanced scheduling strategy for the execution of job flows in heterogeneous-distributed systems on the basis of multi-objective optimization [21,22]. Penmatsa et al. presented a load-balanced scheduling algorithm for the execution of loop-level tasks in grids [23].

However, none of the above studies consider low energy consumption and high system reliability at the same time. These two metrics are essential parts of modern green computing. Modern data centers need to provide a set of solutions with different performance metrics to meet the diverse demands of users, such as high system reliability and low energy consumption in different cases. Hence, the major purpose of this paper is to propose a general approach to solve the bi-objective of low energy consumption and high system reliability on workflow application scheduling in heterogeneous computing systems.

This study addresses the bi-objective optimization problem of high system reliability and low energy consumption for parallel tasks as a combinatorial optimization problem. It includes three nontrivial subproblems, i.e., energy saving, reliability maximizing, and solution selecting. First, appropriate voltage levels are selected for processors so that the schedule length of parallel tasks is acceptable and the total energy consumption is minimal. Second, the selected speed for each parallel task is relatively high so that the total system reliability reaches a high level. Third, as energy saving and system reliability are two conflicting objectives, an effective and efficient solution strategy is devised while selecting the speed and processor for each candidate parallel task.

These problems are efficiently treated to develop an algorithm with an overall good performance. With the adoption of the non-dominated idea and dynamical voltage frequency (DVFS) scaling technology, a novel bi-objective genetic algorithm that aims to achieve low energy consumption and high system reliability is developed.

The major contributions of this paper are listed as follows.

- We show that the problems of minimizing energy consumption and maximizing system reliability under precedence and schedule length constraints are conflicting. A set of non-dominated solutions with different system reliability and energy consumption are provided by BOGA when a user submits a job.
- We develop a class of algorithms to solve the above three nontrivial subproblems. These algorithms are crucial components that constitute BOGA.
- We present an efficient selection strategy that works in the front part of the BOGA loop to determine the non-dominated solutions. The elite individuals are selected as a new population when BOGA finishes each iteration. A fine Pareto front is achieved after the stopping criteria of BOGA are satisfied.
- Through experiments over a large set of randomly generated graphs as well as through the graphs for real-world applications with different characteristics, we prove that the proposed BOGA algorithm outperforms several related multi-objective optimization algorithms in terms of energy consumption and system reliability.