Problem-Oriented Scheduling of Cloud Applications: PO-HEFT Algorithm Case Study

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Abstract - Today we see a significantly increased use of problem-oriented approach to the development of cloud computing environment scheduling algorithms. There are already several such algorithms. However, a lot of these require that the tasks within a single job are independent and do not account for the execution of each task and the volume of data transmitted. We propose a list-based algorithm of problem-oriented planning of execution of applications in a cloud environment that considers the applications' execution profiles. It provides payroll algorithm for the problem-oriented scheduling applications in the cloud environments based on their computing profiles. Scheduling on the basis of lists suggests prioritization of computing tasks and running in blocks to perform according to the obtained priorities. The proposed approach allows us to take into account the costs of the transfer of data between nodes, thereby reducing the total run time of the workflow. The proposed algorithm is based on an algorithm of Heterogeneous Earliest-Finish-Time (HEFT), but contains modifications in calculation of a node level objectives and takes into account the cost of incoming communications of its parent task.

*Keywords* – *scheduling, execution planning, cloud computing, grid computing, HEFT*

# Introduction

Для повышения эффективности распределенных проблемно-ориентированных вычислительных сред, необходимо применение проблемно-ориентированных методов планирования вычислительных задач, использующих информацию о предметной области для прогнозирования вычислительных характеристик задач при планировании и распределении заданий [1].

Особенностью проблемно-ориентированной облачной вычислительной среды является то, что она использует информацию об особенностях классов решаемых задач при планировании и распределении вычислительных ресурсов. Будем требовать, чтобы в рамках проблемно-ориентированной вычислительной среды, для каждого класса задач были определены следующие функции для прогноза процесса выполнения задачи в зависимости от значений входных параметров:

1) функция оценки объема выходных данных при определенных входных параметрах;

2) функция оценки времени выполнения задачи при определенных входных параметрах на машине с указанным вектором характеристик производительности.

Время выполнения функции f на конкретной машине с вектором характеристик производительности ? можно представить в виде оператора, зависящего от вектора входных информационных объектов Iin. К сожалению, невозможно оценить время выполнения функции с идеальной точностью, т.к. вычислительная работа подготовки набора выходных информационных объектов Iout может косвенно зависеть от множества факторов, которые наша модель учесть не может (возможные фоновые процессы, качество предсказания ветвления конкретной версии процессора, объем занятого кэша и др.). Для компенсации данной ошибки, оценку времени выполнения функции можно смоделировать в виде случайной величины, состоящей из ? – детерминированной функции, представляющей зависимость времени выполнения функции f на машине с вектором характеристик производительности ? от вектора входных информационных объектов Iin, и ? – стохастической величины с нулевым математическим ожиданием (M[?]=0), представляющей факторы, не входящие в разрабатываемую модель.

Для оценки времени выполнения задач необходимо обеспечить сбор и хранение статистики запусков по всем классам задач. После каждого запуска задачи в базе данных сохраняется следующая информация: значения параметров запуска, вектор характеристик производительности вычислительной машины, включая количество выделенных процессорных ядер и объем выделенной оперативной памяти, время выполнения и объем сгенерированных выходных данных.

This paper is organized as follows. In section II we present the concept and the basic idea of scheduling applications in cloud environments. In section III we describe the results of the analysis of existing algorithms of resource scheduling. In section IV we describe HEFT and PO-HEFT cloud scheduling algorithms complete with a mathematical task model. In section V we describe the implementation of PO-HEFT algorithm in CloudSim cloud environment simulation package. In section VI we describe the results of benchmarking PO-HEFT against CloudSim's built-in scheduling algorithm. In section VII we summarize the results of our research and give further research directions.

# scheduling applications in cloud environments

Analysis of the main trends in resource scheduling research in distributed problem-oriented environments shows that the theme of the problem-oriented scheduling and load forecasting tasks solution media is an urgent task

Анализ основных направлений исследований в области планирования потоковых приложений в рамках распределенных вычислительных сред показывает, что тема проблемно-ориентированного планирования и решения задач прогнозирования нагрузки сред является актуальной задачей

In the cloud computer data centers is used Holistic Model for Resource Representation in virtualized cloud computing data. This model is designed to represent physical resources, virtual machines, and applications in cloud computing environments. The model can be applied to representcloud applications, VMs, and physical hosts. Each of these entities is described by multiple resources: computing, memory, storage, and networking. The model is scalable, as it does not increase the simulation time and creates a limited memory overhead of less than 10%. A holistic model increases the precision of simulations and enables a number of new simulation scenarios focused on heterogeneity of the hardware resources and virtualization [1].

Computational Intelligence proves to be applicable to multiple resource management problems that exist at all layers of CC [2].

Centers [

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Multiple workflow scheduling strategies with user run time estimates on a Grid

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Одним из наиболее популярных списочных алгоритмов является алгоритм Min-min [Yu J., Buyya R., Ramamohanarao K. Workflow Scheduling Algorithms for Grid Computing. Metaheuristics for Scheduling in Distributed Computing Environments Studies in Computational Intelligence. Springer Berlin Heidelberg. Vol. 146, 2008. P. 173-214]. Главным недостатком списочных алгоритмов является то, что они не анализируют граф задания в целом.

L. B. Sokolinsky and A. V. Shamakina, “Methods of resource management in problem-oriented computing environment,” *Program. Comput. Softw.*, vol. 42, no. 1, pp. 17–26, Jan. 2016.

## Computing environment model

The majority of existing algorithms require that tasks within a single job are independent and do not account for the execution time of each task or the amount of data transmitted. The application is considered to be performed on modern distributed computing systems, and to have a complex structure of the stream, which is a set of ordered tasks related with data dependencies.

We give a formal definition of a task in a distributed computing environment:

A task graph is a labeled weighted directed acyclic graph G=〈T,E,init,fin〉, where T is the set of nodes corresponding to the tasks and E is the set of arcs corresponding to the data streams.

Weight S(e) of arc e defines the amount of data to be transmitted by arc e from the task associated with vertex init(e) to the task associated with vertex fin(e).

One approach to solving the problem is to break the task graph into independent sections. The presence of parallel task blocks, represented in the form of workflow, allows us to immediately use multiple distributed resources to quickly find a solution. When planning task flows, the following criteria must be considered:

* Time to solve a particular task;
* The deployment time of virtual machines. All VM images are stored in the database, and not on on all nodes at once. Image transfer speed in the system is at least equal to the data rate within one group.
* The transmission time of data between nodes in accordance with the network bandwidth. The costs of data transfer can be eliminated by clustering multiple task flow blocks on one resource [10, 12].

The problem is to optimize the distribution of virtual machines on nodes of cloud platform so that the graph solving time is minimal. The problem is reduced to finding sustainable solution between clustering and parallelization for each group, and task is to find the optimal variant of placing workflow at available large number of resources. During our research, we should:

* Analyze existing approaches to cloud workflow scheduling;
* Propose a scheduling algorithm that uses information from previous runs as a heuristic;
* Implement this algorithm in the CloudSim cloud evironment simulation platform;
* Compare this algorithm against existing schedulers within a cloud simulation.

## Restrictions imposed on the computing environment

We assume that in the model of problem-oriented services, the computing environment meets the following conditions.

1. Cloud is a set of nodes connected by a network.
2. The data transfer rate within the same node is infinite.
3. The nodes are combined into groups. We assume that the nodes within the group are connected in the topology of "each-to-each", where a maximum capacity of connections between any two nodes within the same group () is the same and is determined in advance.

C:\Users\Екатерина\Downloads\HEFT.png

Figure 1: The structure of nodes of the cloud platform

1. We assume that the computing nodes belonging to the same group have the same computing power and provide the same amount of resources (memory, storage capacity).
2. Groups of nodes in the cluster are combined. Let us assume that a group within a cluster interconnected topology "each-to-each", with a maximum capacity of connections between any two groups in the same cluster () is the same and is determined in advance.
3. Different groups of nodes with different processing capabilities and different resources vicinity can interact within the same cluster.
4. Clusters are interconnected by high-speed Internet connection. We assume that we are given the maximum network throughput between each pair of clusters. Network bandwidth will be considered the same in both directions (Fig. 1).
5. The network bandwidth between the nodes in the group is greater than the network bandwidth between the groups in the cluster, and the network bandwidth between the groups in the cluster is greater than the network bandwidth between the clusters:
6. Data links are reliable, i.e. there is no loss or duplication of data packets during the transmission.
7. The delays do not affect the data transfer.
8. We will consider two types of nodes in the cloud:

* Computing nodes ensure the provision of computational resources for the functioning of the problem-oriented services through independent virtualized containers. Provide a limited capacity for data storage.
* Storage units enable the storage and remote access to large volumes of data.

1. We assume that the transmission of data in the cloud does not require computational resources and can be conducted in parallel with the computations.
2. We assume that the cloud nodes execute tasks exclusively within the framework of problem-oriented environment, and do not perform any other tasks.

# Approaches to the scheduling

These methods are used for the implementation of scheduling in cloud environments:

* Scheduling on the basis of the theory of management;
* Scheduling using clustering algorithms;
* Scheduling with a time limit;
* Communal method;
* Market method.

Scheduling for all computing blocks in a task graph can be done on the basis of a static or dynamic approach. The static approach involves distribution of computational nodes before starting the job and requires information about the current state of computer network resources, output and consistency of the job prior to the task execution. The dynamic approach allows for the allocation of resources in the course of the assignment, as well as the process of branching in the job structure, which significantly complicates the scheduling process. We propose the introduction of a hybrid approach to scheduling, which uses static methods for primary distribution followed by the dynamic regulation, taking into account the dynamics of the job and the status of network resources to ensure that tasks are rescheduled as needed [7].

We decided to use a CloudSim cloud platform because it allows us to simulate a cloud environment with different scheduling algorithms and to compare their efficiency. CloudSim is a toolkit (library) for simulation of Cloud computing scenarios. It provides basic classes for describing data centers, virtual machines, applications, users, computational resources, and policies for management of diverse parts of the system (e.g., scheduling and provisioning) [1], [2].

# HEFT algorithm for the task of the problem-oriented scheduling

The use of heuristic score-based approach based on the HEFT algorithm for the task of the problem-oriented scheduling in cloud environments.

We offer a list-based algorithm for problem-oriented scheduling in cloud environments based on their computing profiles. List-based scheduling involves the definition of computational units' priorities and starting the execution according to the received priority. The binding to high-priority tasks resources takes place first. The proposed approach allows us to take into account the costs of transmission of data between nodes, thereby reducing the total time of execution of the workflow. The proposed algorithm is based on an algorithm of Heterogeneous Earliest-Finish-Time (HEFT), but contains modifications during the node level computation phase, and takes into account the problem of calculating the incoming communication value of its parent task [11].

Let be the size of the problem , and the be the set of computing resources with an average processing power . Then, the average time to complete the task with all available resources is calculated as

|  |  |
| --- | --- |
|  | (1) |

Let be the amount of data transferred between tasks and , and R be the set of available resources with an average capacity of data transfer . Then the average score on data transfer costs between tasks and for all pairs of p.

(2)

Thus, the priority calculation unit may be defined as

(3)

where is the set of tasks that depend on the task .

Thus, the task priority is directly determined by the priority of all its dependent tasks. Assign tasks to the resources as follows: a task with a higher priority if all the tasks on which it depends, is appointed to the computing resource, providing less time for the task [8].

Fig. 2. Heuristic scheduling algorithm in cloud environments HEFT

|  |
| --- |
| **PROCEDURE:** HEFT  **INPUT:** TaskGraph G(T, E), TaskDistributionList, ResourcesSet R  **BEGIN**  **for** each t T from task graph G  Calculate task execution time according to (1)  **for** each e E from task graph G  Calculate data transfer time according to (2)  Start the width-first search in reverse task order and calculate a rank for each task according to (3)  **while** T has unfinished tasks  TaskList <- get completed tasks from G  Schedule Task (TaskList, R)  Update TaskDistributionList  **END**    **PROCEDURE:** Schedule Task  **INPUT**: TaskList, ResourcesSet R  **НАЧАЛО**  Sort TaskList in reverse task rank order  **for each** t from TaskList  r <- get resource from R that can complete t earlier  schedule t on r  update status of r  **END** |

Taking into account the specifics of the problem-oriented cloud computing environment following modifications apply to this algorithm:

Let be the set of all functions that can be implemented in the subject area. Then a separate problem is nothing more than a single instance of a function with a set of input data objects :

,

We define R as the set of available for the deployment virtual machines with mean production capacity .

In this case, for evaluating the execution time we can apply the following formula:

.(4)

The model of problem-oriented services should take into account the amount of data returned by each task . This may be used by the operator of the expected output ,), which returns the expected total size in bytes of output data objects . Consequently, within the framework of problem-oriented model for the evaluation of data transmission time between two tasks the following formula can be used:

(5)

Where is the bandwidth of data transmission channel in the cloud computing system. During the execution of task it can be estimated as one of the following values:

1) , when the data transmission channel consists of a single node;

2) , when the data transmission channel is shared by a group of nodes;

3) , when the data transmission channel is shared by a cluster of compute nodes.

Thus, the priority of a calculation unit may be defined as: (6)

where is the set of all tasks that are dependent on the task T\_x.

Figure 3 shows the pseudo-code for algorithm of problem-oriented work flow scheduling in a cloud computing environment based on computing profiles.

|  |
| --- |
| **PROCEDURE:** PO-HEFT  **INPUT:** TaskGraph G(T, E), TaskDistributionList, ResourcesSet R  **BEGIN**  **for each** t T from task graph G  Approximate task execution time according to (4)  **for each** e E from task graph G  Approximate data transfer time according to (5)  Start the width-first search in reverse task order and calculate a rank for each task according to (6)  **while** T has unfinished tasks      TaskList <- get completed tasks from task graph G      Schedule Task (TaskList, R)      Update TaskDistributionList  **END**  **PROCEDURE:** Schedule Task  **INPUT:** TaskList, ResourcesSet R  **BEGIN**  Sort TaskList in reverse task rank order  **for each** t from TaskList  r <- get resource from R that can complete t earlier  schedule t on r  update status of r  **END** |

# Implementation

In order to assess the proposed algorithm’s efficiency, we had to develop a benchmark using CloudSim cloud environment simulation platform. We have implemented the PO-HEFT algorithm itself, as well as a naive bruteforce algorithm that finds and ideal scheduling solution.

Unfortunately, due to a great computational complexity of full search bruteforce, we could not benchmark agains it on all but the most trivial use cases. Hence why the PO-HEFT algorithm have only been benchmarked agains CloudSim’s own built-in space-shared scheduling policy which internally uses round-robin for VM scheduling.

The algorithm was implemented as a number of Java classes so that CloudSim can use it as the simulated cloud environment’s scheduler. We have implemented both a custom DatacenterBroker in order to schedule VMs in a data center and a custom CloudletScheduler in order to schedule tasks (cloudlets in CloudSim’s terminology) in a single VM.

# Performance evaluation

The algorithm was tested in a simulation in which virtual machines with homogeneous characteristics have been deployed. The simulated system was given the same work flow 60 times, which greatly exceeds the capacity of the system. For the distribution of the workflow we have used: a scheduler that does not use the information about the previous system runs that is built in CloudSim itself, the perfect scheduler, which implements the ideal scheduling through complete search space enumeration and a scheduler based on the PO-HEFT algorithm, which uses information about previous runs. The computational complexity of the perfect scheduler does not allow its usage in any non-trivial simulation and, therefore, this algorithm is not present in this comparison.

Experiments have shown that the PO-HEFT algorithm is quite efficient for the task. We have measured a total simulated workflow execution time for each algorithm. In a cloud with 500 nodes the execution time with a built-in scheduler was 43 seconds, and with PO-HEFT algorithm this time was 39 seconds which is a significant improvement. Thus, the algorithm is relevant and effective for planning tasks in problem-oriented cloud environments.

# Conlusion

##### In this article, we described the PO-HEFT scheduling algorithm, which aims to provide an efficient workflow scheduling in heterogenous distributed cloud environments. The main distinctive feature of this algorithm is it's ability to adapt the solution based on previous runs, which allows this algorithm to provide better resource utilization.

##### The algorithm's efficiency was assessed in the CloudSim cloud environment simulation software. As a benchmark we used CloudSim's built-in scheduler called "space-shared scheduling policy" which uses round-robin for resource provisioning and virtual machines creation. Our proposed algorithm have shown significant efficiency gains over this simple scheduler.

##### As a further development we will investigate the possibility of deploying this algorithm at a real cluster in order to assess its real-life, non-simulated performance. We will also compare this algorithm against different algorithms that do not use information about previous runs in order to give an empirical prove that this is a viable heuristic in workflow scheduling.

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