Two Approaches to Resource Allocation in Hybrid Fog and Cloud Systems

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Abstract: In this paper, two approaches to the hybrid fog and cloud computing environment are presented. The first is based on the assumption of centralized management performed by cloud, while the latter takes utilization of self-managing concept enabling distributed resource allocation carried by fogs. The appropriate mathematical models are introduced and the optimization problems are formulated. While the first concept turned out to be the mixed nonlinear programming, the second may be interpreted as the noncooperative game. The ideas of the possible solutions are briefly suggested.

1 INTRODUCTION

Recently fog computing and similar concepts attracted much attention. It turned out that the computing resources which are around us (e.g. smartphones, tablets, etc.) has very high computing power in total. Moreover, it may be possible to use it instead of cloud to perform some computing tasks. This, in turn, leads to a reduction in the use of network connections and cloud resources.

In this paper, we introduce to concepts of resource and task allocation in the hybrid fog and cloud computing environment. We assume that the computational task may be divided into the operations. Each operation may be performed either locally - in the fog or globally - in the cloud.

2 STATE OF THE ART

The concept of fog computing was first proposed by Cisco in 2011 (Bonomi, 2011) and its basic assumptions can be found in (Cisco, 2015). The computational fog is to provide cloud computing functionality with the use of devices and network infrastructure located near terminal devices instead of data centers (Bonomi et al., 2012). It has been noticed that a large number of devices with even relatively small unit computing powers such as mobile devices, terminal network devices or other embedded systems provide sufficient resources to perform at least part of the tasks that were originally directed to the cloud. The fog approach, on the one hand, makes it possible to limit the use of cloud computing resources and network communication resources and, on the other hand, allows reducing the delivery times of the data processing results.

In (Varghese et al., 2017) it was demonstrated that in some applications the use of fog instead of the cloud allows to reduce the use of network resources needed to perform computational tasks by up to 90% while providing results in time 20% shorter. The authors of the work (Hassan et al., 2015) reduced the waiting time for the results of the face recognition algorithm by 50% using a computational fog instead of a cloud.

In recent times, solutions have been sought to make the best use of the advantages of fog and cloud computing when both approaches are used within a single hybrid system. The research led to the development of the F2C (fog-to-cloud) (Masip-Bruin et al., 2016) paradigm and the Foud model (Tao et al., 2017). These efforts made possible to design systems that can use both fog and cloud resources simultanously. However, such hybrid systems can operate on the basis of different architectures, which should be chosen depending on practical applications. Sample proposals of structures of fog-cloud systems, which correspond to various potential applications, can be found e.g. in (Bierzynski et al., 2017) or (Skarlat et al., 2017).

At the same time, one of the most important re-

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search areas in the field of fog-cloud systems has become the problems of managing their resources. The effective use of limited local resources of computing fogs and their proper complementation with cloud computing resources is now a key issue. At the same time, the authors of many articles on this topic point out that work in this area is still in the initial phases.

In (Souza et al., 2016a), the authors propose algorithms that allow for the allocation of tasks. They assume that tasks can be divided into operations (called atomic services). Each of the fog nodes can perform only the indicated operations, while in the cloud all of them can be performed. The resources of computing nodes are treated in an abstract way (they represent computational possibilities) and are discrete - they are represented by the so-called slots. Each operation has specific requirements on the number of resources (slots) needed for its implementation. The problem is to assign operations to nodes so as not to exceed the number of available resources and to minimize three criteria simultaneously: delays in delivery of results, node load and energy consumption.

A similar problem was considered in (Souza et al., 2016b), but in this article, the authors considered a system in which only two types of tasks exist and the criterion of its operation was expressed in a total delay in providing all results. In the article (Szydlo et al., 2017), the authors focused on the problem of the separation of operations (performed as part of the task) between the fog and the cloud. Based on the distributed data dissection paradigm, they proposed a method of transforming the task into an operation graph, based on which the assignment of operations to be performed in the cloud or in the fog is to be made. The authors do not address aspects related to the availability of resources. As in previous cases, the problem is solved for a deterministic and static case. The issue related to system adaptation is also overlooked.

In (Hassan et al., 2015), the authors also deal with the problem of separating calculations between fog and cloud. The tasks are represented in the form of an operation graph. As a consequence, the problem itself is reduced to the classical task of splitting the graph. However, the authors consider aspects related to the existence of various computational resources (processor, RAM memory) and network resources (bandwidth). In addition, they point to the importance of the variability of resource availability in making decisions on the allocation of tasks.

In (Taneja and Davy, 2017) the problem was considered, in which not only should the task operations be divided between the fog and the computational cloud, but also assign the execution of individual operations to the fog nodes. Both computing resources in the form of processor power and RAM as well as network resources in the form of connection bandwidth were taken into account. Importantly, it was taken into account that the allowable assignment of operations to nodes must take into account the limited availability of resources.

The authors of the article (Aazam and Huh, 2015) take into account the uncertainty associated with the parameters describing the task. To make a proper reservation of resources, they use predictive models to determine what the task requirements for computing resources (CPU, RAM, mass storage) and network (connection capacity) will be. Reservation of resources is performed independently for each task at the moment of its appearance in the system. It is assumed that the task is indivisible and the manner of its implementation can not be changed. The allocation of resources is carried out in a static manner for a given system state and remains unchanged. A similar approach was also proposed in (da Silva and da Fonseca, 2018).

In (Shah-Mansouri and Wong, 2018), it is assumed that decisions on the allocation of tasks are made by local nodes of the computing fog in a distributed way. It is assumed that each task can be divided in any way between nodes of fog and cloud. In addition, the processing of individual parts of the task takes place in a parallel manner and they do not affect each other. The authors evaluate the operation of the system by the function of perceived quality (Quality of Experience - QoE) taking into account energy consumption and waiting time for the result of the operation. The allocation of tasks is determined only for the current moment, assuming constant and deterministic values of the parameters describing the system. The aspect of resource allocation, the ability to change the methods of performing tasks and system adaptation are omitted. Only a limited amount of computing resources are included, network resources are not considered.

The article (Liu et al., 2017) deals with the problem of allocating tasks for a stochastic case. It is assumed that services in the system consist of streams of indivisible tasks. It is taken into account that these streams have a stochastic character (tasks appear in random times and have a random size). Using queuing models, the authors propose a method for determining the probabilities of redirection of entire tasks to other nodes. The goal is to minimize delays, energy consumption and costs, taking into account constraints related to the availability of computing and communication resources. The decisions are, however, determined for the average values of the parameters describing the tasks and for the deterministic amounts of available resources. In addition, the solution found only for the current moment (statically) assuming the consistency of the way the tasks are carried out.

A similar approach to allocation of tasks in foggy cloud systems can be found in (Yu et al., 2017). It is assumed, however, that computational tasks can be divided in any way between fog nodes and cloud, and processing takes place in parallel. Despite taking into account the stochastic nature of the appearance of tasks, the decisions are determined only for the current moment and only on the basis of average values. The possibility of adapting the system during its operation and the tasks are always carried out in the same way.

In (Pham and Huh, 2016), it was assumed that the tasks can be represented in the form of an operation graph. Each operation has a defined size (number of instructions to be executed) and a volume of result data. Both computing resources (processor capacities) and network resources (bandwidth connections) are included. The system is modeled in the form of a graph whose vertices correspond to computational nodes and edges of communication resources. The problem is considered as a classic task of scheduling tasks on machines (computing nodes). The ranking is found only for the current moment and the system's volatility and uncertainty are not taken into account. Tasks can be implemented only one way. In (Skarlat et al., 2017) the problem of task allocation is considered. Tasks (identified with applications) are divided into operations (services). It is necessary to choose on which fog node or cloud computing the particular operations will be carried out. It takes into account the existence of many limited computational resources (such as CPU, RAM memory, mass storage), but communication resources are omitted. It's assumed only that the data transfer takes a certain time. At the same time, it was noted that these parameters are variable over time and it is proposed to use a simple predictive mechanism (in the form of a weighted average). It is assumed that decisions are made cyclically, at regular intervals, taking into account the current state of the system.

The review of the literature leads to a conclusion that works in the field of fog and hybrid systems are still at a preliminary stage. In particular, no attempt has been made to solve the allocation problems for the distributed case, i.e. when the resource and task allocation problem is solved by each computational fog independently.

3 SYSTEM MODEL

In this section we describe the hybrid fog-cloud system under consideration.

3.1 System Description

Taking into account the indicated principles of the system's functioning, it can be stated that its structure should be layered and correspond to the one shown in Fig. 1. Such a system can be described as a hybrid fog-cloud system, and its individual layers can be characterized as follows:

1. Sensor layer - consists of devices collecting data,
2. Fog layer - consists of devices (usually mobile), which are responsible for redirecting data to the cloud but also able to perform part of the computational tasks needed to provide the service. It consists of:
   - at least one permanent node acting as a device managing the computational fog and enabling the implementation of certain computational tasks,
   - additional nodes providing computational resources, the number of which can change over time,
   - infrastructure of the local network performing data transmissions within the calculation fog (e.g. between local calculation nodes).
3. Transmission layer - responsible for transmitting data from the fog to the cloud.
4. Cloud layer - performing a computational task needed to complete the services and responsible for storing data for all users of the system.

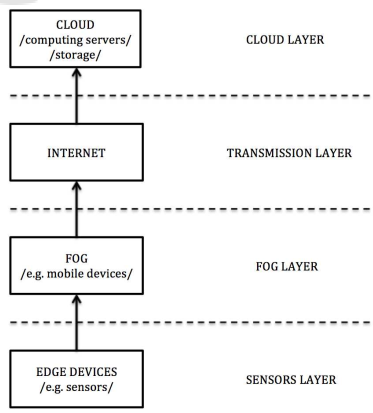

Figure 1: Layered architecture of the considered hybrid fog-cloud system.

In this paper, we also assume that each fog is isolated from the others (it is not possible to use computational resources for the needs of another fog). In contrast, the cloud computing provides a common computing and archiving space for all fogs. In simplified form, it can be illustrated in Fig. 2. The results of computation for the services must be sent to the cloud.

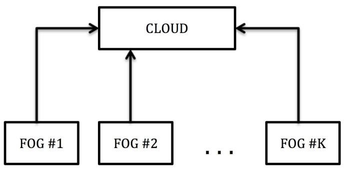

Figure 2: Connection structure of the considered hybrid fog-cloud system.

3.2 Services

We assume that all computational tasks are performed to provide particular services. Each task may be performed at any fog node (but only one) or in the cloud. All tasks may be interrupted at any time of processing. The calculations may be started in the fog and completed in the cloud. WE assume that services generates constant streams of tasks.

As an example, one may consider a video image acquisition and processing system. The basic services of the system under consideration are: a. streaming - the service consists in transferring data from IP cameras (sensor layer) to the cloud in order to provide the currently recorded image and its archiving. Image quality and the amount of data sent to the cloud depend primarily on: number of frames per second (frame per second - fps), frame compression rate. Once the camera may capture video in higher quality than user requires, some image processing tasks may be done - e.g. changing fps or increasing degree of compression. These tasks may be performed either in the fog or in the cloud. If they are carried out locally, the less data is to be send. But even performing them in the cloud is still profitable since it saves the disk space.

3.3 Resources

The resources of the considered system that can be allocated for the needs of individual services can be divided into computational and network (communication). Among computing resources, the most impartant are: CPU, RAM memory and storage. In turn, among network resources, the capacity of links is critical (ie the maximum possible data transfer speed between two network nodes).

The characteristics of the resources of the considered system that can be used in the implementation of specific computational tasks from the perspective of individual layers is as follows:

1. Sensor layer - resources that could be subject to allocation are not considered here. stream.
2. Fog layer:
   - Calculation resources - are located in fog nodes, which most often are mobile devices (tablets, smartphones) or - potentially - other equipment that can share its processor and memory and its appropriate software is possible. The computational resources of the system fog node can be characterized as follows: CPU - mobile processors with relatively low unit efficiency, the amount of RAM and storage are relatively small.
   - Network resources - communication between devices constituting nodes of the computational fog and IP cameras takes place within the local network, usually based mainly on the so-called Wi-Fi routers operating in accordance with the IEEE 802.11 b / g / n / ac standards in the 2.4Ghz and 5Ghz band. Fog nodes are most often equipped with wireless interfaces (WiFi). The amount of network resources of the fog may be characterized as follows. Links' capacities are relatively high (especially when network devices use the latest wireless communication standards and technologies) and not subject to significant changes in time (unless the user uses a local network for other applications - then the resources can be significantly limited or strongly variable), the capacity of local calls may become critical when the number of recording devices and computational cloud nodes increases significantly.
3. Transmission layer:
   - Calculation resources - computational resources are not considered in this layer, as it is only used to transmit data from the fog to the cloud.
   - Network resources - in this case, the key resources concern the access connection between the calculation fog and the Internet, allowing data to be sent to the cloud. These resources can be described as follows. The link capacities may be undoubtedly bottlenecks. They are usually very limited in comparison to the requests. especially when the user uses the mobile network.

4. Cloud layer:
   - Calculation resources - relatively large, but it involves certain costs.
   - Network resources - similar to computing resources and these are easily scalable.

The amount of resources allocated to the performance of individual operations affects primarily the time of their implementation, and consequently determines the time of completion of the task as part of the service. In addition, there may be requirements related to the minimum amount of resources needed to perform a specific service (especially RAM and mass memory). In this paper we make the following assumptions in the context of resources:

- The amounts of available resources within the calculation nodes and network resources can be treated as approximate values.
- From the point of view of system operation, only the resources listed above are relevant.

3.4 Objective

The performance of the system may be measured by the average time of completing tasks. The time of completing particular task is a sum of fog's processing time and cloud's processing time. The processing time depends on the load of the computational node (as well in fogs as in the cloud). The higher is load, the longer is potential processing time.

3.5 Notation

3.5.1 System Parameters

The following notation is used to describe system's parameters:
I_k - set of tasks indexes related to the kth fog,
P_i - the amount of CPU needed to perform ith task,
M_i - amount of RAM needed while ith task is processed,
$S_{start,i}$ - the data volume related to ith task at the begining of processing
$S_{stop,i}$ - the data volume related to ith task when the processing is finished, we assume that the volume of data linearly decrease during processing, i.e. the data volume while the ith task is finished in nth percent is given as $S_i = n/100 * (S_{start,i} - S_{stop,i}) + S_{stop,i}$
J_k - number of kth fog's nodes (for convenience we use $k = 0$ to denote a cloud and we assume $J_0 = 1$).
CPU_{jk} - the amount of CPU resources of the jth node of kth fog,
RAM_{jk} - the amount of RAM resources of the jth node of kth fog,
HDD_{jk} - the amount of storage of the jth node of kth fog,
CAP_k - the link capacity between the kth fog and the cloud,
CPU_{CLOUD} - the amount of CPU resources of the cloud (it is assumed that it is enough to perform all tasks in the cloud, i.e. $\sum_i P_i \leq CPU_{(CLOUD)}$).
Q - the objective function (e.g. the quality of the system).

3.5.2 Decision Variables

The decision variable are as follows:
x_i - the fraction of ith task performed in the fog, $x = [x_i]$,
$y_{ijk} \in \{0,1\}$ - indicated if ith task is assigned to jth node of kth fog, $y = [y_{ijk}]$,
c_i - the link's capacity allocated to transmit ith task from the fog to the cloud, $c = [c_i]$.

3.5.3 Objective Function

Let us assume that the processing time of ith task in the kth fog may be calculated as follows:

$$t_i^F = \sum_j \frac{y_{ijk}}{x_i P_i}$$

and in the cloud:

$$t_i^C = \sum_j \frac{1}{(1-x_i)P_i}$$

. The queing delay of the kth fog node for ith task may be estimated as follows:

$$d_i^F = \sum_j y_{ijk} \frac{1}{CPU_{jk} - \sum_v \sum_q x_q y_{qvk} P_q}$$

and the queing delay of the cloud:

$$d_i^C = \frac{1}{CPU_{CLOUD} - \sum_q (1-x_q) P_q}$$

The transmission delay of ith task between fog and cloud we estimate as:

$$t_i^{F2C} = (x_i/100)((S_{start,i} - S_{stop,i}) + S_{stop,i})/c_i$$

The total delay of processing ith task is:

$$T_i = t_i^F + t_i^C + d_i^F + d_i^C + t_i^{F2C}$$

The performance of the system may be measured as a average total delay of all tasks:

$$Q(x,y,c) = \frac{1}{|I_k|} \sum_i T_i$$

4 PROBLEM FORMULATIONS

4.1 Cloud-based Central Resource Management

For the centralized resource allocation problem, we may give the following formal formulation:
Given: system parameters
Find:

$$(x,y,c) = \arg\max_{(x,y,c)} Q(x,y,c)$$

subject to the following constraints:

$$\forall_k \ \forall_{i \in I_k} \ \sum_{j \in J_k} y_{ijk} \le 1 \tag{1}$$

$$\forall_k \ \forall_{j \in J_k} \ \sum_{i \in I_k} y_{ijk} x_i P_i \le CPU_{jk} \tag{2}$$

$$\forall_k \ \forall_{j \in J_k} \ \sum_{i \in I_k} y_{ijk} M_i \le RAM_{jk} \tag{3}$$

$$\forall_k \ \forall_{j \in J_k} \ \sum_{i \in I_k} y_{ijk} S_{start,i} \le HDD_{jk} \tag{4}$$

$$\forall_k \ \sum_{i \in I_k} c_i \le CAP_k \tag{5}$$

$$\forall_i \ c_i \ge 0 \tag{6}$$

$$\forall_i \ \forall_j \ \forall_k \ 0 \le y_{ijk} \le 1 \tag{7}$$

$$\forall_i \ x_i \in \{0,1\} \tag{8}$$

The constraint (1) guarantees that each task is performed by no more than one fog node. The constraints (2) - (4) means that computational resources are not overloaded (according to the assumptions only fog resource must be taken into consideration). The network resources are not exceeded while (5) is preserved (it is assumed that only transmission layer network resources must be considered). The constraints (6) - (8) define the variables domains.

4.2 Fog-based Distributed Resource Management

Let us introduce auxiliary variables $x^{(k)}$ which consist of only these x_i for which $i \in I_k$. Simirarly we define $c^{(k)}$. Let us also denote $y^{(k)} = [y_{ijk}]$. For convenience, let $x^{(-k)}$ means the vector of variables x_i for which $i \notin I_k$ and $y^{(-k)} = [y_{ijl}]_{l \neq k}$. For simiplicity let us denote $x =< x^{(k)}, x^{(-k)} >$, $c =< c^{(k)}, c^{(-k)} >$ and $y =< y^{(k)}, y^{(-k)} >$.
Finally, for the distributed resource allocation problem, we may give the following formal formulation:

Each fog solves the following problem: Given: system parameters
Find:

$$(x^{(k)}, y^{(k)}, c^{(k)})) =$$
$$= \arg\max_{(x^{(k)}, y^{(k)})} Q(< x^{(k)}, x^{(-k)} >,$$
$$< y^{(k)}, y^{(-k)} >, < c^{(k)}, c^{(-k)} >)$$

subject to the following constraints:

$$\forall_{i \in I_k} \ \sum_{j \in J_k} y_{ijk} \le 1 \tag{9}$$

$$\forall_{j \in J_k} \ \sum_{i \in I_k} y_{ijk} x_i P_i \le CPU_{jk} \tag{10}$$

$$\forall_{j \in J_k} \ \sum_{i \in I_k} y_{ijk} M_i \le RAM_{jk} \tag{11}$$

$$\forall_{j \in J_k} \ \sum_{i \in I_k} y_{ijk} S_{start,i} \le HDD_{jk} \tag{12}$$

$$\sum_{i \in I_k} (x_i/100)(S_{start,i} - S_{stop,i}) + S_{stop,i} \le CAP_k \tag{13}$$

$$\forall_i \ c_i \ge 0 \tag{14}$$

$$\forall_i \ \forall_j \ 0 \le y_{ijk} \le 1 \tag{15}$$

$$\forall_i \ x_i \in \{0,1\} \tag{16}$$

The constraints (9) - (13) corresponds to the appropriate constraints (1) - (5), but only for particular fog.

This is a set of optimization problems and the solution of one affects the others. Such defined problem is called a game and may be considered from the Game Theory perspective. The fogs are the players. The $x^{(k)}$ and $y^{(k)}$ constitutes a strategy. The feasible strategies are defined by the constraints. The objective is the payoff.

5 SOLUTION

Assuming that Q is the concave function, one may notice, that the cloud-based central resource management problem is the mixed integer nonlinear programming and to solve it, the appropriate optimization methods may be applied - e.g. the Bender's decomposition.

On the other hand, fog-based distributed resource management problem is the game, since each fog solves their own optimization problem simultanously and these solutions affects the objective (so-called payoff) of other fogs. In this case, the solution is perceived as an equilibrium. The most common is application of a Nash equilibrium since it is a solution that once obtained, no one is going to change their decision independently.

6 FINAL REMARKS

In this paper, we described the proposition of hybrid fog and cloud system. We discussed which resources are critical for the system's performance. We also formulate the allocation problems for the case of central and distributed resource management in the introducted systems and briefly discussed the possible solution method.

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