A Bag-of-Tasks Scheduler Tolerant to Temporal Failures in Clouds

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Abstract—Cloud platforms have emerged as a prominent environment to execute high performance computing (HPC) applications providing on-demand resources as well as scalability. They usually offer different classes of Virtual Machines (VMs) which ensure different guarantees in terms of availability and volatility, provisioning the same resource through multiple pricing models. For instance, in Amazon EC2 cloud, the user pays per hour for on-demand VMs while spot VMs are unused instances available for lower price. Despite the monetary advantages, a spot VM can be terminated, stopped, or hibernated by EC2 at any moment.

Using both hibernation-prone spot VMs (for cost sake) and on-demand VMs, we propose in this paper a static scheduling for HPC applications which are composed by independent tasks (bag-of-task) with deadline constraints. However, if a spot VM hibernates and it does not resume within a time which guarantees the application's deadline, a temporal failure takes place. Our scheduling, thus, aims at minimizing monetary costs of bagof-tasks applications in EC2 cloud, respecting its deadline and avoiding temporal failures. To this end, our algorithm statically creates two scheduling maps: (i) the first one contains, for each task, its starting time and on which VM (i.e., an available spot or on-demand VM with the current lowest price) the task should execute; (ii) the second one contains, for each task allocated on VM spot in the first map, its starting time and on which on-demand VM it should be executed to meet the application deadline in order to avoid temporal failures. The latter will be used whenever the hibernation period of a spot VM exceeds a

Performance results from simulation with task execution traces, configuration of Amazon EC2 VM classes, and VMs market history confirm the effectiveness of our scheduling and that it tolerates temporal failures.

Index Terms—Clouds, Temporal failures, Scheduling

I. INTRODUCTION

High Performance Computing (HPC) applications are typically executed in dedicated data centers. However, in the past few years, cloud computing has emerged as an attractive option to run these applications due to several advantages that it brings when compared with a dedicated infrastructure. Clouds provide a significant reduction in operational costs, besides offering a rapid elastic provisioning of computing resources like virtual machines and storage. However, in cloud environments, besides the usual goal of minimizing the execution time of the HPC application, it is also important to minimize the monetary cost of using cloud resources, i.e., there exists a trade-off between performance and monetary cost.

In this paper, we are interested in HPC bag-of-task (BoT) applications with time constraints (deadlines) within which they must finish. BoT applications are composed of independent tasks which can be executed in any order and in parallel. Although simple, the BoT approach is used by several HPC applications such as parameter sweep applications, chromosome mapping, Monte Carlo simulation, computer imaging applications [1], [2], [3], [4]. Furthermore, they may require deadline-bounds where the correctness on the computation also depends on the time the computation of all tasks ends.

Infrastructure-as-a-Service (IaaS) existing cloud platforms (e.g., Amazon EC2, Microsoft Azure, Google Cloud, etc.) enable users to dynamically acquire resources, usually as virtual machines (VMs), according to their application requirements (CPU, memory, I/O, etc.) in a pay-as-you-use price model. They usually offer different classes of VMs which ensure different guarantees in terms of availability and volatility, provisioning the same resource through multiple pricing models. For instance, in Amazon EC2, there are basically three classes¹: (i) reserved VM instances, where the user pays an upfront price, guaranteeing long-term availability; (ii) ondemand VM instances which are allocated for specific time periods and incur a fixed cost per unit time of use, ensuring availability of the instance during this period; (iii) spot VM instances which are an unused instances available for lower price than on-demand price.

The availability of spot VMs instances fluctuates based on the spot market's current demand. The allocation of a spot instance involves defining the VM type and a maximum price for how much the user is willing to pay. However, if there are not enough instances to meet clients demands, the VM in question can be interrupted by the cloud provider (temporarily or definitively). Despite the risk of unavailability, the main advantage of spot VMs is that their cost is much lower than on-demand VMs since the user requests unused instances at steep discounts, reducing the costs significantly.

With Amazon's more recent announcement, an interrupted spot can either terminate, stop, or hibernate. Hence, when requesting a spot instance the user specifies the required type as well as the action that Amazon EC2 should take in case the VM instance is interrupted. Whenever a spot instance is

¹https://aws.amazon.com/ec2/instance-types/

hibernated by EC2, its memory and context are saved to the root of EC2 Block Storage (EBS) volume and, during the VM's pause, the user is only charged for EBS storage. EC2 resumes the hibernated instance, reloading the saved memory and context, only when there are enough availability for that type of instance with a spot price which is lower than the user's maximum price. Contrarily to stopped or terminated instances whose user is warned two minutes before the interruption of them, hibernated instances are paused immediately after noticing the user.

Our proposal in this work is to provide a static cloud scheduler for Bag-of-Tasks applications using, for cost sake, hibernate-prone spot instances as much as possible, respecting the application deadline constraints while also minimizing the monetary costs of bag-of-tasks applications. However, if a spot instance hibernates, it might happen that it will not resume within a time which guarantees the deadline constraints of the application. In this case, a temporal failure would take place, i.e., correct computation is performed but too late to be useful (inability to meet deadlines). Thus, in order to avoid temporal failure in case of spot instance hibernation, our scheduler statically computes the time interval that an hibernated instance can stay in this state without violating the application's deadline. If the instance does not resume till the end of this interval, our scheduler will move the execution of the current tasks of the spot instance as well as those not executed yet to on-demand instances, in order to guarantee the application's deadline. Note that even after migrating the remaining task execution to on-demand VMs, the scheduler continues to look forward to minimizing monetary costs.

The rest of the paper is organized as follows. Section II discusses some related work. Section III describes our proposed static scheduling, including its algorithms. Evaluation results from simulations conducted with real traces are presented in section IV. Finally, Section V concludes the paper and presents some future directions.

II. RELATED WORK

Bag-of-tasks on clouds are widely used not only for scientific applications but also for many commercial applications. In [5], Facebook reports that the jobs running on their own internal data centers are mostly independent tasks. Many works propose then scheduling the execution of independent tasks both on homogeneous and heterogeneous cloud environments [6]. In the former, the performance and pricing of all available VMs are the same. In this case, authors usually consider either reserved VMs [7] or on-demand VMs [8]. For instance, Thai et al. [8] study scheduling of applications on on-demand VMs distributed across different datacenters, focusing on the trade-offs between performance and cost while Yao et al. [7] provides a solution that satisfies job deadlines while minimizing monetary cost. The proposed heuristics use both on-demand and reserved VMs. Works on heterogeneous cloud consider different types of VMs. For instance, in [9] the authors present a heuristic algorithm for executing a bag-oftasks applications taking into account either budget or deadline

constraints. In [6], Thai et al. present an extensive survey and taxonomy of existing research in scheduling of bag-of-task applications on clouds.

Several works propose to tolerate failures (crash) of VMs in Clouds using checkpointing, passive or active replication, or task resubmission approaches. Some of them, similarly to our approach, must avoid job and/or application's deadline violation.

Checkpointing [10], [11] approaches periodically save the execution state of a VM as an image file. These mechanisms are costly since data centers have limited network resources and may readily become overloaded when a huge number of checkpoint image files need to be stored. Moreover, they are not suitable for real-time context or jobs with deadline constraints since periodically checkpoints and resume of failed tasks are time-consuming.

Replication and resubmission of tasks are the other mechanisms widely used to tolerate failures [12]-[14]. Using replication, several copies of the same task are executed to support fault tolerance. Most of studies use a single primary-backup scheme considering one primary and one or several backup (copy) tasks scheduled on different computing instances [13], [14]. The copies of a task are executed only when the primary task fails. In order to reduce the response time in case of failure, overlapping techniques are proposed [13] in a Grid context where a backup is scheduled for each primary on a different host. A backup is executed when its primary cannot complete execution due to a failure but it does not require fault diagnosis. Zheng et al. [13] propose an algorithm to find an optimal backup schedule for each independent tasks. Wang et al. [14] extend Zheng's results in a cloud context and using an elastic resource provisioning.

Despite the use of overlapping techniques, primary-backup schemes require that the tasks deadlines have enough time for executing backups in case of failure. Then, several works study active replication [15]–[17] allowing backups to execute concurrently with its primaries. Al-Omari et al. [15] improve the primary-backup scheme by proposing the primary-backup-overloading technique, in which the primary of a task can be scheduled onto the same or overlapping time interval with the backup of another task on a processor. In [16], authors present a comprehensive study of replication schedulers where all replicas of a task start executing concurrently and the next task is started as soon as one of the previous task replicas finish. Benoit et al. [17] adopt a more conservative approach where the next task can only start when all the replicas of the previous task finished.

Contrarily to our approach, the above solutions need to schedule both the primary and backup tasks and the latter take the execution control if the former fail. Neither of them use backup tasks to avoid temporal failure. In addition, in our case, they are only executed in case of VM's hibernation and risk of temporal failures.

Some works take into account Amazon spot VMs instance features. In [18], Lu et al. use hybrid instances, including both on-demand instances for high priority tasks and backup,

and spot instances for normal computational tasks. Authors of [19] propose to switch to on-demand resources when there is no spot instance available to ensure the desired performance. Using both on-demand and spot VM instances, SpotCheck [20] provides the illusion of an IaaS platform that offers always-available on-demand VMs for a cost near that of spot VMs. Also claiming performance of on-demand VMs, but at a cost near that of the spot market, the authors in [21] present the SpotOn batch service computing, that uses fault-tolerance mechanism to mitigate the impact of spot revocations. To our knowledge no work studies the impact of the new hibernation feature of spot instances on scheduling algorithms.

III. A STATIC SCHEDULER OF BAG-OF-TASKS APPLICATIONS IN CLOUDS

Aiming at reducing monetary costs, our proposed scheduling uses hibernate-prone spot instances. However, due to the possibility of hibernation and also the need to meet the application's deadline, the scheduler might migrate tasks that run on spot instances to on-demand ones, whenever the duration of an instance hibernation would induce a temporal failure. We denote primary tasks those which are allocated on VMs (spot or on-demand) that guarantee application's deadline with minimum monetary cost and we denote backup tasks those which are allocated on on-demand VMs and were originally primary tasks allocated on spot VMs. Backup tasks are only executed in case the hibernation state remains for such a long period of time that it is impossible to meet the deadline of the application, avoiding, thus, temporal failures. Therefore, a task might have two versions (primary and backup) which are statically scheduled on two different cores with time exclusion.

The scheduling outputs two allocation mappings: one with primary tasks and the other one with backup tasks.

Concerning the primary mapping, the proposed strategy aims at minimizing the monetary costs, by adopting hibernate-prone spot instances with the highest processing power. Regarding the backup mapping, our strategy aims at minimizing monetary costs, by using the minimum number of the cheapest on-demand VMs, without violating the application's deadline.

We assume that each task of the BoT application is executed in one core, requiring some main memory and that a set of different types of VMs are usually offered by cloud providers with a varying number of virtual cores (VCPUs) and memory sizes. Therefore, a VM running on a multi-core machine can execute more than one task simultaneously (one VCPU per task) provided there is enough main memory to allocate them. We also consider that VMs are offered in two different markets, spot and on-demand, where, contrarily to the former, the latter can not hibernate. Note that our solution only allocates spot VMs of those types that support hibernation.

Figure 1 shows an example where the hibernation does not require backup tasks execution. In this example, a spot instance starts hibernating in time p and finishes in y, before the time limit, $start_bkp$, when the backups should be triggered. Then, the deadline D can be met without executing the backups. On the other hand, Figure 2 presents a case where it is necessary

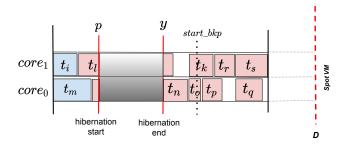


Fig. 1. Hibernation without Backup Execution.

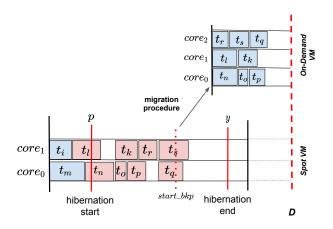


Fig. 2. Hibernation with Backup Execution.

to execute the backup tasks in an on-demand virtual machine to meet the deadline, since the hibernation exceeded the time limit, $start_bkp$.

Let M be the set of virtual machines, B the set of tasks that compose a bag-of-task application, and $T = \{1, \ldots, D\}$ the set of feasible periods, where D is the deadline defined by the user. For each VM, M keeps its storage capacity and the number of cores with the corresponding computation power. Set B keeps, for each task, information about (i) its execution time on a machine with known computational power (base time duration) and (ii) the amount of main memory that the task needs. Let $Queue^{vm_j} \subset B$ be the set with all tasks scheduled on vm_j .

It is worth mentioning that the execution time of a task is re-calculated as the product between the original execution time and the VM slowdown where it will be executed. A VM slowdown is defined as $\frac{P_B}{P_{vm_j}}$, where P_B is the processing capacity of the machine used to calculate the basis time, and P_{vm_j} is the processing capacity of the VM. Thus, the slowdown represents the processing capacity of a VM when compared with the machine used to compute the basis time duration.

When a VM is allocated for a user, he/she pays for a full-time interval called *slot*. That time is usually one hour.

Thus, if a VM is used for 61 minutes, for example, the user will be charged for two *slots* (120 minutes). Note that one slot can correspond to several periods. For example, if each period corresponds to one minute, a slot of one hour would correspond to 60 periods. It is, thus, in the user's best interest to maximize the use of a slot already allocated.

Let $start_slot^{vm_j}$ and $end_slot^{vm_j}$ be the time when the first slot was allocated to vm_j and the end time of the last allocated slot for this same VM respectively, such that $start_slot^{vm_j} < end_slot^{vm_j}$. Whenever the execution time of a task allocated to vm_j exceeds the $end_slot^{vm_j}$, the user has to pay for another full interval. Thus, if part of that interval is not used by any task, we have a waste of time. To compute that waste, we define $waste^{vm_j}$ in Equation 1, that is the time interval inside the last contracted slot at which vm_j remains idle after executing all tasks allocated to it.

$$waste^{vm_j} = end_slot^{vm_j} - end_{t_{max}}$$
 (1)

Such that $end_{t_{max}} = \max_{\forall t_l \in Queue^{vm_j}} (end_{t_l})$ and end_{t_l} is the end time of task t_l .

A. Primary Task Scheduling

Algorithm 1 shows the primary scheduling heuristic which is a greedy algorithm that allocates the set of tasks $t_i \in B$ to a set of VMs (spot and on-demand VMs). Tables I and II present the used variables and functions respectively. The algorithm receives $B,\ M,\ D,$ and VM_time_{limit} as input parameters. The VM_time_{limit} defines the maximum occupation period of a VM. For example, if D=100(h) and $VM_time_{limit}=0.5$, the scheduling of the tasks should be done so as not to exceed the period $D*VM_time_{limit}=50(h)$. Since the objective is to respect the application deadline (even in the presence of hibernation) while minimizing monetary costs, all the choices made by the heuristic are guided by the VMs' prices, and by the deadline D and VM_time_{limit} , defined by the user.

Initially, tasks are ordered in descending order by the memory size they require (line 1). Then, for each task, the algorithm applies a best fit heuristic that tries to include it in an already allocated slot of a virtual machine that presents the highest waste of time (lines 7 to 13), since it has enough memory and ensures that the task insertion will respect $D*VM_time_{limit}$. If such a VM does not exist, the heuristic tries to allocate new slots in an already allocated VM with enough memory to execute the task, but now with the smallest waste (lines 16 to 23). Similarly to the previous case, the slot allocation must not violate $D*VM_time_{limit}$ (line 19).

Allocating slots in an already allocated VM reduces boot time overhead in comparison of allocating a new VM. However, if such an allocation is not possible, the algorithm must allocate a new VM. In this case, the heuristic defines the best type of VM in terms of execution time (line 25) and, then, it chooses the market where this VM shall be acquired: ondemand or spot, considering the offered prices (lines 26 to 30). Finally, it updates the primary scheduling map (line 35).

Algorithm 1 Primary Task Scheduling

```
Input: B, M, D, VM \ time_{limit}
 1: sort(B);
 2: PQ = \emptyset;
 3: A_VM = \emptyset; /* set of allocated VMs */
 4: for all t_i \in B do
      sort_by_max_waste(A_VM); /* using Equation 1 */
      inserted = False;
      /*Check if vm_k has sufficient time and memory in an already
      allocated slot to execute t_i without violating the limit D *
      VM timelimit */
 7:
      for all vm_k \in A\_VM do
 8:
         if check\_insertion(t_i, vm_k, D * VM\_time_{limit}) then
 9:
            insert(t_i, vm_k);
10:
            inserted = True;
            break;
11:
12:
         end if
13:
      end for
      /*Check if it will be necessary to allocate a new slot on an
      already allocated VM or if it will be necessary to allocate a
      new VM*/
      if not inserted then
14:
         vm_{aux} = NONE;
15:
         sort\_by\_min\_wast(A\_VM);
16:
17:
         for all vm_k \in A\_VM with enough memory do
            /*get the number of slots necessary to execute t_i on
            vm_k*/
18:
            n = number\_of\_slots(t_i, vm_k);
            if end\_slot^{vm_k} + (n*slot) < D*VM\_time_{limit} then
19:
20:
               vm_{aux} = vm_k;
21:
               break:
            end if
22:
23:
         end for
24:
         if vm_{aux} is equal to NONE then
25:
            vm_{aux} = best\_VM(t_i, M);
            if spot\_price^{vm_{aux}} < odm\_price^{vm_{aux}} then
26:
              vm_{aux}^{market} = spot;
27:
28:
              vm_{aux}^{market} = on	ext{-}demand;
29:
30:
            end if
         end if
31:
32:
         n = number\_of\_slots(t_i, vm_{aux});
         /*Allocate the number of slots required to execute t_i in
         vm_{aux}*/
         allocate\_slots(vm_{aux}, n);
33:
34:
         insert(t_i, vm_{aux})
35:
         update(A_VM); /*Update the set of allocated VMs*/
36:
      end if
37: end for
38: PQ = create\_primary\_map(A\_VM);
```

Figure 3 shows an example of scheduling of nine tasks in a virtual machine with two cores. In the example, there exist two gaps (one per core) which occur due to lack of memory to allocate a task within the current slot. The waste of time and deadline D are also shown.

B. Backup Task Scheduling

Let $Succ_{t_k}^{vm_j} \subset Queue^{vm_j}$ be a set containing task t_k and all its successors, i.e., all tasks that are allocated to the same core where t_k is allocated and that execute after the end of t_k . Let $Parallel_{t_i}^{vm_j} \subset Queue^{vm_j}$ be a set containing all tasks that execute in parallel with t_i in vm_j . In order

TABLE I Variables of Primary Scheduling Heuristic 1

| Name | Description | |
|-------------------------|--|--|
| В | Set of tasks | |
| M | Set of VMs | |
| D | Deadline defined by the user, to be respected even | |
| | in presence of VM hibernation | |
| VM_time_{limit} | Parameter that determines the maximum occupa- | |
| | tion period of a VM | |
| A_{VM} | Set of VMs selected to execute primary tasks | |
| t_i | Task i | |
| inserted | Boolean variable that indicates whether task t_i was | |
| | successfully scheduled | |
| vm_k, vm_{aux} | Virtual machines | |
| slot | Minimum contracted time for a VM (for example, | |
| | in AWS the slot is 1 hour) | |
| n | Number of contracted slots | |
| $end_slot^{vm_k}$ | End of last contracted slot of vm_k | |
| vm_{aux}^{market} | Market where vm_{aux} will be contracted: on- | |
| | demand or spot | |
| $spot_price^{vm_k}$ | Price of a slot of vm_k in the spot market | |
| $odm_price^{vm_{aux}}$ | Price of a slot of vm_k in the on-demand market | |
| PQ | Scheduling map of primary tasks containing VMs | |
| | and the corresponding execution queues | |

 ${\it TABLE~II} \\ {\it Functions~and~Procedures~of~Primary~Scheduling~Heuristic~1} \\$

| Name | Description |
|----------------------------------|--|
| sort(B) | Sort the set of tasks B in descend- |
| , , | ing order by memory size demand |
| $sort_by_max_waste(A_VM)$ | Sort the set of VMs A_VM in |
| | descending order by the waste size |
| $sort_by_min_waste(A_VM)$ | Sort the set of VMs A_VM in |
| | ascending order by the waste size |
| $check_insertion(t_i, vm_k, D)$ | Check if vm_j has an already con- |
| | tracted slot with enough idle time |
| | and memory to execute task t_i , and |
| | if that insertion respects the dead- |
| | line D |
| $insert(t_i, vm_k)$ | Insert task t_i into the execution |
| | queue of vm_k |
| $number_of_slots(t_i, vm_k)$ | Compute the number of slots nec- |
| | essary to execute task t_i in vm_k |
| $best_VM(t_i, M)$ | Select the VM that executes task |
| | t_i with the minimum number of |
| | periods of time |
| $allocate_slots(vm_{aux}, n)$ | Allocate (contract) n slots in |
| | vm_{aux} |
| $update(A_VM)$ | Update A_VM either with new |
| | slots in an already selected VM or |
| | with the inclusion of a new VM |
| $create_primary_map(A_VM)$ | Create the scheduling map of pri- |
| | mary tasks |

to avoid temporal failures due to vm_j 's hibernation while executing t_i in one of its core, it is necessary to determine which backup tasks must be executed in this case. To this end, we define $Rec_Group_{t_i}^{vm_j} \subset Queue^{vm_j}$, as presented in Equation 2. The set $Rec_Group_{t_i}^{vm_j}$ is obtained by the union of all $Succ_{t_k}^{vm_j}$, such that $t_k \in Parallel_{t_i}^{vm_j}$ or $t_k = t_i$. We also define the set $S_VM_{t_i} \subset M$, that contains all VMs that will be used to execute backup tasks of $Rec_Group_{t_i}^{vm_j}$, if a migration occurs. Figure 4 shows an example of $Succ_{t_k}$ and

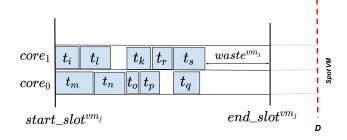


Fig. 3. Primary Scheduling of tasks within a VM slot.

 $Rec_Group_{t_k}^{vm_j}$ sets of task t_k allocated to vm_j .

$$Rec_Group_{t_i}^{vm_j} = \bigcup_{\substack{t_k \in (Parallel_{t_i}^{vm_j} \cup \{t_i\})}} Succ_{t_k}^{vm_j}$$
 (2)

We also define the backup start time, $start_bkp_{t_i}^{vm_j}$, as presented in Equation 3. It defines how long the hibernation state of vm_j can be tolerated before any action of migrating tasks of $Rec_Group_{t_i}^{vm_j}$ to backup ones is triggered.

$$start_bkp_{t_i}^{vm_j} = D - runtime(Rec_Group_{t_i}^{vm_j}, S_VM_{t_i}) - 1$$
 (3)

Such that $runtime(Rec_Group_{t_i}^{vm_j}, S_VM_{t_i})$ is the number of periods necessary to execute all tasks of $Rec_Group_{t_i}^{vm_j}$ in the VMs of $S_VM_{t_i}$ plus the number of periods necessary to boot the VMs of $S_VM_{t_i}$.

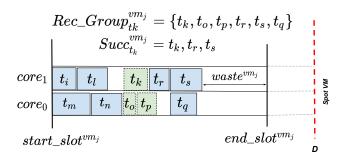


Fig. 4. Example of a task t_k , its successors and which backup tasks might be executed to prevent vm_j from a temporal failure while executing task t_k $(Rec_Group_{t_i}^{vm_j})$.

The proposed backup scheduling algorithm is presented in Algorithm 2, where Table III shows the used variables and Table IV describes the used procedures and functions. As can be seen in line 4, $Rec_Group_{t_i}^{vm_j}$ is created for each task $t_i \in Queue^{vm_j}$.

This algorithm employs a scheduling strategy similar to that presented in Algorithm 1, in which tasks are scheduled on different VMs using a best-fit heuristic. However, unlike the Algorithm 1, in Algorithm 2, the VMs selection prioritizes the on-demand VM with the cheapest monetary cost, resulting from the product of its price and the execution time of a backup task on it.

Note that the backup scheduling has to ensure that if a migration event occurs, the number of periods required to perform the backup tasks respects the deadline. Thus, the VMs chosen in the function get_best_VM (lines 8 and 10) guarantees that $end_{t_i} + runtime(Rec_Group_{t_i}^{vm_j}, S_VM_{t_i}) < D$, where end_{t_i} is the end time of the primary task t_i .

After scheduling all backup tasks of $Rec_Group_{t_i}^{vm_j}$, the period when the migration of tasks will have to start to meet the deadline, $start_bkp_{t_i}^{vm_j}$, is computed (see lines 15 and 16).

Algorithm 2 Backup Task Scheduling

```
Input: A_VM, M, D
 1: B_VM = \emptyset;
 2: for all vm_j \in A\_VM such that vm_j^{market} = spot do

3: for all t_i \in Queue^{vm_j} do

/*Create the Rec\_Group_{t_i}^{vm_j} using Equation 2*/

4: Rec\_Group_{t_i}^{vm_j} = create\_recovery\_Group(t_i)
           /* Schedule each t_k \in Rec\_Group_{t_i}^{vm_j} on a set of VMs.
           The VMs choice is guided by the monetary cost resulting
           from the product of price and execution time */;
 5:
           S_{-}VM_{t_i} = \emptyset;
           for all t_k \in Rec\_Group_{t_i}^{vm_j} do
 7:
               vm_{bkp} = NONE;
              /* Select a VM able to execute t_k, without violating the
               deadline, with the smallest monetary cost*/
               vm_{bkp} = get\_best\_VM(t_k, S\_VM_{t_i});
 8:
               if vm_{bkp} is NONE then
 9:
10:
                  vm_{bkp} = get\_best\_VM(t_k, M);
               end if
11:
12:
              insert(t_k, vm_{bkp});
               update(S_VM_{t_i}, vm_{bkp});
13:
14:
           rtime = runtime(Rec\_Group_{t_i}^{vm_j}, S\_VM_{t_i});
15:
           start\_bkp_{t_i}^{vm_j} = compute\_stbkp(rtime, D);
16:
           update(B_VM, S_VM_{t_i});
17:
        end for
18:
19: end for
20: BQ = create\_backup\_map(B\_VM);
```

IV. EXPERIMENTAL RESULTS

This section presents execution times and monetary costs of simulations accomplished with real BoT applications, using the configuration of Amazon EC2 virtual machines, and considering a real VMs market history.

According to the information on Amazon Web Server (AWS)², only the VMs of families C3, C4, C5, M4, M5, R3, and R4 with memory below 100 GB, running in the spot market, are able to hibernate if an interrupt occurs. Therefore, for the purposes of this work, the fourth generation general purpose VMs (M4) and the third and fourth generation

TABLE III
VARIABLES OF BACKUP SCHEDULING HEURISTIC

| Name | Description | | |
|---------------------------|---|--|--|
| M | Set of VMs | | |
| D | Deadline defined by the user, to be respected even | | |
| | in presence of VM hibernation | | |
| A_VM | Set of VMs selected to execute primary tasks | | |
| $B_{-}VM$ | Set of VMs selected to execute backup tasks | | |
| vm_j | VM selected to execute primary tasks | | |
| $Queue^{vm_j}$ | Set of tasks scheduled on vm_j | | |
| $Rec_Group_{t_i}^{vm_j}$ | Set of backup tasks to be executed due to hibernation | | |
| | of vm_j along t_i execution | | |
| $S_VM_{t_i}$ | Set of VMs selected to execute backup tasks of the | | |
| | $Rec_Group_{t_i}^{vm_j}$ | | |
| t_k | A backup task | | |
| vm_{bkp} | VM selected to execute backup task t_k | | |
| rtime | Number of periods required to execute all tasks of | | |
| | Number of periods required to execute all tasks of $Rec_Group_{t_i}^{vm_j}$ using VMs of $S_VM_{t_i}$ | | |
| $start_bkp_{t_i}^{vm_j}$ | Time when the migration of tasks in vm_i must start | | |
| | due to hibernation along t_i execution | | |
| BQ | Scheduling map of backup tasks containing VMs and | | |
| | the starting times of backup tasks | | |

TABLE IV
FUNCTIONS AND PROCEDURES OF BACKUP SCHEDULING HEURISTIC

| Name | Description |
|---|--|
| $create_recovery_Group(t_i)$ | Create $Rec_Group_{t_i}^{vm_j}$ using Equation 2 |
| $get_best_VM(t_k, S_VM_{t_i})$ | Select a VM of $S_VM_{t_i}$ that executes t_k with minimum monetary cost |
| $insert(t_k, vm_{bkp})$ | Insert backup task t_k into the execution queue of vm_{bkp} |
| $runtime(Rec_Group_{t_i}^{vm_j}, S_VM_{t_i})$ | Calculate the number of periods necessary to execute all tasks in $Rec_Group_{t_i}^{vm_j}$ using VMs of $S_VM_{t_i}$ |
| $compute_stbkp(rtime, D)$ | Calculate the time when the migration procedure has to start to execute backup tasks for <i>rtime</i> periods respecting D |
| $update(B_VM, S_VM_{t_i})$ | Include VMs of $S_VM_t_i$ into B_VM |
| $create_backup_map(B_VM)$ | Create the scheduling map of backup tasks |

VMs optimized for computation (C3 and C4) were used. By choosing the third and fourth generation VMs, it was possible to compute the slowdown using the data from [22].

The workload used in the evaluation were obtained from [23], a database that contains the execution traces of jobs submitted to Google's servers throughout the month of March 2011. Based on these traces, we have defined: (i) the number of tasks of a job; (ii) the execution time of each task of the job; and (iii) the average memory footprint. For the experiments, four BoT-type jobs were chosen from the first 10 days of the traces. Table V summarizes the main characteristics of these

²https://docs.aws.amazon.com/AWSEC2/latest/UserGuide/spot-interruptions.html

jobs, followed by the corresponding deadlines considering the virtual machines used in our tests. We adopted the shortest deadlines which enable the generation of valid primary and backup scheduling, for each job. These values were computed iteratively, using VM_time_{limit} value equals to 0.5, starting with D = 1(h) in increments of 1 hour, stopping at the first valid scheduling given by the algorithms 1 and 2. The execution times were obtained from Google machines used in 2011. As the hardware information and computational capacity of these machines are not provided, we assumed that these times were obtained with the VM with the lowest computational power, whose memory capacity was sufficient to meet the requirements of the tasks. As we can observe in Table VI, among the VMs, the ones containing VCPUs with the lowest computational power are c3.large and m4.large. Therefore, they are considered our baseline regarding processing capacity. Spot and on-demand VM prices were obtained on September 10, 2018, considering us-east-1 and us-east-1a regions. Table VI shows the characteristics of these VMs, along with the corresponding slowdown values of their VCPUs. Based on the latter and considering, as mentioned above, that the duration of the tasks, extracted from Google traces, were obtained from execution them on the slowest VMs (base time duration), the duration of each task in the other VMs was obtained through the product of the respective slowdown value by its base duration.

| TABLE V | | | | | |
|-------------|----------|-----------|--|--|--|
| BOT ATTRIBU | JTES ANI | DEADLINES | | | |

| Job ID | #Tasks | #Tasks Memory Execution time of a task | | | D | |
|--------|---------|--|------|-------|--------|-------|
| J00 1D | # 1asks | Wichiory | min. | avg. | max. | |
| J207 | 31 | 6.10 | 7.03 | 19.75 | 49.31 | 17.00 |
| | | GB | (h) | (h) | (h) | (h) |
| J402 | 103 | 2.90 | 7.87 | 29.83 | 94.04 | 29.00 |
| | | GB | (h) | (h) | (h) | (h) |
| J819 | 68 | 3.97 | 6.42 | 18.87 | 51.53 | 16.00 |
| | | GB | (h) | (h) | (h) | (h) |
| J595 | 97 | 3.14 | 7.15 | 45.80 | 120.39 | 40.00 |
| | | GB | (h) | (h) | (h) | (h) |

TABLE VI VMs attributes

| Type | #VCPUs | Memory | On- | Spot | slowdown |
|------------|--------|---------|---------|----------|----------|
| | | | demand | price | |
| | | | price | | |
| m4.large | 2 | 8.00 GB | 0.1\$ | 0.0324\$ | 1.000 |
| c3.large | 2 | 3.75 GB | 0.10\$ | 0.0294\$ | 1.000 |
| c4.large | 2 | 3.75 GB | 0.1\$ | 0.0308\$ | 0.655 |
| m4.2xlarge | 8 | 32.0 GB | 0.4\$ | 0.1326\$ | 0.672 |
| m4.xlarge | 4 | 16.0 GB | 0.2\$ | 0.0648\$ | 0.477 |
| m4.4xlarge | 16 | 64.0 GB | 0.8\$ | 0.3257\$ | 0.513 |
| c3.xlarge | 4 | 7.50 GB | 0.21\$ | 0.0588\$ | 0.323 |
| c4.xlarge | 4 | 7.50 GB | 0.199\$ | 0.0617\$ | 0.332 |
| c3.2xlarge | 8 | 15.0 GB | 0.42\$ | 0.1175\$ | 0.475 |
| c4.2xlarge | 8 | 15.0 GB | 0.398\$ | 0.1262\$ | 0.447 |
| c3.4xlarge | 16 | 30.0 GB | 0.84\$ | 0.2350\$ | 0.163 |
| c4.4xlarge | 16 | 30.0 GB | 0.796\$ | 0.2535\$ | 0.162 |
| c4.8xlarge | 36 | 60.0 GB | 1.591\$ | 0.4986\$ | 0.162 |
| c3.8xlarge | 32 | 60.0 GB | 1.68\$ | 0.4700\$ | 0.161 |

A. Experimental results in different hibernation scenarios

In order to evaluate the effectiveness of our scheduling solution in terms of makespan and monetary cost, we compared it with an strategy (On-demand) that uses only ondemand virtual machines, while for evaluating the impact of hibernation, we compared it with a strategy that migrates tasks as soon as the VM, where the tasks have been allocated, hibernates (Immediate Migration), i.e., the latter does not consider the possibility that the VM might resume. Furthermore, we also consider two possible scenarios of execution of our scheduling: (1) no spot VM hibernates (No Hibernation) and (2) a spot VM hibernates and, in this case, either the tasks need to be migrated (Hibernation with Migration) or the VM resumes in time to not violate deadline (Hibernation). In case of hibernation, the latter initiates two hours after the job starts. For the Hibernation with Migration execution, the duration of hibernation is set to 1000 hours, thus forcing task migration; for Hibernation, hibernation duration is just 3 hours and, therefore, task migration is not carried out. Aiming a more accurate analysis of the results, only one spot VM can hibernate in Hibernation and Hibernation with Migration executions. In addition, only one backup migration takes place in *Hibernation with Migration* execution. Finally, the experiments randomly select the spot VM that should hibernate.

1) Hibernation without Migration: Figures 5 presents the monetary costs in the *Hibernation* scenario, i.e., our scheduling does not migrate tasks because the hibernated spot VM instance resumes in time to meet the application's deadline. As we can observe in the figure, its monetary cost is similar to the one without hibernation, represented by the *Hibernation* and No Hibernation bars respectively. Such a result is expected since, according to the new pricing policy defined by AWS in December 2017, the user only pays for the time the spots are running, and during hibernation, the user is charged only for storage, whose price on September 10, 2018 was 0.10 per GB per month. As, in the experiments, the maximum hibernation time is shorter than 30 hours, it is, thus, negligible. When our solution is compared with the one that migrates tasks as soon as the hibernation occurs (Immediate Migration), we observe that the latter is more expensive than the second in 59.97%, 26.74%, 55.15% e 40.51%, for J207, J402, J819 and J595, respectively. Such a difference in price can be explained since in the *Immediate Migration*, the user was charged for the two hours of execution of the spot VMs as well as for the ondemand VMs used for migration. On the other hand, it is worth mentioning that the Immediate Hibernation monetary cost is, for the four jobs, on average, 57.31% lower than the (On-demand) one. This happens because part of the tasks were executed as primary ones in spot VM with high computational power, and, therefore, fewer slots were needed to complete execution on the on-demand VMs.

Figure 6 shows that our solution, *Hibernation*, has a makespan longer than the *Immediate Migration* strategy. This occurs because the former has an additional 3 hours due to

hibernation, while the latter migrates immediately, continuing running the job's tasks within this 3 hours.

In contrast, since the VMs usually chosen by the *Immediate Migration* strategy are low cost ones, performing poorly, its makespan can be longer than *On-demand* and *No Hibernation* ones, that allocate VMs with higher computation power. Moreover, when the virtual machine hibernates, the executing task is re-started from the beginning in another VM. So, its execution time can be computed (in the makespan) almost twice in the worst case.

2) Hibernation with Migration: Table VII presents the number of VMs and the corresponding types used before and after migration for each job, where the hibernated VM is indicated by (H). Note that we consider that only one VM hibernates in these tests, i.e., even if several instances of a same VM type are allocated, only one of them may hibernate. Figures 7 and 8 respectively show the monetary costs and makespans in the scenario where our scheduling (Hibernation with Migration) migrates tasks of a hibernated spot VM.

TABLE VII

VMS USED TO EXECUTE JOBS BEFORE AND AFTER MIGRATION

| Job ID | Before Migration | After Migration |
|--------|------------------------|-------------------------|
| J207 | (H) 1-c3.4xlarge(spot) | 1-c3.4xlarge(on-demand) |
| | 1-c3.8xlarge(spot) | 1-c3.8xlarge(spot) |
| | 1-c4.8xlarge(spot) | 1-c4.8xlarge(spot) |
| J402 | (H) 5-c3.4xlarge(spot) | 1-c3.4xlarge(on-demand) |
| | 3-c4.8xlarge(spot) | 4-c3.4xlarge(spot) |
| | | 3-c4.8xlarge(spot) |
| J819 | 1-c3.4xlarge(spot) | 1-m4.4xlarge(on-demand) |
| | (H)1-c3.8xlarge(spot) | 1-c3.4xlarge(on-demand) |
| | 1-c4.8xlarge(spot) | 1-c3.4xlarge(spot) |
| | | 1-c4.8xlarge(spot) |
| J595 | 2-c4.8xlarge(spot) | 2-c4.8xlarge(on-demand) |
| | (H)3-c3.8xlarge(spot) | 2-c4.8xlarge(spot) |
| | 2-c3.4xlarge(spot) | 2-c3.8xlarge(spot) |
| | | 2-c3.4xlarge(spot) |

The monetary cost of Hibernation with Migration strategy is equal to the *Immediate Migration* since the backup map used by both of them are similar. These costs are higher (on average, 30.74% in our experiments) than the one required by the primary scheduling alone (No Hibernation), since the former use spot VMs within the first two hours of execution, as well as on-demand VMs for backup migration. On the other hand they are 136.00% lower than On-demand strategy costs. In terms of makespan, the *Hibernation with Migration* makespans is close to the deadlines defined in the Table V. Such a behaviour is expected since our approach waits till the $start_bkp$, which is the latest time that hibernation can be tolerated without exceeding the deadline. Note that in the case of the Immediate Migration strategy, the makespan is shorter than the *Hibernation with Migration* one. In our experiments, this difference was, on average, 74.26%.

Note that, although in some cases, the tasks can migrate to VMs of equivalent processing powers (see the case of J207), even in *Immediate Migration* strategy, the makespan increases. As pointed out in the previous section, it happens because the execution time of a task, initially started in a VM that

hibernates along its execution, can be computed almost twice, when it migrates, in the worst case.

When comparing *Hibernation* with *Hibernation with Migration*, the duration of hibernation has an impact in both makespans due to the duration of the execution itself. However, in the case of *Hibernation*, where the hibernated spot VM resumes in time to respect the deadline, the monetary cost is lower than *Hibernation with Migration*, as we can confirm in Figures 5 and 7.

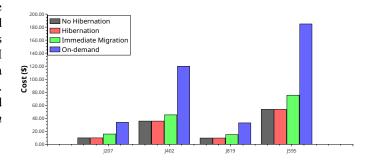


Fig. 5. Monetary costs considering that the spot VM resumes.

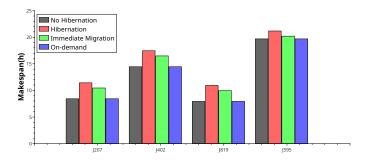


Fig. 6. Makespans considering VM the spot VM resumes.

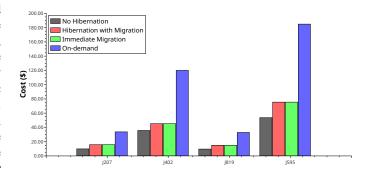


Fig. 7. Monetary costs with tasks migration.

B. Experimental Results with hibernation based on the variation of spots price

The results presented in this section are from experiments that consider spot price variations for regions us-east-1 and

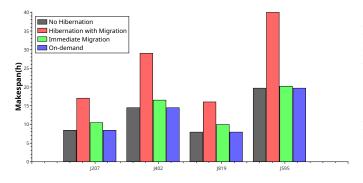


Fig. 8. Makespans with tasks migration.

zone us-east-1a between March and April of 2017, defining hibernation traces for the VMs of Table VI. That history of price variation predates the changes in AWS pricing policies, occurred in December 2017, which stabilized the prices of VMs such that peaks of variation ceased to occur³. As shown in Figure 9, in the previous policy, prices could have significant peaks of variation, with intervals lasting a few minutes or hours.

The hibernation traces were generated considering a fixed threshold of \$0.4, which represents the average price value in the first 24 hours of the history. Thus, the onset of hibernation is the period in which the VM price is higher than this value. Analogously, when the price drops to a value below the threshold, we consider that the VM resumes execution. The generated traces has two hibernation points: (1) c4.8xlarge VMs hibernation at 4.21 hours after the start of execution and lasting 43.51 minutes; (2) c3.4xlarge VMs hibernation at 23.7 minutes after the start of execution and lasted 1.22 hours.

The number of VMs affected by hibernation is not the same for all evaluated jobs. While in the J207 and J819 jobs only 2 VMs hibernate, in Job J402 there are 8 hibernations of different VMs. This variation is expected, since different job tasks are scheduled to VMs of different types.

As can be observed in Figure 10, our solution, *Hibernation*, presents the lowest monetary cost, with an average difference of 167.43 %, relative to the *Immediate Migration*'s one, and 240.94 % in relation to the *On-demand*'s one. It is noteworthy that in Job J402, *Immediate Migration* has a cost which is 6.73 % higher than the *On-demand*'s one. The former used 8 ondemand VMs for migration, which raised the monetary cost, added to the costs of the VMs spots used until the beginning of their hibernation. On the other hand, for Job J402, our approach presents a significantly lower cost than the *Immediate Migration*'s one (260.26 %), since the duration of none of the of hibernation of the corresponding spot VMs triggered the migration of their tasks.

Regarding makespan, shown in Figure 11, our approach is 7.52 % longer than *On-demand*'s one and 24.92 % shorter than *Immediate Migration*'s one. These difference can be explained since the duration of VMs hibernation is up to

1.22 hours, it is not necessary to start the task migration process in any of the evaluated jobs. Therefore, this increase is due only to the hibernation of the VMs. On the other hand, in *Immediate Migration* the scheduling of backup tasks chooses firstly cheaper on-demand VMs, usually with lower computational power.

Although our approach increases the makespan when compared *On-demand*'s one, the monetary costs are lower than the two other approaches. Thus, the results from the experiments with the hibernation trace confirm those from the previous experiments.

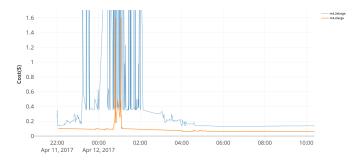


Fig. 9. Sample of the price variation of two EC2 VMs in the spot market during april 2017.

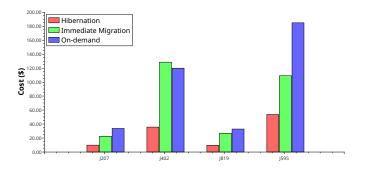


Fig. 10. Monetary costs with hibernation based on AWS price history.

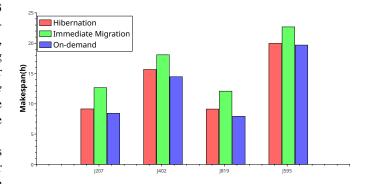


Fig. 11. Makespans with hibernation based on AWS price history.

³https://aws.amazon.com/blogs/compute/new-amazon-ec2-spot-pricing/

V. CONCLUDING REMARKS AND FUTURE WORK

This paper proposed a static scheduling for bag-of-task applications with deadline constraints, using both hibernation-prone spot VMs (for cost sake) and on-demand VMs. Our scheduling aims at minimizing monetary costs of bag-of-tasks, respecting application's deadline and avoiding temporal failures. Although we have theoretically evaluated the proposed strategy, the characteristics of Bot applications and VMs, as well as the VM market price variation, were acquired from real scenarios. Our results confirmed the effectiveness of our scheduling and that it tolerates temporal failures.

Short-term directions of our work comprise the automation of the computing of both the minimum deadline and the VM_time_{limit} , in accordance with the characteristics of the application and the available virtual machines as well as the maximum number of hibernations tolerated at each spot virtual machine. Thus, the user will always have a feasible static scheduling for the expected scenario. In longer-term future, we also intend to work in a dynamic version of the proposed scheduling which periodically takes checkpoints of the tasks, so that, in the migration case, the tasks can start their executions from the last checkpoints, instead of being re-started from the beginning.

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