CS528

Robust Scheduling of **Scientific Workflows** with Deadline and **Budget Constraints** in Clouds

Minimizing Redundancy to Satisfy Reliability Requirement for a Parallel Application on Heterogeneous Service-oriented Systems

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Introduction

- **Scientific workflows** Scheduling in Cloud
  - Cost and Deadline common criteria
- Reliability and Robustness is also Important
- Robust scheduling
  - that handles performance variations of Cloud resources and
  - failures in the environment is essential in the context of Clouds
- Robust and fault-tolerant schedule
  - while minimizing makespan.

Failure in Cloud

- Failures also affect the overall workflow execution and increase the makespan.
- Failures in a workflow application are types
  - Task failures, VM failures, WF level failures
- Task failures may occur due to
  - dynamic execution environment configurations,
  - missing input data, or
  - system errors.
- VM failures are caused by
  - hardware failures and load in the datacenter

Failure in Cloud

- Workflow level failures can occur due to
  - server failures, Cloud outages,
- Prominent fault tolerant techniques that handle such failures are
  - retry, alternate resource, check-pointing, and replication
- Workflow management systems
  - should handle performance variations and
  - failures while scheduling workflows

Robust Scheduler

- A schedule is said to be robust if
  - it is able to absorb some degree of uncertainty
  - in the task execution time
- Robust schedules are much needed in
  - mission-critical applications and
  - time-critical applications
- Robust and fault-tolerant scheduling algorithms
  - identify these aspects and provide a schedule
  - that is insensitive to these uncertainties
  - by tolerating variations and failures
  - in the environment up to a certain degree.

Robust Scheduler

- Robustness of a schedule is always
  - measured with respect to another parameter such as makespan, schedule length
- Robustness is usually achieved
  - with redundancy in **time or space**
  - Adding **slack time** or **replication of nodes**.
- Robust Scheduling Approach
  - efficiently maps tasks on resources
  - judiciously adds slack time based on the deadline and budget constraints

System Model

- **Cloud environment** in system model has a single datacenter
  - that provides heterogeneous VM/resource types

$$VT = \{vt_1, vt_2, \ldots, vt_m\}$$

- Each VM type has : config. and price
- Configuration of VM type differs
  - with respect to memory, CPU measured in (MIPS) and OS.
- Each vt_i has a $Price(vt_i)$ associated with it
  - charged on an unit time basis
  - (e.g. 1 hour, 10 minutes, etc.)

Kind of Failure/Uncertainty

- Two kinds of uncertainties
  - task failures and performance variations of VMs.
- Performance variations in the system arise due to
  - factors like load, network delays, VM consolidation, etc.
- Due to the performance variation of a VM
  - Execution time of task increase/decrease by ***y***
- ***y*** is a random variable with a mean value of zero.
- Actual execution time (AET) of a task is

$$AET(t_j) = e_j (1 + y),$$

  - where e_j is the expected execution time of task t_j .

Workflow representation

- **Workflow** as DAG , $G = (T, E)$,
  - where T is a set of nodes, $T = \{t_1, t_2, \ldots, t_n\}$, each node represents a task
  - E represents a set of edges between tasks, which can be control and/or data dependencies.
- Each workflow : bounded by user defined
  - deadline D, money budget B constraints.
- Each task t_j has a task length (Payload/work) of
  - len_j given in Million Instructions.
- Task length and MIPS value of VM are used
  - Estimate the execution time on a particular VM type

Makespan and Deadline of Workflow

- **Makespan:** ***M*** is total elapsed time required to execute the entire workflow

$$M = finish(t_n) - ST$$

  - ***ST*** is the submission time of the workflow
  - $finish(t_n)$ is the finish time of the exit node t_n.
- Deadline Meeting Desirable : $M \leq D$
- **Total Cost:** ***C***, is total cost of workflow execution
  - which is sum of price for VMs used to execute the workflow, $C=\sum_{i=1}^{m} Price(vt_i) * Time(vti)$
- Budget Meeting Desirable : $C \leq B$

Quantifying Robustness

- Robustness metric : *robustness probability* R_p
  - likelihood of the workflow to finish before the given deadline

$$R_p = (TotalRun - FailedRun)/(TotalRun)$$

  - where ***TotalRun*** is number of times the experiment was conducted
  - ***FailedRun*** is number of $finish(t_n) \leq D$ was violated.
- Robustness metric : *tolerance time* R_t
  - Amount of time a workflow can be delayed without violating the deadline constraint

$$R_t = D - finish(t_n)$$

  - Expressing the amount of uncertainties it can further withstand.

Critical Path (CP)

- **Definition:** *critical path* of a workflow is
  - Execution path between entry and exit nodes of the workflow with longest execution time
- **Definition:** *critical parent (CP)* of t_j is the parent t_p
  - whose sum of start time, data transfer time and execution time
  - is maximum among other parent nodes.

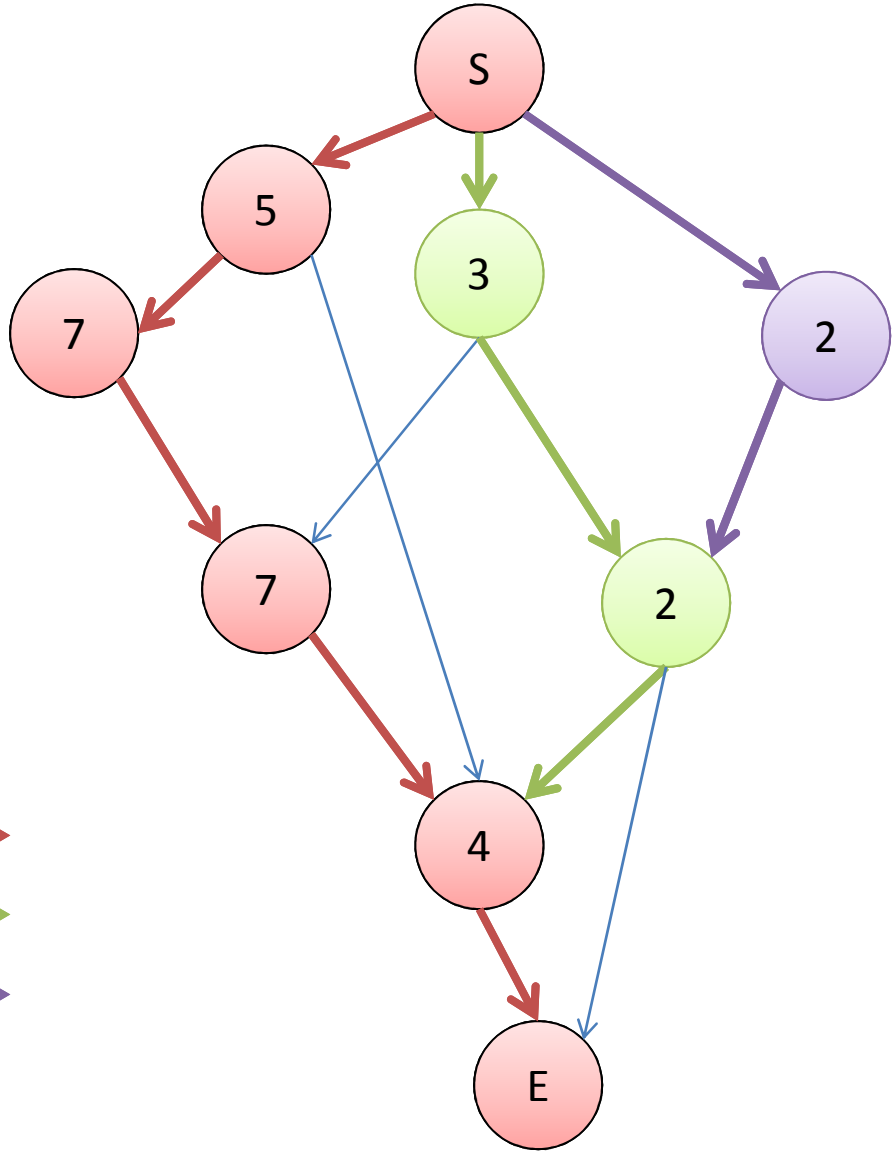
Partial Critical Path (PCP)

- **Definition :** *partial critical path (**PCP**)* of t_j is
  - a group of tasks that share a high dependency between them
- ***PCP*** is determined by identifying
  - the unassigned parents
- Unassigned parent is a node that
  - is not scheduled or assigned to any ***PCP***
- ***PCP*** is created
  - By finding the unassigned critical parent of the node and
  - Repeating the same for the critical parent recursively
  - Until there are no further unassigned parents.

Partial Critical Path (PCP)

- Partial critical paths can be scheduled
  - On a single resource, optimizing time and cost
- ***PCP***s of a workflow are **mutually exclusive**
  - i.e., each task can be in only one ***PCP***.
- Approaches need to decomposes the workflow
  - into smaller groups of tasks (***PCP***s),
  - which helps in scheduling.
- For every ***PCP***
  - the best suitable VM type with a robustness type is selected.

PCP Example



PCP 1 →
PCP 2 →
PCP 3 →

Find PCP in DAG

Algorithm 1: FindPCP(t) //FindPCT(t_n) initial call

//Determine the PCP and allocate a VM for it.

input : task ***t***

while *t has unassigned parent* **do**

PCP ← ***NULL***, t_j ← ***t***

while *there exists an unassigned parent of* t_j **do**

add critical parent t_p of t_j to ***PCP***

t_j ← t_p

call AllocateResource(***PCP***)

for $t_j \in$ ***PCP*** **do**

marks t_j as assigned

call FindPCP(t_j)

Scheduling PCP with Robustness

- Robustness type defines the amount of slack
  - that added to the PCP execution time
  - It dictates the amount of fluctuation in **the execution time a PCP (*ET(PCP)*)** can tolerate.
- Example of four types of robustness that can be associated with a PCP
  1. **No-robustness** : not add any slack time to ***ET(PCP)***
  2. **Slack** : adds a predefined limit of time to ***ET(PCP)***
  3. **One node failure**: largest ET among the PCP nodes is added to ***ET(PCP)***
     - Sufficient slack time to handle failure of task with largest ET in the PCP.
  4. **Two node failure** : Two largest ET of nodes PCP is added to ***ET(PCP)***

Selection of VM type & Associated Robustness

- Exhaustive solution set generated

$$SS = \{ s_1, s_2, \ldots, s_{m*l} \}$$

  - where ***m*** is the number of VM types (**m** is small)
  - ***l*** is the number of robustness types (***l*** is small)
- *SS* consists of solutions with
  - every possible robustness type for every VM type
- Each solution for a PCP, $s_i = \{vt_i, RT_i, PCP_{ci}, PCP_{ti}\}$ for VM type vt_i consists of
  - Robustness type (RT_i),
  - PCP cost (PCP_{ci}) and
  - PCP execution time (PCP_{ti})

PCP Deadline Constraints

- *SS* is reduced into a smaller set of feasible solutions
  - based on deadline and budget constraints
- *D* is evaluated by adding the PCP execution time
  - Of the chosen instance and robustness type
  - with top level and bottom level

$$\mathbf{\mathit{TopLevel} + \mathit{PCP}_t + \mathit{BottomLevel} \leq \mathit{D}}$$

- ***TopLevel*** of PCP : sum of execution times of nodes
  - on the longest path from the entry node to the first node of PCP.
- ***BottomLevel*** of PCP : sum of execution times of nodes
  - on the longest path from the end node of the PCP to the exit node.

PCP Budget Constraints

- Budget Constraint is $PCP_c \leq PCP_b$
  - where PCP_c is the total cost of the PCP.
  - PCP Budget ***PCPb*** : amount can be spent on the PCP
- PCP_b is decomposed from the overall budget

$$PCP_b = (PCP_t/TT) * B$$

  - where, ***TT*** is the total time of the workflow, sum of execution times of the all the tasks on VM type, vt_{ref} .
  - VM with the least MIPS value as the reference type, vt_{ref}
  - PCP_t is the total execution time of the PCP on vt_{ref}.
- When $PCP_b < LP_r$,
  - Price required to execute on the cheapest resource,
  - PCP_b is assigned the value LP_r.

Best Solution for PCP

- *findBestSolution* method chooses the appropriate VM type vt_i for a **PCP**
  - based on the resource selection policy from the feasible solution set ***FS***.
- Three resource selection policies used three objectives, namely
  - *robustness*, *time* and *cost*
  - priorities among these objectives change for each of these policies.

Policies for Best Solution: for PCP

- Robustness-Cost-Time (RCT)
  - Prioritize Robustness over Cost
  - Prioritize Cost over Time
- Robustness-Time-Cost (RTC)
  - Prioritize Robustness over Time
  - Prioritize Time over Cost
- Weighted
  - Assign weights for each of them

Policies for Best Solution: RCT

- Prioritize Robustness(R) over Cost, Cost over Time
- Objective: max(R), min(Cost) and min(makespan)
- Solutions in feasible solution set are sorted based
  1. On the robustness type (R),
  2. Sol with Same R are sorted : increasing cost
  3. Sol with R and C are sorted : increasing time
- Best solution from this sorted list is picked
  - VM type with the associated robustness type
  - is mapped to the tasks of the PCP
- Solutions chosen have high robustness with lower cost

Policies for Best Solution: RTC

- Prioritize Robustness(R) over Time, Time over Cost
- Feasible solution set are sorted based on
  - Robustness, Time and then Cost
- RTC policy selects a solution
  - with high robustness with minimal makespan
- Choices of RTC and RCT policies
  - might have the same robustness type
  - but will vary with respect to the VM type they select

Policies for Best Solution: Weighted

- Users can define their own objective function
  - using the three parameters
  - robustness, time and cost
  - and assign weights for each of them.
- Each value is normalized
  - by taking min and max values for that parameter
- Weights are applied to the normalized values of
  - robustness, time and cost,
  - and based weights the best solution is selected
- Weighted policy : generalized policy
  - used to find solutions according to user preferences

Putting Altogether: Approach

AllocateResource(PCP) *//Alloc suitable robust resource to PCP*

input : PCP, **output**: Robust Resource for PCP

for *Every Instance type* **do** *//Create Solution Set Exhaustively*

    for *Every Robustness type* **do**

        Create Solution Set with PCP_t and PCP_c

FS = null; *Calculate* PCP_b;

for *Every solution in SS* **do**

    time = PCP$_t$ + TopLevel + BottomLevel;

    if *time <= D* *and* **PCP$_c$ <= PCP$_b$ then**

    Add to *Feasible Solution Set (FS)*

//finds best solution according to the chosen policy

RobustResource = findBestSolution(FS, Policy);

Assign every task in PCP to the RobustResource

Reference:

Xie et.al, *Minimizing Redundancy to Satisfy Reliability Requirement for a Parallel Application on Heterogeneous Service-oriented Systems,* IEEE Trans. On Service Computing. 2017.

Introduction

- Large Data Center have many generations of Server
- Bound to be heterogeneous and different failure rate
- Reliability is widely identified as
  - an increasingly relevant issue in heterogeneous service-oriented systems
  - Because processor failure affects the QoS to users
- Replication-based fault-tolerance is
  - a common approach to satisfy application's reliability requirement

Reliability

- Reliability is defined as
  - the probability of a schedule successfully completing its execution,
  - and it has been widely identified as an increasingly relevant issue
- Fault-tolerance by primary-backup replication
  - A primary task will have 0, 1, or k backup tasks
  - is an important reliability enhancement mechanism.
- problem of minimizing redundancy
  - to satisfy reliability requirement for DAG-based parallel application
  - on heterogeneous service-oriented systems

Reliability: Measure

- primary-backup replication scheme
  - The primary and all the backups are called replicas
- Although replication-based fault-tolerance is
  - an important reliability enhancement mechanism
  - but can not be 100% reliable in practice
- Therefore, if an APP application can
  - satisfy its specified reliability requirement
  - Named as reliability goal or reliability assurance then it is considered to be reliable
- Example: APP's reliability requirement is 0.9
  - Only if APPS 's reliability exceeds 0.9, will be reliable.

Issue with Reliability using Redundancy

- Reliability is important QoS requirements
- Replication-based fault-tolerance
- For resource providers,
  - minimizing resource redundancy caused by replication is one of the most important concerns
- Adding more replicas
  - Could increase both reliability and
  - Redundancy for a parallel application
- Both criteria are conflicting
  - low redundancy and high reliability,
  - short schedule length and high reliability

Application Models

- Let $U = \{u_1, u_2, \ldots, u_{|U|}\}$ represent a set of heterogeneous processors
  - where $|U|$ is the size of set U
- Parallel application running on processors is
  - Represented by a DAG $G=(N, W, M, C)$ with known values.
- N represents a set of nodes in G, and
  - Each node $n_i \in N$ is a task with different execution time values on different processors.
- Task executions is non-preemptive

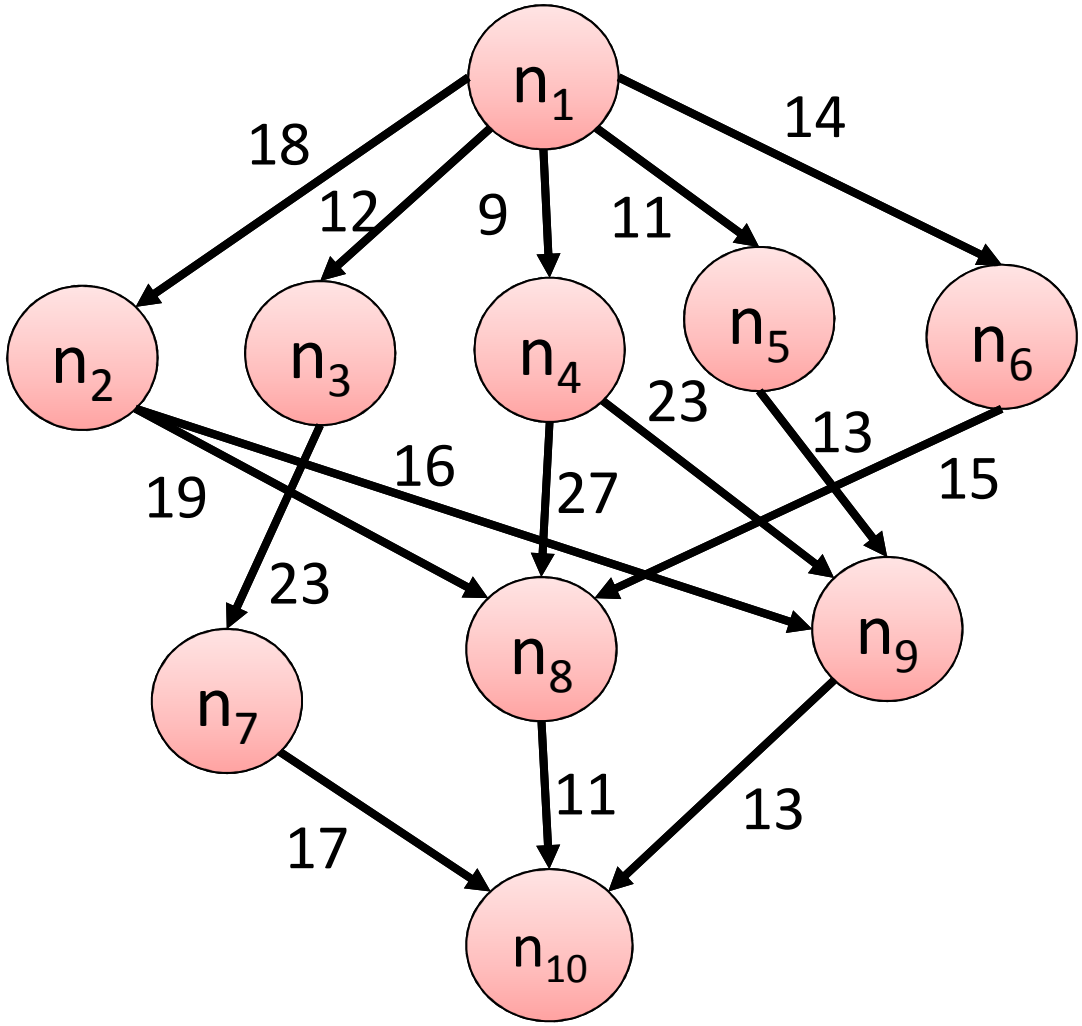
Application Models

- Set of immediate predecessor tasks of n_i : $pred(n_i)$
- set of immediate successor tasks of n_i : $succ(n_i)$
- Tasks without predecessor tasks : n_{entry}
- Tasks with no successor tasks : n_{exit}
- If an application has
  - Multiple entry a dummy entry node
  - Multiple exit tasks, then a dummy exit task
  - Dummy task with zero-weight dependencies is added to the graph.
- *Weight* W is an $|N|X|U|$ matrix in which
  - $w_{i,k}$ denotes the execution time of n_i running on u_k

Application Models

- Set of communication edges is M
  - each edge $m_{i,j} \in M$: communication from n_i to n_j
- Communication time $c_{i,j} \in C$: of $m_{i,j}$
  - if n_i and n_j are assigned to different processors
  - because two tasks with immediate precedence constraints need to exchange messages.
- When tasks n_i to n_j : allocated to same processor,
  - $c_{i,j}$ becomes zero because
  - Intra-processor communication cost is negligible

Application Models: Example



Task	u_1	u_2	u_3
n_1	14	16	9
n_2	13	19	18
n_3	11	13	19
n_4	13	8	17
n_5	12	13	10
n_6	13	16	9
n_7	7	15	11
n_8	5	11	14
n_9	18	12	20
n_{10}	21	7	16

Reliability Model

- Two major types of failures
  - transient failure (also called random hardware failure)
  - permanent failure
- Once a permanent failure occurs
  - Processor cannot be restored unless by replacement.
- Transient failure appears for a short time
  - and disappear without damage to processors
- Mainly takes the transient failures into account in our consideration

Reliability Model

- Suppose you are going from IITG to Airport
  - **CAR M** : 1990 model Maruti 800 car, car is around 30 year old and chances of failure is high
  - **CAR** B : BMW 5 series 2020 car, new cars, chances of failure is low
- Occurrence of failure is dependent on
  - Failure rate of CAR and Distance travelled
- I will prefer not to go above 1km in Car M
- Reliability: Exponential of Failure Rate and Distance $\boldsymbol{R(F, D) = e^{-F.D}}$

Reliability Model

- Occurrence of transient failure for a task follows
  - Poisson distribution
- Reliability of an event in unit time *t* is

$$R(t) = e^{-\lambda.t}$$

  - where λ *constant failure rate per time unit* of processor
- Let λ_k is failure rate of the processor u_k
- Reliability of n_i executed on u_k in its execution time

$$R(n_i, u_k) = e^{-\lambda_k w_{ik}}$$

- Failure probability for n_i without using the active replication is $1 - R(n_i, u_k) = 1 - e^{-\lambda_k w_{ik}}$

Reliability with Replicas

- Each task has replicas with the active replication
- Let num_i ($num_i \leq |U|$) : number of replicas of n_i.
  - Replica set of n_i is $\{n^1_i, n^2_i, \ldots, n^{numi}_i\}$
  - where n^1_i is the primary and others are backups.
- As long as one replica of n_i successfully completed
  - then recognize, there is no occurrence of failure for n_i
- Reliability of n_i is updated to

$$R(n_i) = 1 - \prod_{x=1}^{num_i} 1 - R(n_i^x, u_{pr(n_i{}^x)})$$

where $u_{pr(n_i{}^x)}$ represents assigned processor of n^x_i

- Reliability of the parallel application with precedence-constrained tasks $R(G) = \prod_{n_i \in N} R(n_i)$