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UNIVERSITÀ DEGLI STUDI DI ROMA
Macroarea di Ingegneria

A QoS-Aware Broker for Multi-Provider Serverless Applications

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My thesis is focused on "**serverless computing**".

It is a development paradigm according to which:

- The provider takes care of all aspect of server management.
- Small-granularity billing pricing model: **pay-as-you-go**.
- Cloud application are abstracted as a group of so-called **serverless functions**, which are computation units implementing a business functionality.

Serverless Computing: Overview

A serverless function is executed inside a containerized environment: the so-called **function instance**.

The FaaS platform **automatically** scales the number of function instances.

FaaS platforms impose a **limit** on the number of function instance runnable at the **same time** called **concurrency limit**.

A delay is observed when a new function instance is started by the provider: this event is called **cold start**.

Serverless Computing: Overview

To invoke a **serverless function**, users have to specify a so-called **serverless function configuration**.

- Generally, the **amount of memory allocated** to a serverless function.

Configuration parameters **significantly** affect the **cost** and **response time** of serverless functions.

Serverless Computing: Problems

- The lack of support for application whose functions are hosted on **multiple providers**.
- The lack of support for serverless function implementations abstraction, that is, for the so-called **concrete functions**.
- The fulfillment of **non-functional requirements** concerning the **quality of service** (QoS) levels that should be guaranteed for **multi-provider serverless applications**.
- The fulfillment of **functional requirements** concerning the **orchestration** of multi-provider applications.

Solutions concerning QoS fulfillment **already exist**.

- Many solutions rely on **QoS-aware scheduling algorithms** while others rely on the formulation and **solving of optimization problems**.
  - Generally, proposed solution do **not** support Multi-Provider serverless applications.

- Despite there are some exceptions, current solution are unaware of both the current status of FaaS platforms and user traffic.

Thesis Goals

Goal # 1

To guarantee the **satisfaction of QoS levels** for multi-provider serverless applications.

It was necessary to develop:

1. An **analytical model** to evaluate aforementioned class of applications.
2. A **methodological way** to find the “best” configuration to satisfy QoS constraints.
   - By solving an **optimization problem** (LP).
3. A custom **heuristic algorithm** to rapidly resolve the aforementioned optimization problem.

Goal # 2

The **orchestration** for multi-provider serverless applications.

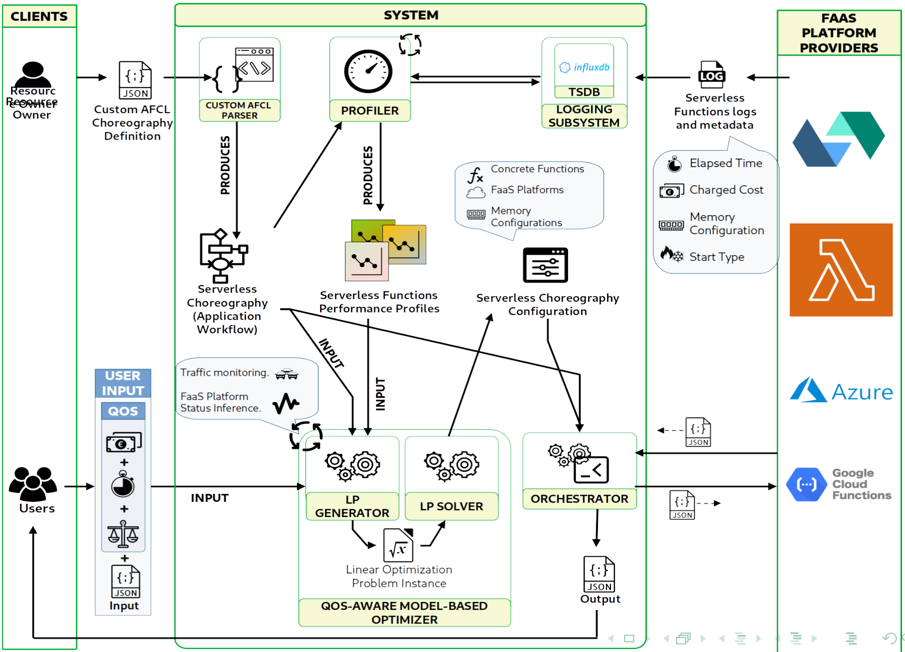
To achieve it, I had to build:

1. A **software framework**
   - Users/Serverless application management (CRUD operations, profiling tasks, orchestration task, etc.)
2. An extension to an already existent **representation scheme** to define a serverless application workflow.
   - Based on an existing language called **abstract function choreography language** (AFCL).

Prototype

Main features of our software framework:

- **Client-server architecture**.
- **Cloud-native** application.
- Includes a set of **adapters** to interact with following FaaS providers:
  - AWS Lambda.
  - Apache OpenWhisk.
- **REST** architectural style.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influxdb
TSDB
LOGGING SUBSYSTEM
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Serverless Functions logs and metadata
Elapsed Time
Charged Cost
Memory Configuration
Start Type
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Concrete Functions
FaaS Platforms
Memory Configurations
Serverless Choreography (Application Workflow)
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FaaS Platform Status Inference.
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ORCHESTRATOR
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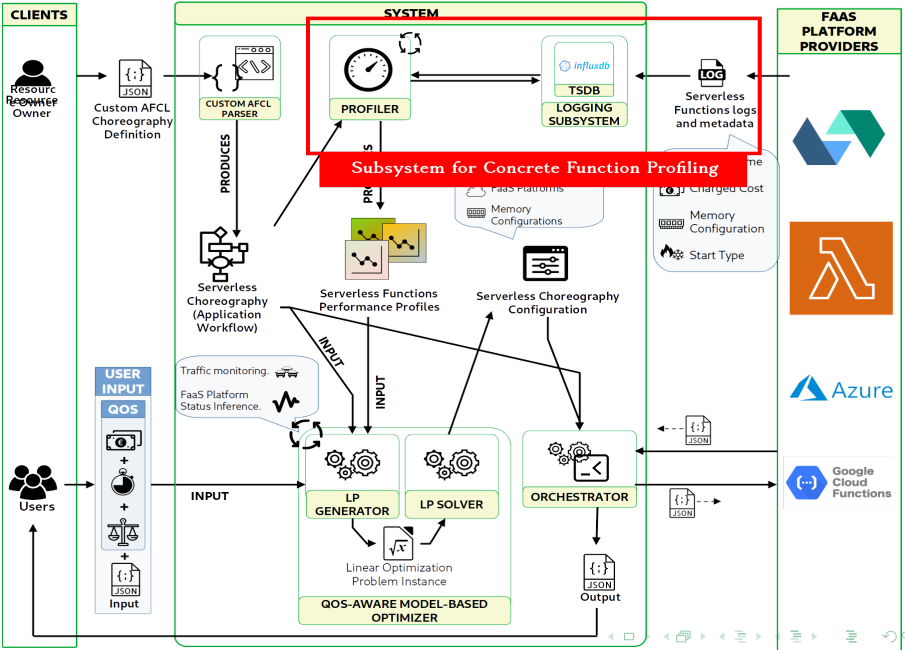
QOS-AWARE MODEL-BASED OPTIMIZER
Output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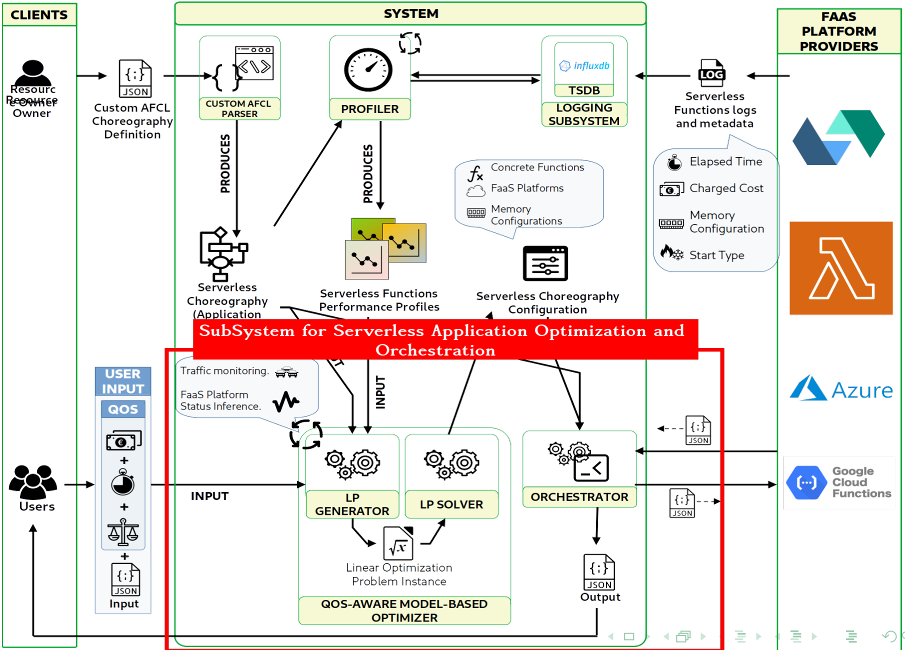
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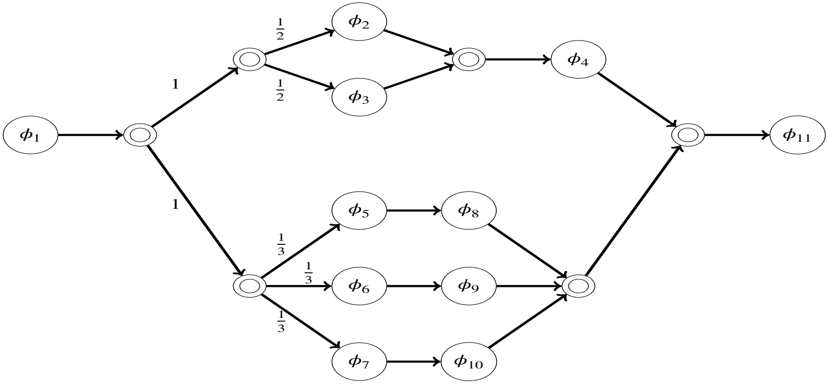
Serverless applications are abstracted to a **weakly connected weighted directed graph**.



System Model

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- Estimations of **average response time** and **cost** under **any** possible configuration of all concrete functions is done using **exponential moving average** approach.
- An estimation of the **probability** according to which a request follows a cold start is required.
  - This is done using **Erlang-B** formula by modeling FaaS platform providers by **sets** of $M/G/K(t)/K(t)$ queueing systems.
    - $K(t)$: the number of function instances at time t.

Optimization Problem

- To achieve our goal consisting in finding the best configuration to guarantee QoS constraints, we have to solve an **optimization problem**.
  - It is based on **multi-dimensional multi-choice knapsack problem formulation** (MMKP).

$$max \quad \sum_{i=1}^{|\mathcal{F}_{\mathcal{E}}(\mathcal{C})|} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot p_{\phi_{i_j}}(t) \tag{5.10}$$

$$\text{subject to} \quad \sum_{i=1}^{|\mathcal{F}_{\mathcal{E}}(\mathcal{C})|} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot c_{\phi_{i_j}}(t) \le C \tag{5.11}$$

$$\begin{aligned} &\sum_{\phi_i \in \mathcal{F}_{\mathcal{E}}(\mathcal{C}) \setminus \mathcal{F}_{\mathcal{E}}(\widetilde{\mathcal{P}})} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot rt_{\phi_{i_j}}(t) + \\ &\quad + \sum_{\phi_h \in \delta_{\mathcal{C}}} \sum_{j=1}^{|\mathbf{F}_{\phi_h} \times \mathbb{N}|} y_{\phi_{h_j}} \cdot rt_{\phi_{h_j}}(t) \le RT \qquad \forall \delta_{\mathcal{C}} \in \Delta_{\mathcal{C}} \end{aligned} \tag{5.12}$$

$$\sum_{i=1}^{|\mathcal{F}_{\mathcal{E}}(\mathcal{C})|} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot a_{(\phi_{i_j}, \omega_P^{(l)})} \le l - R(\mathbf{Q}_{\omega_P^{(l)}}, t) \qquad \forall \omega_P^{(l)} \in \widetilde{\mathbf{S}}_{\mathcal{C}} \tag{5.13}$$

$$\sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} = 1 \qquad \forall i \in \mathbb{N} \cap [1, |\mathcal{F}_{\mathcal{E}}|] \tag{5.14}$$

$$y_{\phi_{i_j}} \in \{0, 1\} \qquad \begin{array}{r} \forall i \in \mathbb{N} \cap [1, |\mathcal{F}_{\mathcal{E}}|] \\ \forall j \in \mathbb{N} \cap [1, |\mathbf{F}_{\phi_i} \times \mathbb{N}|] \end{array}$$

$$\max \sum_{i=1}^{|\mathcal{F}_{\mathcal{E}}(\mathcal{C})|} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot p_{\phi_{i_j}}(t) \tag{5.10}$$

Objective Function

$$\text{subject to} \quad \sum_{i=1}^{|\mathcal{F}_{\mathcal{E}}(\mathcal{C})|} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot c_{\phi_{i_j}}(t) \leq C \tag{5.11}$$

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$$+ \sum_{\phi_h \in \delta_{\mathcal{C}}} \sum_{j=1}^{|\mathbf{F}_{\phi_h} \times \mathbb{N}|} y_{\phi_{h_j}} \cdot rt_{\phi_{h_j}}(t) \leq RT \qquad \forall \delta_{\mathcal{C}} \in \Delta_{\mathcal{C}} \tag{5.12}$$

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Cost Constraint

$$\sum_{\phi_i \in \mathcal{F}_{\mathcal{E}}(\mathcal{C}) \setminus \mathcal{F}_{\mathcal{E}}(\widetilde{\mathcal{P}})} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot rt_{\phi_{i_j}}(t) + \\ + \sum_{\phi_h \in \delta_{\mathcal{C}}} \sum_{j=1}^{|\mathbf{F}_{\phi_h} \times \mathbb{N}|} y_{\phi_{h_j}} \cdot rt_{\phi_{h_j}}(t) \leq RT \qquad \forall \delta_{\mathcal{C}} \in \Delta_{\mathcal{C}} \tag{5.12}$$

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Response Time Constraint

$$\boxed{\sum_{\phi_i \in \mathcal{F}_{\mathcal{E}}(\mathcal{C}) \setminus \mathcal{F}_{\mathcal{E}}(\widetilde{\mathcal{P}})} \sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} \cdot rt_{\phi_{i_j}}(t) + + \sum_{\phi_h \in \delta_{\mathcal{C}}} \sum_{j=1}^{|\mathbf{F}_{\phi_h} \times \mathbb{N}|} y_{\phi_{h_j}} \cdot rt_{\phi_{h_j}}(t) \leq RT \quad \forall \delta_{\mathcal{C}} \in \Delta_{\mathcal{C}} \quad (5.12)}$$

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Capacity Constraint

$$\sum_{j=1}^{|\mathbf{F}_{\phi_i} \times \mathbb{N}|} y_{\phi_{i_j}} = 1 \qquad \forall i \in \mathbb{N} \cap [1, |\mathcal{F}_{\mathcal{E}}|] \tag{5.14}$$

$$y_{\phi_{i_j}} \in \{0, 1\} \qquad \begin{array}{r} \forall i \in \mathbb{N} \cap [1, |\mathcal{F}_{\mathcal{E}}|] \\ \forall j \in \mathbb{N} \cap [1, |\mathbf{F}_{\phi_i} \times \mathbb{N}|] \end{array}$$

Heuristic Algorithm

I develop a custom heuristic algorithm based on **ant colony optimization** (ACO); it is called **pre-provisioned colony optimization algorithm with lazy pheromone update**.

- It is based on a set of computational agents, called **artificial ants**, which **iteratively** construct a solution.
- At each iteration, each agent moves from a solution to another, applying a series of stochastic **local** decisions whose policy is based on following parameters:
  - **Attractiveness**.
  - **Pheromone trail**.

Heuristic Algorithm

Pheromone trails are updated during **every iteration**.

Pheromone trails are used to decide which solutions should be preferred during **next iterations**.

- A **lazy approach** for pheromone trails update is used.
- A **pre-provisioning tactic** is used to anticipates data needs assuring a **lower latency**.

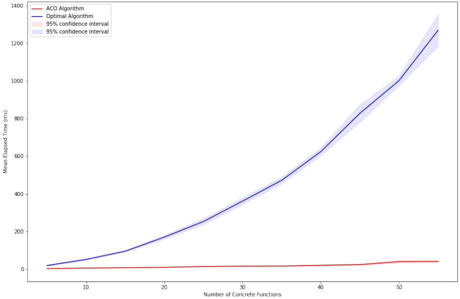
Validation Test

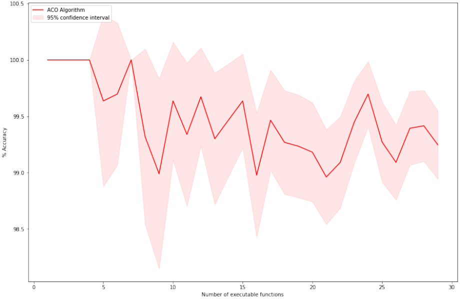
We validate our model through several experiments using an image-processing serverless application.

- Firstly, we check the respect of user specified QoS constraints in a static way thorough several **sequential invocations**.
- Then, we test the model in a dynamically way thorough **several concurrent and parallel invocations**.
    - That experiment aimed to **run out of capacity** on one FaaS provider and so force our prototype to schedule the concrete function on the other.

Heuristic Algorithm Evaluation

- We compared performance of our heuristic algorithm with that of optimal algorithm through several experiments.





Conclusions

1. I presented an analytical model to evaluate the performance of multi-provider serverless application
2. I defined an optimization problems formulation to address the problem of finding a suitable configuration in order to meet user defined QoS constraints
3. I developed a heuristic algorithm to rapidly solve it.
4. I validate proposed solution through test and experimental evaluations using my prototype.

Thanks for your attention!

Questions?