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Distributed workload control for federated service discovery

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Abstract

The diffusion of the internet paradigm in each aspect of human life continuously fosters the widespread of new technologies and related services. In the Future Internet scenario, where 5G telecommunication facilities will interact with the internet of things world, analyzing in real time big amounts of data to feed a potential infinite set of services belonging to different administrative domains, the role of a federated service discovery will become crucial. In this paper the authors propose a distributed workload control algorithm to handle efficiently the service discovery requests, with the aim of minimizing the overall latencies experienced by the requesting user agents. The authors propose an algorithm based on the Wardrop equilibrium, which is a game-theoretical concept, applied to the federated service discovery domain. The proposed solution has been implemented and its performance has been assessed adopting different network topologies and metrics. An open source simulation environment has been created allowing other researchers to test the proposed solution.

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1. Introduction

In the last years, an internetization process aimed at interconnecting everything by means of software interfaces has characterized the ICT evolution. This process spans off a number of novel research areas and related business opportunities. Internet of Things (IoT), Big Data, Future Internet, 5G Networks, etc. are the leaves of the same

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technology tree having internet as its root. As described in^{1,2}, these technologies transformed the internet into a virtual world in which anyone and anything can exchange, consume and provide resources, services, applications, data, information or knowledge, no matter what device, location, context, situation or communication technology they have. The heart of the internet lies in its network infrastructure: on top of it, all the ICT novelties have flourished. The 5G networks represent the beyond the state of the art internet infrastructures. 5G networks will face an unprecedented set of requirements, constraints and situations due to necessity of providing a Full Immersive Experience to its users and an Anything as a Service handler to all its available resources. The management, control and supervision of such a complex, heterogeneous, networked system requires highly scalable approaches and cost-effective solutions. In particular, to make services available to a generic end user, a service discovery functionality is needed. A typical service discovery architecture is based on the interaction of two entities: the service provider and the user agent. The *service provider* stores the information on services, receives queries, performs filtering functionalities, retrieves the services matching the queries. The *user agent* triggers the service discovery process manually or automatically, performs queries on services and receives the list of available and suitable services.

In literature there are a number of service discovery protocols³, but the totality of them is strictly related to a specific network technology, device, operating system or application and is not feasible to cope with the heterogeneity of a typical Future Internet context. An attempt to face this challenge has been done by the 5G Public Private Partnership (5G-PPP) and Future Internet Public Private Partnership (FI-PPP) initiatives, supported by related research projects such as FIWARE and FICORE (see⁴ for more details). In these projects, multi-protocol service discovery frameworks⁶ have been presented able to work in a federated environment, where different service providers, belonging to different administrative domains, share the overall user agents demand of available services. In literature there are many research works presenting architectural solutions that support federated service discovery^{9,10,11,12}, but none of them have investigated from a theoretical point of view the problem of balancing the user agents' requests through the service providers to guarantee a homogeneous latency. In this respect, the authors after having considered several candidate theoretical methodologies^{13,14} have selected Wardrop equilibrium theory⁸.

This paper is just based on the work performed by the authors in the framework of the PLATINO (Platform for Innovative Services in Future Internet) project⁵. The authors present a distributed algorithm based on control and game theory that convergences toward a workload balance between different service providers serving user agents in a federated scenario. The algorithm is based on the game theory concept of Wardrop equilibrium (see Section 3), which, in the literature, has been mainly applied to the transportation field, to develop routing algorithms^{17,18}, and to the communication field, to develop routing¹⁹ and load-balancing algorithms^{20,21}. The paper is organized as follows. In section 2 some preliminary definitions on graph theory have been provided. In section 3 the federated service discovery problem is formulated as a dynamic system, and the properties of its evolution are analyzed to show their convergence toward a Wardrop equilibrium. In section 4 some numerical examples show how the proposed solution performs in different scenarios and how fast it convergences to a feasible solution.

2. Graph theory

Let consider a generic weighted directed graph $G = (V, E, A)$, where V is the finite set of nodes, $E \subseteq V \times V$ is the set of edges, where $(p, q) \in E$ if an arc from p to q exists, and $A = \{a_{pq}\}_{p,q \in V} \in [0; K]^{n \times n}$, with $K > 0$, is the adjacency matrix, where $a_{pq} > 0$ if $(p, q) \in E$, $a_{pq} = 0$ otherwise. The *order* of G is equal to the number $|V| = n$ of nodes; the *size* of G is equal to the number $|E|$ of edges. A node $q \in V$ is an adjacent node, or *neighbor*, of node $p \in V$ if there is an edge $(p, q) \in E$ connecting them. Let N_p be the set of neighbours of p : $N_p = \{q \in V | a_{pq} > 0\}$, $p \in V$. The *degree* of a node is equal to the number $|N_p|$ of its neighbors.

A *path* is a sequence of distinct edges which connects a sequence of adjacent nodes. Let \mathcal{P} be the set of the paths in G . Two nodes $p, q \in V$ are *connected* if there is a path $\pi \in \mathcal{P}$ from p to q , otherwise, they are disconnected. A weighted directed graph G is *strongly connected* if every pair of nodes is connected.

The *length* of a path $\pi \in \mathcal{P}$ is the weighted number of edges in π . The *distance* between two nodes $p, q \in V$ is the length of a shortest path between them if p and q are connected, it is infinite otherwise. The *diameter* of a strongly connected graph G is the maximum distance between two nodes.

Finally, a graph G is *undirected* if A is symmetric, *directed* otherwise.

In this paper, the service providers are identified as nodes, and the communication links connecting them as edges.

3. Problem formulation

3.1. Service provider workload

Consider the set V of service providers. At a given time $t \geq 0$, each service provider $p \in V$ serves a workload $x_p(t) \in \mathbb{R}_{\geq 0}$ associated to the requests coming from the different user agents. $x_p(t)$ can be measured in terms of job units. Each job unit is a mix of processing, caching, network and database actions needed to satisfy each atomic user agent request of service discovery. The jobs vector $\mathbf{x}(t) = [x_p(t)]_{p \in V}^T$ represents the amount of jobs units (workload) served by each provider, at a given time $t \geq 0$. The initial jobs vector at time $t = 0$ is indicated as $\mathbf{x}_0 = \mathbf{x}(0)$. The main role of the service providers is to manage the overall workload λ requested by the user agents. At a given time $t \geq 0$, a jobs vector is feasible if the sum of the service providers' workloads is equal to the total workload, λ :

$$\sum_{p \in V} x_p(t) = \lambda, \forall t \geq 0 \quad (1)$$

3.2. Latency functions

Each service provider responds to the $x_p(t)$ jobs units requested by the user agents with a latency that depends on the value of $x_p(t)$. Each service provider $p \in V$ has a latency function $l_p(x): \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ that maps the workload $x_p(t)$ to the latency (expressed in time units) that the user agents served by the service provider p will experience. The following properties characterize a latency function $l_p(x), \forall p \in V$:

1. $l_p(0) = 0$
2. $l_p(x)$ is non decreasing

The Kleinrock independence approximation⁹ can be used to model the latency function of a given provider $p \in V$:

$$l_p(x) = \begin{cases} x(\mu_p - x)^{-1} & \text{if } 0 \leq x \leq \lambda < \mu_p \\ \lambda(\mu_p - \lambda)^{-1} & \text{otherwise} \end{cases} \quad (2)$$

Let $\Lambda = \{l_p(x)\}_{p \in P}$ be the set of latency functions.

3.3. Federated service providers

Service providers can exchange jobs units with each other in order to minimize the latency offered to the served user agents. In a federated scenario, not all the service providers are neighbours. It means that, due to commercial agreements or network constraints, there could not exist a direct link (p, q) between a couple of service providers $p, q \in V$. However, in a federated scenario each couple of service providers $p, q \in V$ is connected, meaning that even if they are not neighbours, there exist $n \geq 1$ service providers $p_i \in V, i \in \{1, 2, \dots, n\}$ such that the $n + 1$ couples of service providers $\langle p, p_1 \rangle, \langle p_1, p_2 \rangle, \dots, \langle p_n, q \rangle$ are all neighbours. The service provider sequence $\langle p, p_1, \dots, p_n, q \rangle$ is a path connecting the service provider p to the service provider q . The adjacency matrix $A = \{a_{pq}\}_{p, q \in P}$ models how the service providers can interact with each other. The generic element a_{pq} represents the maximum rate (expressed as jobs unit per unit of time) the service provider p can swap jobs unit to the service provider q . In a federated scenario it is assumed that the adjacency matrix A is strongly connected.

3.4. System dynamics

In a federated scenario, the service providers' main objective is to cooperate in a distributed way to guarantee that the latency offered to the user agents applying for a service discovery service is minimal. It means that, at time $t \geq$

0, each service provider $p \in V$ migrates a quantity of job units to another service provider $q \in V$ if $l_p(x_p(t)) > l_q(x_q(t))$. The system dynamics is built on the algorithm developed in⁷. The differential equation describing the jobs vector evolution is:

$$\dot{x}_p(t) = \sum_{q \in V} (a_{qp} r_{qp}(t) - a_{pq} r_{pq}(t)), \forall p \in V \quad (3)$$

Where the *migration ratio* r_{pq} between two providers $p, q \in V$ is defined as:

$$r_{pq}(t) = x_p(t) \cdot \mu_{pq}(x) = x_p(t) \cdot \mu(l_p(x_p); l_q(x_q)), \quad (4)$$

where $\mu(l_p, l_q): \mathbb{R}_{\geq 0} \times \mathbb{R}_{\geq 0} \rightarrow [0, 1]$ is the *migration policy function*, i.e., a function determining the amount of job units assigned to the service provider p that are migrated to the service provider q . A commonly used migration policy is the *linear migration policy*, defined as:

$$\mu(l_p, l_q) = \max\left\{0, \frac{l_p - l_q}{\Delta l_{max}}\right\}. \quad (5)$$

Where $\Delta l_{max} = \max_{p \in V} l_p - \min_{q \in V} l_q$. The *migration policy set*, denoted with Ξ , is given by the set of migration policy functions associated to each couple of service providers $p, q \in V$.

If the system starts from a feasible jobs vector x_0 , it evolves always in feasible jobs vectors; indeed, the system dynamic defined in (3) has the following property:

$$\sum_{p \in V} \dot{x}_p(t) = \sum_{p \in V} \sum_{q \in V} (a_{qp} r_{qp} - a_{pq} r_{pq}) = \sum_{p \in V} \sum_{q \in V} a_{qp} r_{qp} - \sum_{p \in V} \sum_{q \in V} a_{pq} r_{pq} = 0, \quad (6)$$

and, therefore,

$$\sum_{p \in V} x_p(t) = \sum_{p \in V} x_p(0) = \lambda, \forall t \geq 0.$$

3.5. Wardrop equilibrium

The objective of the system dynamics defined in (3) is the convergence towards *stable* jobs vectors; a jobs vector is stable when no fraction of the user agents' demand can decrease the overall latency by moving unilaterally from one service provider to another. It is easy to see that this implies that all service providers must offer the minimal latency: this condition is called *Wardrop equilibrium*.

Definition 1 (Wardrop Equilibrium). A feasible jobs vector $x = [x_p(t)]_{p \in V}^T$ is at a Wardrop equilibrium if, for every couple of providers $p, q \in V$, with $x_p > 0$, $l_p(x_p) \leq l_q(x_q)$ holds. ■

For practical reasons, it is not necessary to wait until the system dynamics achieves a Wardrop equilibrium. The evolution of the system dynamics can terminate whenever the maximum variation $\delta(t)$ between the latencies experienced by the user agents is below an acceptable tolerance δ_{max} , i.e., the convergence time, denoted with t^* , is the first time instant when the following inequality is met:

$$\delta(t) = \max_{p \in V} l_p(x_p(t)) - \min_{p \in V} l_p(x_p(t)) \leq \delta_{max}.$$

3.6. Distributed workload control problem

Definition 1 (Federated discovery control problem). Given a set V of service providers, a total user agents demand λ expressed in job units, a set Λ of latency functions, an initial jobs vector $x_0 = [x_p(0)]_{p \in V}^T$, a strongly connected adjacency matrix $A = \{a_{pq}\}_{p, q \in V}$, a migration policy set $\Xi = \{\mu(l_p, l_q)\}_{p, q \in V}$ and a tolerance $\delta_{max} > 0$, the distributed workload control problem for federated service discovery Π is the tuple $\Pi = \langle V, \lambda, \Lambda, x_0, A, \Xi, \delta_{max} \rangle$

controlled by the system dynamics defined in (3). ■

Theorem 1 – Given a distributed workload control problem for federated service discovery $\Pi = \langle V, \lambda, \Lambda, \mathbf{x}_0, A, \Xi, \delta_{max} \rangle$ controlled by the system dynamics defined in (3), where:

- a. V is the set of service providers with $|V| = n > 1$;
- b. $\lambda > 0$;
- c. Λ is a set of Kleinrock latency functions;
- d. \mathbf{x}_0 is a feasible jobs vector;
- e. A is a strongly connected adjacency matrix;
- f. Ξ is a set of linear migration policy functions;
- g. $\delta_{max} > 0$.

The dynamics (3) characterizing problem Π admits a solution.

Proof of theorem 1.

For the sake of simplicity the service providers can be enumerated from 1 to n . Given the system dynamics defined in (3) and the definition of the migration ratio in (4) it holds that, $\forall i \in \{1, 2, \dots, n\}$:

$$\dot{x}_i(t) = \sum_{j=1}^n (a_{ij}x_j(t)\mu_{ji}(\mathbf{x}(t)) - a_{ij}x_i(t)\mu_{ij}(\mathbf{x}(t))) = \sum_{j=1}^n a_{ji}(t)x_j(t)\mu_{ji}(\mathbf{x}(t)) - x_i(t)\sum_{j=1}^n a_{ij}(t)\mu_{ij}(\mathbf{x}(t)).$$

Let us define:

$$g_{ij}(\mathbf{x}) = g_{ij}(\mathbf{x}(t)) = a_{ij}\mu_{ij}(\mathbf{x}(t)).$$

It follows that:

$$\dot{x}_i(t) = \sum_{j=1}^n x_j(t)g_{ji}(\mathbf{x}) - x_i(t)\sum_{j=1}^n g_{ij}(\mathbf{x}),$$

that is:

$$\dot{\mathbf{x}} = \begin{bmatrix} -\sum_{j=2}^n g_{1j}(\mathbf{x}) & g_{12}(\mathbf{x}) & \dots & g_{1n}(\mathbf{x}) \\ g_{21}(\mathbf{x}) & -\sum_{j=1, j \neq 2}^n g_{2j}(\mathbf{x}) & \dots & g_{2n}(\mathbf{x}) \\ \dots & \dots & \dots & \dots \\ g_{n1}(\mathbf{x}) & g_{n2}(\mathbf{x}) & \dots & -\sum_{j=1}^{n-1} g_{nj}(\mathbf{x}) \end{bmatrix} \mathbf{x}.$$

In compact notation, the system is written as

$$\dot{\mathbf{x}}(t) = g(\mathbf{x}(t))\mathbf{x}(t) = f(\mathbf{x}(t));$$

$$\mathbf{x}(0) = \mathbf{x}_0.$$

This is a non-linear, autonomous dynamic system. It is worth to note that $f(\mathbf{x}(t))$ satisfies the standard conditions for the existence and uniqueness of solutions since, from assumptions c. and f., $f(\mathbf{x}(t))$ is continuous with respect to \mathbf{x} and t . It means that the system dynamics is well defined. ■

Theorem 2 – Given a distributed workload control problem for federated service discovery $\Pi = \langle V, \lambda, \Lambda, \mathbf{x}_0, A, \Xi, \delta_{max} \rangle$ controlled by the system dynamics defined in (3), under the same conditions of Theorem 1, it follows that:

1. The distributed workload control problem for federated service discovery Π converges toward a unique feasible jobs vector \mathbf{x}^* that is at a Wardrop equilibrium;
2. At the Wardrop equilibrium all the latencies are equal and minimal, that is $l_p(\mathbf{x}_p^*) = l_{WE} > 0, \forall p \in V$ and, consequently, the tolerance $\delta(t^*) = 0$.

It means that it necessarily exists a time $\bar{t} \in [0, \infty[$ such that $\delta(\bar{t}) \leq \delta_{max}$.

Proof of theorem 2.

From assumption c. the latency functions have the following properties, $\forall p \in V$:

- $l_p(0) = 0$

- $l_p(x)$ is strictly increasing
- $l_p(0)$ is continuously differentiable in $[0, +\infty[$

The proof derives from the proof of the theorem 1 demonstrated in⁸ (which demonstrates the convergence to Wardrop equilibria on time-varying graphs). Furthermore, being the latencies functions strictly increasing, from⁷ it follows that the Wardrop equilibrium is unique. ■

4. Numerical examples

To assess the performances of the proposed solution, the authors performed simulations for different distributed workload control problems $\Pi = \langle V, \lambda, \Lambda, \mathbf{x}_0, A, \Xi, \delta_{max} \rangle$ controlled by the system dynamics defined in (3).

Three topologies have been considered: (a) undirected full-mesh; (b) undirected, balanced binary tree; (c) directed ring, as shown in Fig. 1. For each topology, an increasing number of nodes $|V| = n = 5i, i \in \{1,2,\dots,10\}$, and a decreasing tolerance (measured in seconds) $\delta_{max} \in \{0.01, 0.005, 0.001\}$ have been considered. In all the simulations, the global workload $\lambda = 1$ jobs units was considered. The set Λ is given by n Kleinrock latency functions specified in (2) where: $\mu_i = 1.1$ if $i \leq n/2, \mu_i = 1.2$ otherwise (i.e., two service provider groups are defined). The set Ξ uses the linear migration policy function specified in equation (5). The initial feasible jobs vector \mathbf{x}_0 is randomly generated, and it is equal for the simulation runs having the same number n of service providers.

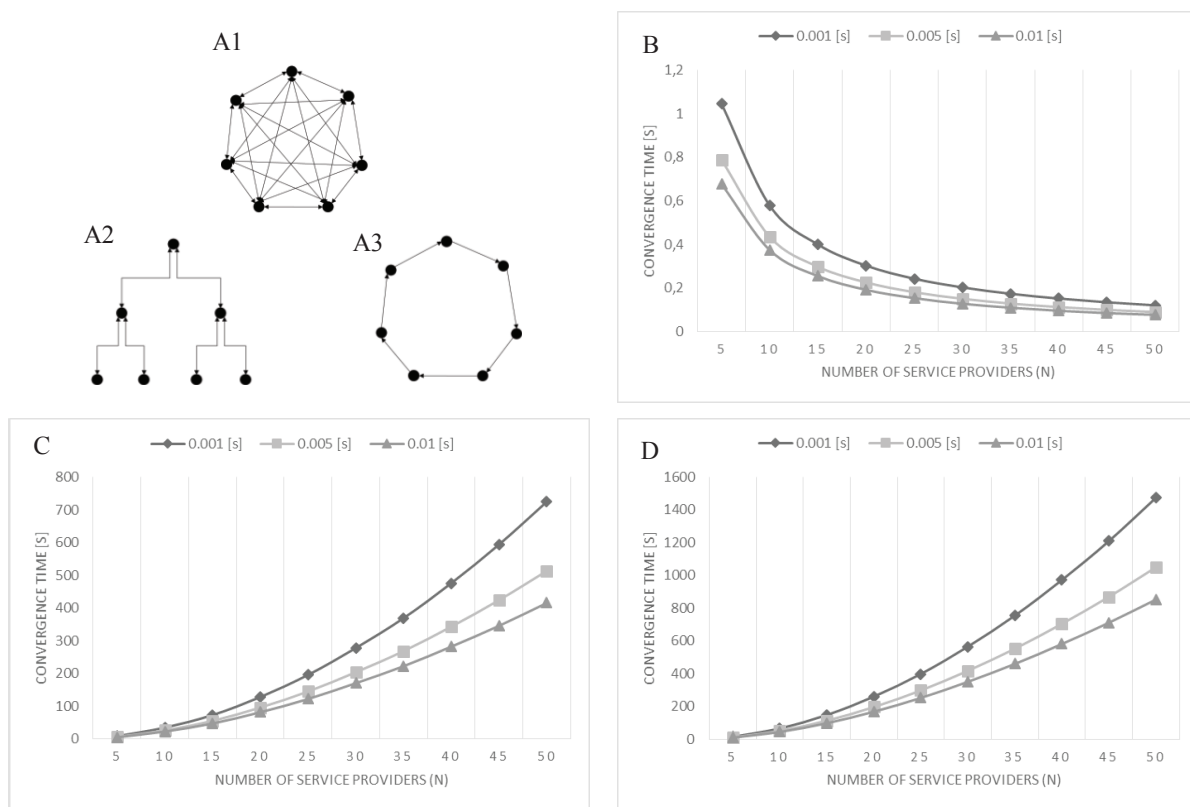


Fig. 1. : Topologies: (A1) undirected full-mesh; (A2) undirected, balanced binary tree; (A3) directed ring and impact of topology on the convergence time: (B) undirected full-mesh, (C) undirected balanced binary tree, (D) directed ring.

The simulation results show that the convergence time depends on the number of interconnections between the federated service providers. In an undirected full-mesh topology the number of interconnection is $n(n - 1)$,

consequently when n increases, the convergence time decreases in a more-than-linear fashion. In an undirected, balanced binary tree topology, the number of interconnections is $2\log_2 n$ and the diameter is $\log_2 n$; when n increases, the convergence time increases in a more-than-linear fashion. In a directed ring topology the number of interconnection is n and the diameter is n , and the convergence time increases with n in a more-than-linear fashion. The undirected full-mesh and the directed ring topologies represent respectively the best and the worst connectivity scenarios, whereas the balanced binary tree is representative of a strict hierarchical topology of federated service providers. To show how the proposed algorithm converges to a balanced solution, we considered a balanced binary tree topology with $n = 31$, and with tolerance $\delta_{max} = 0.0001$ seconds. The set Λ is given by n Kleinrock latency functions described in (2) where: $\mu_i = 1$ if $i \leq n/3$, $\mu_i = 10$ if $n/3 < i \leq 2n/3$, $\mu_i = 20$ otherwise (three groups of providers).

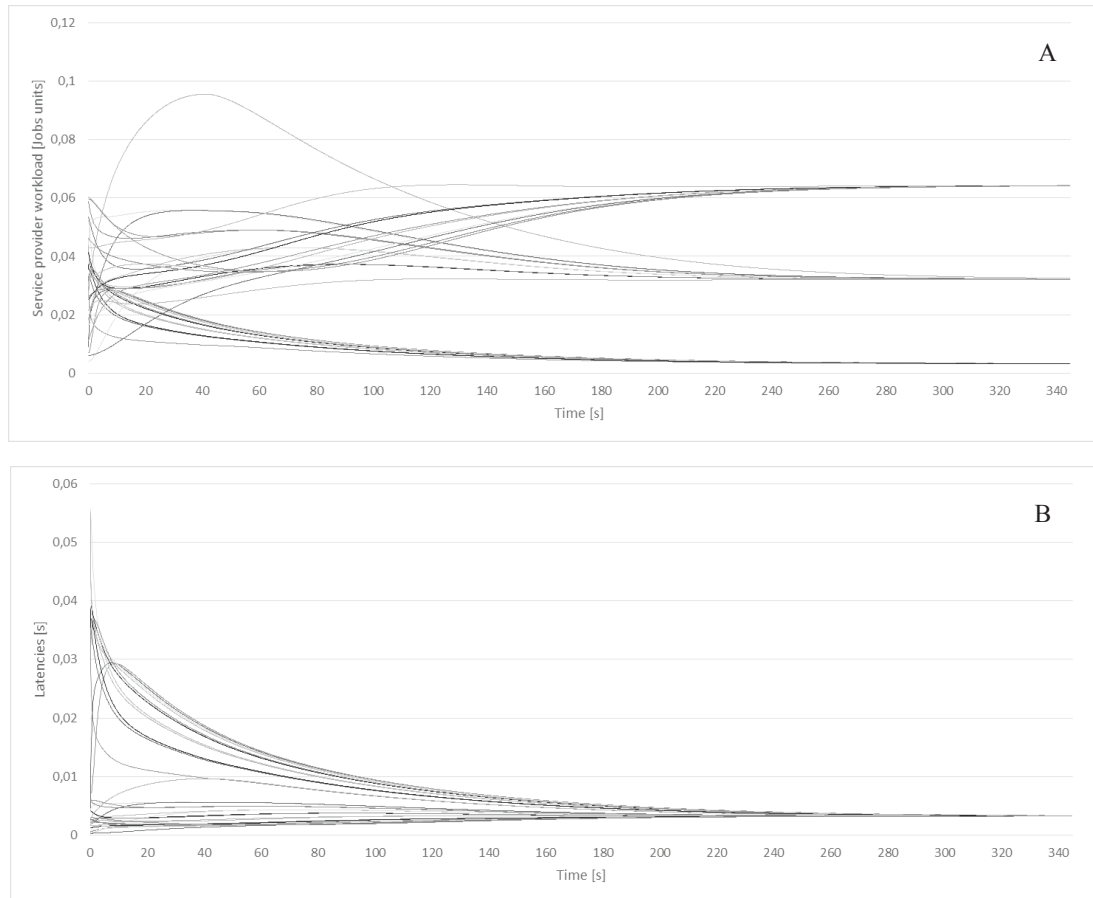


Fig. 2. : Service providers workloads dynamic (A), service providers latencies dynamic (B).

As expected the simulation of the service providers latencies' dynamics shows that the latencies converge to the same value (that is at a Wardrop Equilibrium), whereas the service providers workloads' dynamics convergences exponentially to three different steady-state values of the three latency functions.

5. Conclusions

The paper proposes a distributed workload control algorithm to efficiently handle the service discovery requests in a federated scenario, with the aim to minimize the overall service provider latencies experienced by the requesting user agents. The algorithm behaves as a dynamic system that evolves over the time and the paper demonstrates that, under proper assumptions, it converges toward a Wardrop equilibrium. The experimental results show that the convergence to the solution is exponential and strictly depends on the number of interactions between the service providers. The interesting results obtained in the experimentation phase pave the way to deeply study the properties of the proposed solutions, e.g., demonstrating the convergence velocity or showing what happens if the global workload λ changes rapidly over time. In order to repeat the tests, the authors have created a web-based testing platform that can be accessed via a HTML5 browser to the following link: <http://www.icaruservices.it/wardrop>. An easy to use, web-based graphic user interface allows to control (configure, start, proceed step by step, pause and reload) the simulation and to download the results as a comma separated values file that reports, for each simulation time-step, the jobs vector, the latency functions and the tolerance values. Furthermore, in combination with Reinforcement Learning techniques, similar game-theoretic networked scenarios are currently being investigated, with specific focus on resource management and Quality of Experience control problems^{15,16,24,25}, resource allocation problems in smart grids^{22,23} and related security issues^{26,27}.

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