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► **To cite this version:**

Daniele Santoro, Daniel Zozin, Daniele Pizzolli, Francesco de Pellegrini, Silvio Cretti. Foggy: a platform for workload orchestration in a Fog Computing environment. 2017 IEEE International Conference on Cloud Computing Technology and Science (CloudCom), Dec 2017, Hong Kong, China. hal-02073503

HAL Id: hal-02073503

<https://hal.science/hal-02073503>

Submitted on 10 Apr 2019

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Foggy: a platform for workload orchestration in a Fog Computing environment

Daniele Santoro*, Daniel Zozin*, Daniele Pizzolli*,
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Abstract

In this paper we present Foggy, an architectural framework and software platform based on Open Source technologies. Foggy orchestrates application workload, negotiates resources and supports IoT operations for multi-tier, distributed, heterogeneous and decentralized Cloud Computing systems.

Foggy is tailored for emerging domains such as 5G Networks and IoT, which demand resources and services to be distributed and located close to data sources and users following the Fog Computing paradigm. Foggy provides a platform for infrastructure owners and tenants (i.e., application providers) offering functionality of negotiation, scheduling and workload placement taking into account traditional requirements (e.g. based on RAM, CPU, disk) and non-traditional ones (e.g. based on networking) as well as diversified constraints on location and access rights. Economics and pricing of resources can also be considered by the Foggy model in a near future.

The ability of Foggy to find a trade-off between infrastructure owners' and tenants' needs, in terms of efficient and optimized use of the infrastructure while satisfying the application requirements, is demonstrated through three use cases in the video surveillance and vehicle tracking contexts.

Index Terms

Workload orchestration, Negotiation, Fog Computing, Internet of Things, Docker, Kubernetes, OpenStack.

I. INTRODUCTION

In the last few years, Cloud computing has undergone a deep transformation driven by the technological evolution, namely new containerization techniques, and by new requirements imposed by emerging 5G and IoT domains. From the technological standpoint, the operating system virtualization, i.e. the containerization complements the traditional virtual machines one, because it is more lightweight, flexible, and portable. Thus, developers and cloud providers can devise innovative architectural patterns such as microservices and novel paradigm like Infrastructure as Code. At the same time, emerging 5G networks and pervasive IoT technologies demand for distributed and decentralized support by Cloud services: Cloud Computing must escape from centralized data centers and Cloud services should be provided closer to the users or data sources. This corresponds to the vision of Fog Computing [1].

Several advantages of such an approach, including real time responses, low network latency and bandwidth usage, fault tolerance and support to data privacy, are well known in literature [2]. Scenarios in which these new cloud technologies can be applied include IoT, Automotive, Industry 4.0, Tactile Internet applications. At the same time, a whole new set of stakeholders can benefit, including, e.g., cloud providers, telecommunication providers, IoT providers, cloud integrators, innovative industries and application providers.

Our reference application scenario is a smart city one, where a Fog infrastructure is connected with IoT sensors and cameras. The infrastructure belongs to a given owner (O) that offers resources and services on this infrastructure to different tenants (T), wanting to deploy innovative applications and competing for the same resources. Tenants can negotiate resources and services which the infrastructure owners can guarantee and reserve to specific applications. In this scenario, business-related problems that should be

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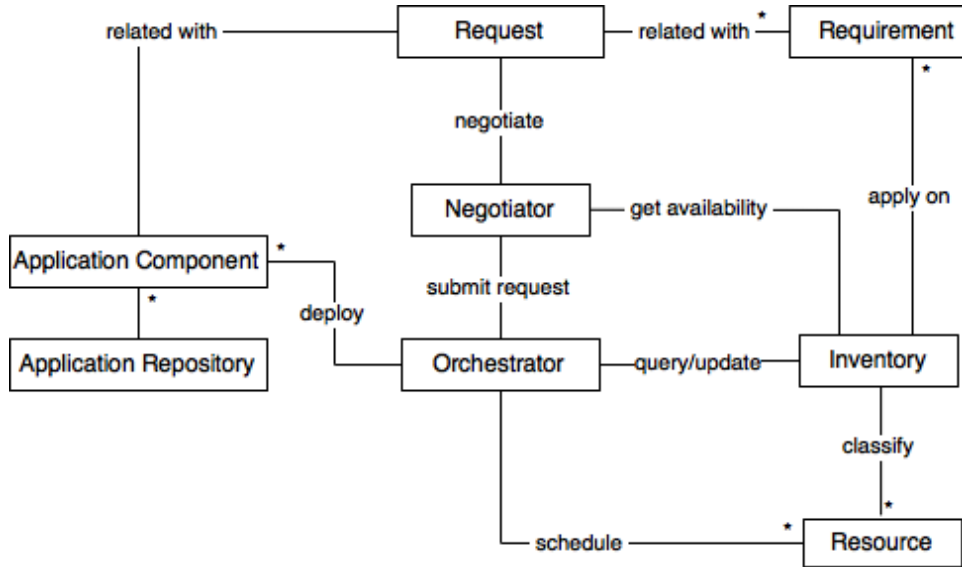


Fig. 1. Logical diagram representing the Foggy platform.

addressed include: i) maximize the usage of the infrastructure avoiding over provisioning (O); ii) satisfy the contractual SLA, i.e. minimize SLA violations across tenants (O); iii) maximize revenues (O); iv) negotiate requested resources, services and corresponding SLA (T); v) adapt to changing requirements in a flexible manner (e.g. burst of data, need for real-time processing, more workload to process, etc.) (T); vi) minimize economic costs (T).

From a technological point of view, conversely, handling deployment and operations and managing workload orchestration and efficient placement in a distributed, heterogeneous, decentralized, multi-tier cloud environment adds many “degrees of freedom” to similar problems with respect to a centralized and homogeneous cluster of resources [3]. In fact, devices and services are scattered on the territory, and not always connected to data centers (e.g., a public cloud) through reliable and homogeneous network connections. In this context, the process of scheduling applications should account for a wider range of different parameters. It is reasonable to foresee a whole new class of policies with respect to the legacy ones currently used to allocate computing and network resources in traditional systems. Such policies should indeed cover jointly context-awareness, location detection, and network performance.

Even though many scientific papers, envisioning a tight coupling and integration of IoT, Cloud and Future Network technologies, have been published in recent years [4], very few effort has been carried out on the development of platforms to make this integration possible and optimized. Foggy, as an evolution of a previous work [5], is meant to improve the aforementioned integration and the experimentation on workload management, thanks to a model of ICT resources that considers not only computation and storage ones, but also the kind, location, spatial distribution and the networking among them, leveraging osmotic computing concepts [6].

The architecture and implementation of Foggy will be presented in Sec. II and III. Three use cases that are meant to elucidate the Foggy’s capabilities to orchestrate workloads in a distributed environment are then described in Sec. IV. Finally concluding Sec. V comments on achieved results and suggests next research directions.

II. ARCHITECTURE

Foggy aims at managing the workload placement in a Fog infrastructure satisfying requirements of deployed applications that in turn request to access and use resources and services offered by that

infrastructure.

The design of Foggy platform focuses on a multi-tier Cloud Computing context generally composed by more than three (3+) tiers specialized for Fog environments: i) *Cloud* tier which offers high resource capacity and is generally far from the source of data; ii) *Edge Cloudlets* tier composed by physical or virtual nodes which have medium resource capacity and are closer to data sources; iii) *Edge Gateways* tier that is composed by nodes with low storage and computational capacity which are located very close to data producers; iv) *Swarm of Things* tier is where IoT devices (sensors, actuators, cameras, smartphones) are hosted and where raw data is produced. Foggy aims at controlling the first three tiers.

Fig. 1 shows the main components of Foggy and their relationships in the form of a logical model. In order to build this model we considered two reference schedulers, namely, OpenStack [7] and Kubernetes [8].

A deployment *Request* is of the form: $Request = \{app_component, [Req1, Req2, \dots, ReqN]\}$ and consists of: i) the *Application component* to be deployed and ii) a set of optional deployment *Requirements*. *Application Component* is an independently deployable, replaceable and upgradable unit of software, such as a microservice, which plays a specific role as part of a larger application. It is generally distributed via software container images (e.g., a Docker container image), which are stored in an *Application Repository* (e.g., a Docker registry).

Requirement offers a way for the tenant to specify constraints imposed to the deployment/execution of the *Application Component* in terms of *Resources* requested and/or specific application needs (e.g., location, access rights).

Resource refers to any computational, storage or network capacity provided by the nodes of the infrastructure. Regarding computational and network resources, Foggy identifies a set of profiles in order to simplify how the associated requirements are expressed. Thus, computational resources on a node such as vCPUs, RAM and disk are characterized by the following usage profiles: *General purpose* (default profile), *Compute optimized*, *Memory optimized* and *Storage optimized*. Network resources such as bandwidth, latency and jitter are defined between an *Application Component* (thus the node where it is executed) and a service endpoint (e.g., a stream from a camera). They are classified with the following usage profiles: *Best Effort* (default profile), *Interactive application*, *Signaling and video streaming*, *Interactive and real-time video*.

The *Inventory* stores the status (i.e., resources availability) of the distributed infrastructure together with the resources location. It is populated with information from external systems like SDN network orchestrators and/or IaaS managers (e.g., ONOS, OpenStack). Information maintained by the *Inventory* are key for the Foggy operations and must be preserved, for this reason it is based on a consistent, distributed and highly available key value store, such as etcd [9]).

The *Negotiator* handles the submitted *Requests*, negotiating with the tenants the possibility to satisfy the associated requirements. The resources' availability status is retrieved from the *Inventory*.

The *Orchestrator*, in response to deployment requests, deploys *Application Components* on the node that best satisfy the requirements imposed. It embeds a custom, shared state scheduler [10] which extends the Kubernetes one and supports non-traditional requirements (i.e. beyond computational and storage capacity).

Foggy receives deployment *Requests* submissions from tenants through a RESTful API and processes them one by one following a First Come - First Served (FCFS) policy. First step is to go through a transaction mechanism handled by the *Negotiator*. In this phase the request from the tenant is either accepted or rejected. The second step is responsibility of the *Orchestrator* that, by querying the *Inventory*, applies filtering and ranking rules to identify the best nodes to host the requested *Application Component*. It first i) filters the nodes that can satisfy the requirements specified in the deployment request; then it ii) ranks the remaining nodes according to a "priority function"; iii) chooses the highest from the rank

results; and iv) deploys on that node the container image of the accepted application component. Finally, the *Orchestrator* updates the *Inventory* to reflect the global status of the resources.

III. IMPLEMENTATION

We present hereafter the technical details of the implemented solution including specific reference to the technologies adopted in Foggy. To support such a flexible environment OpenStack acts as the IaaS layer, while Kubernetes acts as the container orchestration tool. This scheme permits to achieve application and services orchestration in a lightweight and flexible manner. In Fig. 2 we present the schema of our deployment: the three main software platforms, i.e., OpenStack, Kubernetes and Foggy are stacked one above the other.

OpenStack: the OpenStack distributed deployment follows the architecture proposed by the Fog/Edge Massively Distributed Cloud Working Group [11]. This deployment installs OpenStack controller nodes on the Cloud tier while compute nodes on both Cloud and Edge Cloudlets tiers, keeping them interconnected via "WANWide" links.

Kubernetes: a customized Kubernetes cluster is installed in a hybrid way depending on the tier: on the Cloud and Cloudlets tiers, it is distributed on top of OpenStack virtual machines, thus granting maximum isolation and flexibility, while on the Edge Gateways tier it is directly installed on the bare metal nodes due to scarce computational resources.

Foggy: The Foggy platform, composed by three main modules: *Negotiator*, *Orchestrator* and *Inventory*, is deployed by Kubernetes using Docker containers. The *Application Repository* (e.g., Docker registry) can be public or private and it is generally deployed on the Cloud tier but the place where images are located can affect the start-up time of *Application components*, which in turn, are deployed by Foggy on top of Kubernetes worker nodes.

Physical testbed: the Cloud tier is hosted in the FBK CREATE-NET data center, while the Edge Cloudlet tier is composed by 3 nodes (Intel i7 CPU, 16GB RAM, 480GB SSD). At the Edge Gateways level we deployed small and low power consumption devices (Raspberry Pi version 3) that serve as both i) hardware abstraction layer and ii) network provider for non-IP IoT devices. For the specific use cases demoed in this paper, the Swarm of Things tier is composed by access points (TP-Link TL-WR740N), cameras (Tennis JPT3815W-HD) and smartphones (Samsung GT-I9195); indeed several other devices could be attached to validate different scenarios.

To test Foggy, we need to control the status and performances of the interconnections among the 3+ tiers. Using the EnOS tool [11], we are able to emulate various OpenStack deployments with different kinds of connectivity. As an example, EnOS can emulate a real world situation in which the link between the Edge Cloudlets and the Cloud tiers is offered by an xDSL connection with low bandwidth and high latency capabilities.

IV. STORYBOARD AND USE CASES

As introduced earlier, the reference scenario is the smart city one where the Fog infrastructure is owned and managed by a public entity (e.g., a municipality). The infrastructure allows to access cameras installed on public streets and squares. With Foggy, the municipality can lease this infrastructure to multiple tenants. Tenants, in turn, can deploy components of their applications close to cameras, thus leveraging the advantages of the Fog Computing paradigm for better user experience and premier grade service.

In order to showcase the advantages of Foggy compared to an IoT platforms based on a conventional cloud-only approach (i.e., without the Fog tiers), three use cases have been devised. In the first two, a tenant wants to process video streams coming from cameras in order to perform face detection. The very first represents a baseline case: a cloud-only IoT application acquires data by streaming them directly from a camera to specific application component running in the central cloud. The second demonstrates how Foggy, as specified by the application deployment request, can schedule the workload

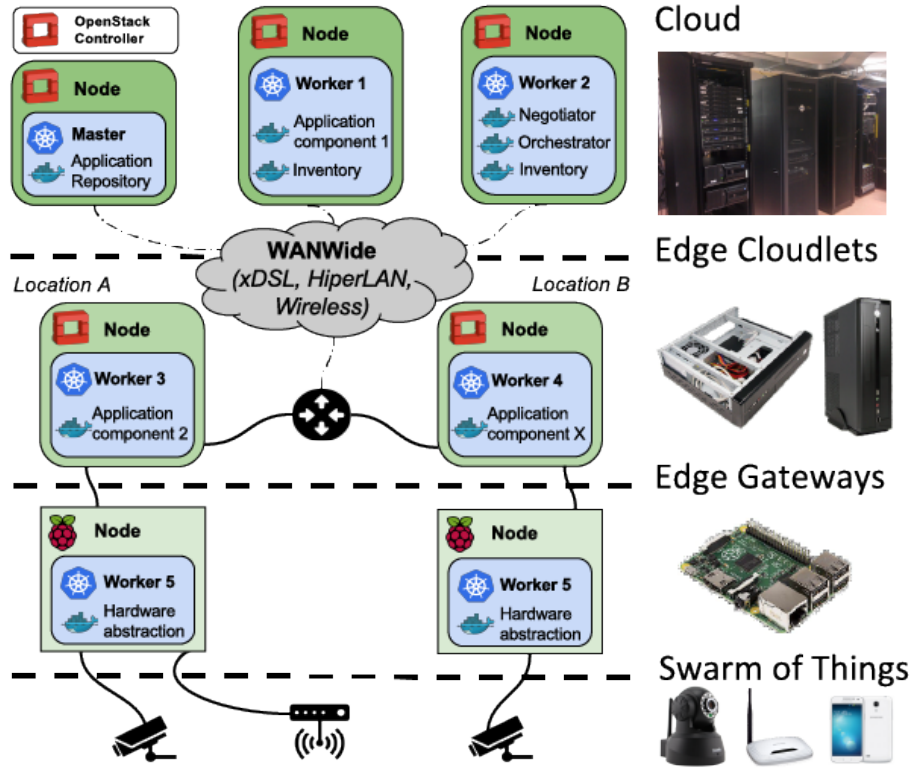


Fig. 2. Representation of the Foggy testbed: (left) deployment architecture in a smart city, (right) kind of hardware for each tier.

close to the data source: when face detection from a video stream is performed close to the source, the traffic load towards the cloud is reduced and the service level of the application is maintained even in case of limited network performance. The third use case highlights the ability of Foggy to orchestrate the workload based on the geographic location: the key scenario involves privacy constraints which need to be satisfied. A tenant wants to track vehicles location and, for privacy concerns, such sensible data is processed only within a geographically limited area before being sent, anonymised, to the central cloud. Deploying the tracking functionality at the edge also increases the application resiliency by avoiding to lose data in case of connectivity faults between Cloud and Edge.

A. Cloud-only Face Detection

In this use-case a tenant wants to extract human faces [12] from a video stream. The video stream is generated by a camera and forwarded to a cloud data-center, where it is processed. No intermediate Fog tier is used. The bandwidth has to be sufficient to stream the video produced by the camera to the remote server in the central cloud. Scalability problems arise when multiple cameras are used, since bandwidth requirements increase accordingly. The application is composed by two microservices: *face_detection* and *face_store*. The former detects and extracts faces from a video stream while the latter stores them for persistency. This demonstration comprises the following steps:

- 1) The tenant submits to Foggy two deployment requests: $r_1 = \{face_detection\}$ and $r_2 = \{face_store\}$. Note that in both r_1 and r_2 no deployment requirement is specified;
- 2) Foggy, accounting for the current status of the infrastructure, tries to deploy the microservices by satisfying the tenant requests. Since no particular requirement is specified, both microservices are deployed on the central cloud;
- 3) The streaming video from the camera is collected and face detection is performed;

4) Detected faces are saved in an object storage.

If another application is deployed and requires video streams from cameras, bandwidth usage increases and the performance of concurrently deployed applications may experience degradation.

B. Bandwidth-aware Face Detection

This application performs same activity as in the previous scenario. However, now the tenant specifies the face detection microservice to be deployed close to the data source. In this way, only the detected faces are extracted and forwarded to the cloud, thus reducing the bandwidth consumption with respect to the cloud-only face detection scenario. This demonstration is composed by the following steps:

1) The tenant submits to Foggy two deployment requests: $r_1 = \{face_detection, n_{svs}\}$ and $r_2 = \{face_store\}$. Where n_{svs} indicates a network requirement specifying a *Signaling and video straming* profile between the *face_detection* and the endpoint (e.g., the camera).

2) Foggy, accounting for the current status of the infrastructure, deploys the microservices satisfying the tenant requests. It deploys the *face_detection* on a cloudlet close to the camera in order to meet the requirement in terms of the network profile. Since the *face_store* doesn't specify any requirement, it is deployed on the central cloud;

3) Only extracted faces (not the whole stream) are sent to the cloud: this greatly reduces bandwidth consumption.

If another application using the same camera is added, graceful degradation of performance occurs since available bandwidth is sufficient to satisfy several concurrent applications.

C. Privacy-aware Vehicles Tracking

In this scenario a tenant needs to track vehicles moving on certain streets where cameras are installed, e.g., for the purpose of traffic flows analysis. Tracking is performed by recognizing license plates [13] and associating them with the location and the timestamp. Since this practice involves privacy issues, licence plates are anonymized as soon as they are collected.

Anonymization is performed by the *anonymizer* microservice: data privacy constraints suggest that the microservice should run on the local cloudlet where the camera is installed. The anonymized data is then forwarded to a second microservice, namely, the *analyser*, hosted on the central cloud and performing further analysis and final storage. This demonstration comprises the following steps:

1) The tenant submits to Foggy two deployment requests: $r_1 = \{anonymizer, location\}$ and $r_2 = \{analyser\}$. Where *location* indicates a geographical requirement specifying that the deployment has to be done in a given region;

2) Foggy, accounting for the current status of the infrastructure, deploys the microservices satisfying the tenant's requests. It deploys the *anonymizer* on the selected cloudlet in order to meet the location requirement while the *analyser* is deployed on the cloud;

3) Only anonymized data are moved to the central cloud: this guarantees data privacy;

4) In the case when a network fault happens between cloud and edge, data is not lost because it is cached in the cloudlet and then, once connectivity is restored, it is sent to the cloud (this would not be possible without the presence of a cloudlet).

V. CONCLUSION

In this paper we have described Foggy, an architectural framework and a software platform for workload orchestration and resource negotiation in a multi-tier, highly distributed, heterogeneous and decentralized Cloud Computing system. Through the presentation of three use cases, Foggy proves to be able to orchestrate the workload in a Fog Computing environment. It acts as a matchmaker between infrastructure owner and tenants improving i) the efficient, effective and eventually optimized use of the infrastructure and ii) the application performances to satisfy the requirements imposed.

After this initial deployment, we shall pursue, among the others, the following aspects: i) a negotiation phase to involve also economic aspects (i.e., pricing and billing) able to handle both tenants' and infrastructure owners' needs; ii) modelling more complex interactions among different application components; iii) different scheduling policies other than the FCFS one; iv) new use cases to demonstrate real scenarios with multi-components application in a way to measure impact and performance at infrastructure and application level.

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