ENABLING WIRELESS COMMUNICATIONS AND NETWORKING TECHNOLOGIES FOR EDGE COMPUTING

Orchestration of Microservices for IoT Using Docker and Edge Computing

Muhammad Alam, João Rufino, Joaquim Ferreira, Syed Hassan Ahmed, Nadir Shah, and Yuanfang Chen

The authors propose a modular and scalable architecture based on lightweight virtualization. The provided modularity, combined with the orchestration supplied by Docker, simplifies management and enables distributed deployments, creating a highly dynamic system. Moreover, characteristics such as fault tolerance and system availability are achieved by distributing the application logic across different layers, where failures of devices and micro-services can be masked by this natively redundant architecture, with minimal impact on the overall system performance.

Abstract

The world of connected devices has led to the rise of the Internet of Things paradigm, where applications rely on multiple devices, gathering and sharing data across highly heterogeneous networks. The variety of possible mechanisms, protocols, and hardware has become a hindrance in the development of architectures capable of addressing the most common IoT use cases, while abstracting services from the underlying communication subsystem. Moreover, the world is moving toward new strict requirements in terms of timeliness and low latency in combination with ultra-high availability and reliability. Thus, future IoT architectures will also have to support the requirements of these cyber-physical applications. In this regard, edge computing has been presented as one of the most promising solutions, relying on the cooperation of nodes by moving services directly to end devices and caching information locally. Therefore, in this article, we propose a modular and scalable architecture based on lightweight virtualization. The provided modularity, combined with the orchestration supplied by Docker, simplifies management and enables distributed deployments, creating a highly dynamic system. Moreover, characteristics such as fault tolerance and system availability are achieved by distributing the application logic across different layers, where failures of devices and micro-services can be masked by this natively redundant architecture, with minimal impact on the overall system performance. Experimental results have validated the implementation of the proposed architecture for on-demand services deployment across different architecture layers.

Introduction

In the last decade, cloud computing (CC) has been a trending research topic and received an increasing amount of attention from both the scientific and industrial communities. Ergo, several reputable companies, such as Google, Facebook, and Apple, have developed their own cloud-based services, which have become daily work tools for millions of users. In these systems, data and information are centrally stored, and most of the computational workload is performed in the cloud. Such systems are very cost-efficient, scalable, and provide quasi-unlimited data storage for organizations. However, with the recent hype surrounding the Internet of Things (IoT) and its applications, both developers and users are experiencing one of the downsides of CC: longer latencies. Applications with very strict bounded time requirements, such as smart health, cooperative intelligent transport systems, and industrial applications, suffer the most. Furthermore, with the realization that IoT is going to play a vital role in the development of more advanced applications and solutions for the most common problems, the production of low-cost smart devices and sensors has reached an unprecedented growth rate. These devices are the driving force behind IoT and produce a tremendous amount of data that, in most cases, must be transformed, processed, stored, and analyzed online. Those computational endeavors are usually centrally handled by cloud-based solutions, but the unique properties of the information received (rate, volume, and variety) are saturating the network, creating severe management problems.

People rely heavily on personal digital assistant applications, often running on smartphones, tablets, and sometimes on wearable equipment (i.e., watches and glasses). As a result, users are increasingly demanding that their personal devices instantly connect and interact with smart objects around them to get information and assistance as well as to use available services without being subjected to complex registration processes. Inside a personal ecosystem, people can be facilitated in many different ways based on their context, preferences, and predefined ontologies. These personal edge devices have the capability of generating and processing the vast amount of data that is produced. Therefore, in order to improve the end-user experience (e.g., accessing the requested contents in a shorter time), it would be more reasonable to push some computations closer to these edge devices. Therefore, this idea has led to the introduction of a new layer (mediation layer) between cloud and end devices that has the ability to host small applications and also the fog layer [1]. These days, the devices offer more computational power, providing flexibility at the application layer and offering a point of service to both nomadic devices and central services. The combination of such capabilities with the presented limitations and challenges have paved the way to a new paradigm, edge comput-

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ing (EC). Pushing computing applications, data, and services away from centralized nodes into the logical extremes of the network, EC is being presented as the most prominent solution for the aforementioned challenges [2]. This approach requires leveraging resources on connected devices but also on those that may not always be accessible, and making them work cooperatively to achieve common goals [3]. As can be seen in Fig. 1, this on-device approach helps reduce the latency for critical applications and the dependencies on the cloud layer, and better manage the massive data deluge.

In the pursuit of the most suited topology for the presented work in this article, several architectures were explored in the literature. For instance, in designing a distributed software architecture, the use or consideration of micro-service [4] is a relatively new concept. This is mainly because the micro-services introduce a way to deal with creating applications as an arrangement of small autonomous services that is completely different from monolithic architecture design. As a result, various parts of the same application can be independently implemented, making it conceivable to break down huge applications in small services with a particular target to achieve.

On the other hand, achieving visualization through a container-based approach is not a new concept; it is done through Docker [5]. Docker is an open source platform to develop and run distributed applications much faster and independent of the underlying operating systems. Key advantages of using Docker for distributed applications are less CPU overhead, versioning control, easy portability, and improved network performance [6]. Therefore, Docker has been be used in many recent works. For example, in [7], the authors have used Docker as a distributed service platform for fault tolerance of services in [8]. For IoT applications, Docker-based gateways were introduced and tested in [9]. Moreover, architectures' flexibility and scalability were tested through mirco-services in [10]. It is evident from the previous works that Docker or other container-based technologies have sufficiently penetrated the distributed application development market and could be a reasonable contender for CC and EC, and can be used to customize the IoT platform by offering data processing services closer to the end user. Therefore, in this article, for running the IoT applications at different architecture layers, we propose an approach of combining Docker and micro-services that runs on top of a scalable and modular EC architecture. In the proposed approach, services isolation is achieved through containerization, while containerized service scalability is achieved through the application of Docker tools. In addition, the applications are treated as independent micro-services, which makes the system more modular and decentralized.

The rest of this article is organized as follows.The proposed architecture and working are described. Then a test case scenario that represents the implementation of the proposed architecture using gateways and edge devices is presented. Next, the experimental tests and validation through the obtained results are discussed. The last section presents major conclusions.

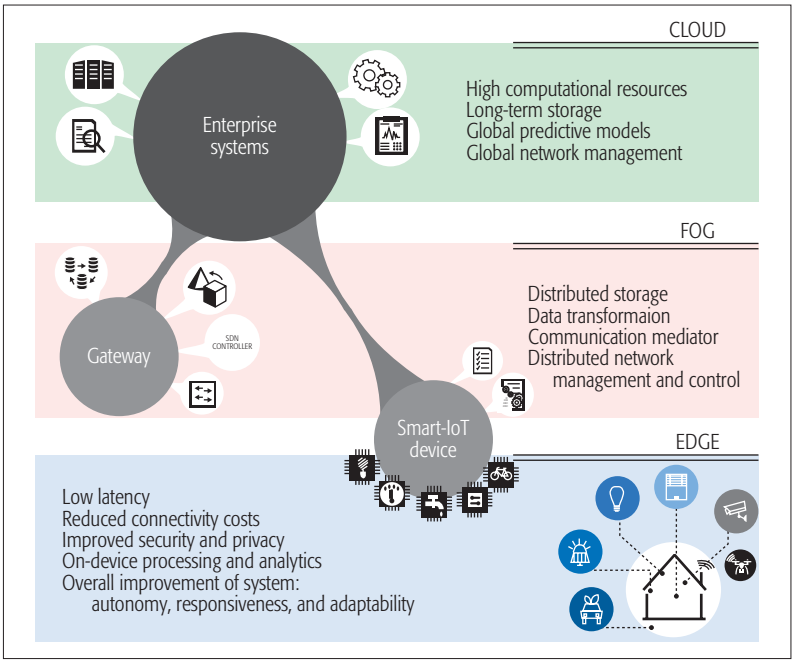

Figure 1. Representation of cloud, fog, and edge computing.

Proposed Architecture

In our topology, an application is a set of stateless services that can be distributed across single or multiple machines. In fact, each application is decomposed in independently deployable software components with highly specific functions, encapsulating its implementation. The provided modularity allows the services to be small and loosely coupled and much easier to understand, improving both maintainability and testability. This property is achieved using a containerization software (Dockers), embedded in each device, providing the minimum suitable environment for the application.

As depicted in Fig. 2, the three different layers, each growing in computational resources, compose our proposed architecture. The nodes present in the edge layer hold the closest position to the service goal, and are capable of sensing, monitoring, and communicating with their surrounding environment. Gateways cooperatively cache and process data to reduce the system response time. Therefore, the middle layer mediates the communication between both ends and offers a single entry point to the local systems. Multiple local domains meet at the enterprise layer, where resource-intensive applications run.

In highly dynamic distributed systems, such as the one presented, having an entity capable of managing multiple nodes and their resources is of utmost importance. Hence, the role of the manager is to ensure the most efficient allocation of resources by keeping track of the service deployment. Thus, as an orchestrator, the manager can group, scale, and update hundreds or thousands of containers in a cluster of machines. Moreover, the messaging hub was introduced and used to hide the technical specifications and complexities of different components. This multilayer entity allows a manager to define communication channels to applications, reducing the intra-service network overhead.

Enterprise systems have three main objectives: data warehousing, treatment, and business logistics. Therefore, long-term storage, analysis, and management of enormous volumes of unstructured data are conducted at the cloud. Performing these CPU/memory demanding applications at a centralized position allows a granulated model of the overall system, providing predictive capabilities and almost-real-time system response to adversity.

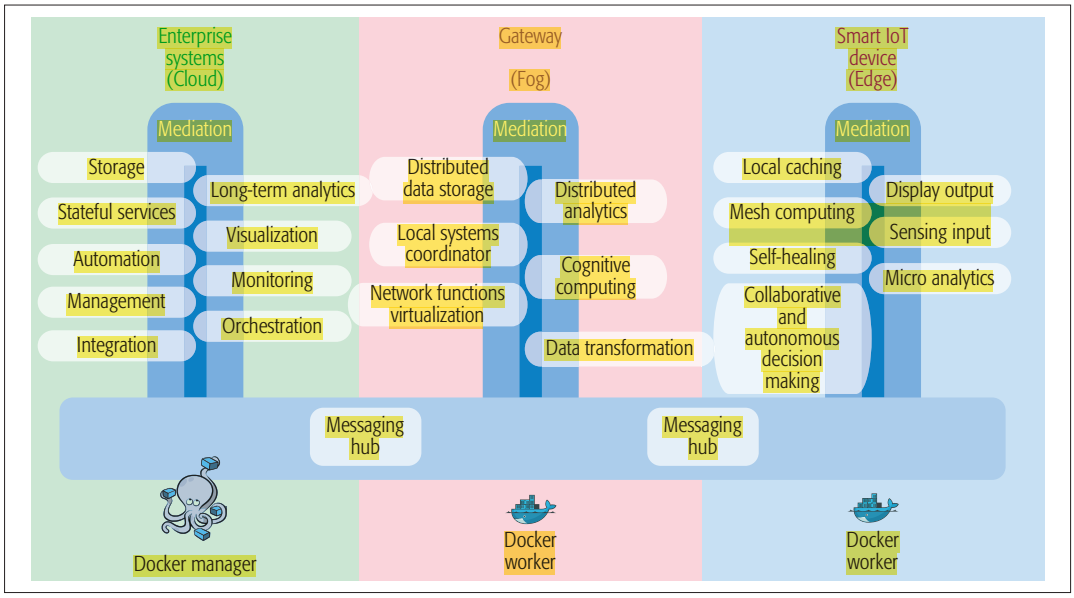

Figure 2. Overview of the proposed architecture.

Smart IoT Devices

In our topology, edge devices have an extremely important role as both the human-machine interface and the local environment perceiver. With their computational capabilities duplicating every five years, it is also in this layer where greater innovation is expected. Thus, these devices are presented as cyber-physical systems capable of hosting Docker containers. Using virtualization, we expect to operate over these devices, managing them locally through gateways and orchestrating them centrally in the cloud.

Gateways

The middle layer offers a connection point to end layers. From the edge device perspective, gateways offer a local connection point, timely and reduced latency response, and coordination support. Moreover, gateways send the status of connected edge devices to the cloud, transform the data received, perform simple analytics, and virtualize network functions, ensuring users' best quality of experience.

In order to achieve adaptability, we followed the software-defined (SD) approach. Following the SD networks procedure, different channels are used for control and data, and the cloud can push network rules to gateways that are later enforced by end devices. Additionally, we use the SD storage strategy and allow storage peers to be deployed in different layers to meet complex requirements. The system can only be fully adaptable if it presents cognitive features. Therefore, data mining is performed in the cloud to define data patterns that can be used by gateways. The SD local intelligence is achieved using the received patterns to adapt accordingly. Its main function is to detect erroneous local system behavior, check components' responsiveness, and ensure that edge devices are complying with system policies.

Messaging Hub

Similar to other service-oriented architectures, the key communication component proposed is a messaging bus. In our topology, this component is a multi-layer cluster of services capable of handling a huge volume of messages per second. Moreover, each application has a dedicated channel for intra-communication, eliminating direct communication between publisher and subscriber and reducing the subsequent challenges.

Enterprise Layer

Enterprise systems have three main objectives: data warehousing, treatment, and business logistics. Therefore, long-term storage, analysis, and management of enormous volumes of unstructured data are conducted at the cloud. Performing these CPU/memory demanding applications at a centralized position allows a granulated model of the overall system, providing predictive capabilities and almost-real-time system response to adversity. The resulting models are defined and translated into orchestration rules, and disseminated and enforced across gateways for supervised control of the local systems.

Key Characteristics

In the vision of IoT, all devices are connected in a global network through a plethora of active radio technologies. In addition, the large number of devices that are connected to the IoT produce tremendous amounts of data. In a conventional approach (architectures), this data is usually stored and processed at a central cloud, greatly reducing and limiting the bandwidth of the communication technologies. Therefore, our proposed architecture makes sure that data gets collected and analyzed at the most efficient and logical places between the source and the cloud, balancing the load and pushing the computation and intelligence to the appropriate layers.

The disruptive growth of IoT is continually forcing the industry to answer new challenges. The current monolithic platforms are not handling the pandemic hardware and software advances. In comparison, while adding new features to such systems would imply a system restructure, in the presented topology, by combining lightweight virtualization with orchestration we can update

the system in real time. Moreover, the system can spread the application logic across different devices, making use of often underutilized resources, or even replicate the same service to improve reliability.

In summary, the proposed architecture supports IoT's key attributes: heterogeneity, scalability, and adaptability. In fact, in the presented topology, the incorporation of highly modular and loosely coupled architecture with a messaging hub shields applications from the other layers' technical details and specifications. Consequently, heterogeneous systems can communicate with reduced effort. Scalability is ensured through cachable, replicated, stateless services and a publishing-subscribing system. Furthermore, the orchestrator can adapt the system to meet different requirements, guaranteeing overall evolvability and adaptability.

Test Case Scenario

The proposed architecture is validated through a use case scenario that highlights its capabilities for the IoT deployment and is depicted in Fig. 3. The scenario depicts a typical smart home appliance; two different end devices are periodically communicating with central servers deployed in the cloud through a gateway. In fact, the gateway is being used as a mediator, locally caching the information sent by the ES and distributing it to different edge devices, alleviating the edge workload and resources used. The end devices work as cyber-physical systems that can be remotely controlled and can also interact directly with the user.

In this topology, services can be moved from layer to layer. As stated before, one of the challenges of this architecture concerns inter-service dependencies and stateful services. In fact, services with multiple dependencies within different layers reduce the scalability and increase the response time of the system. Therefore, we designed a test case scenario for the deployment of a time-sensitive service. This time-sensitive service is initialized, deployed, and scaled by the enterprise systems. The service itself is used as proof of concept. It reduces the inter-service dependencies while still sending data to and from the cloud.

Implementation

For the implementation of the test case, easily obtainable and off-the-shelf hardware was used in order to facilitate reproducible results and research. Thus, a total of three Raspberry Pi 3s (RPis) compose both the gateway and end devices. The operating system adopted for the local systems was Alarm armv7 for Broadcom [11], a minimal operating system for RPi. RPis 3 are small single-board computers (SBCs) with 4 ARM Cortex-A53 1.2 GHz CPU and 1 GB RAM, while also having integrated WiFi. Composing the edge layer, two RPis were connected to an I2C display and used to present the data directly to the user. The remaining RPi was used as a gateway forming the fog layer. End devices interact wirelessly (using WiFi) with the gateway, which is then connected to the Internet to interact with the cloud. The cloud consists of an Intel core i5 laptop computer with 8 GB memory, running Archlinux OS and Docker

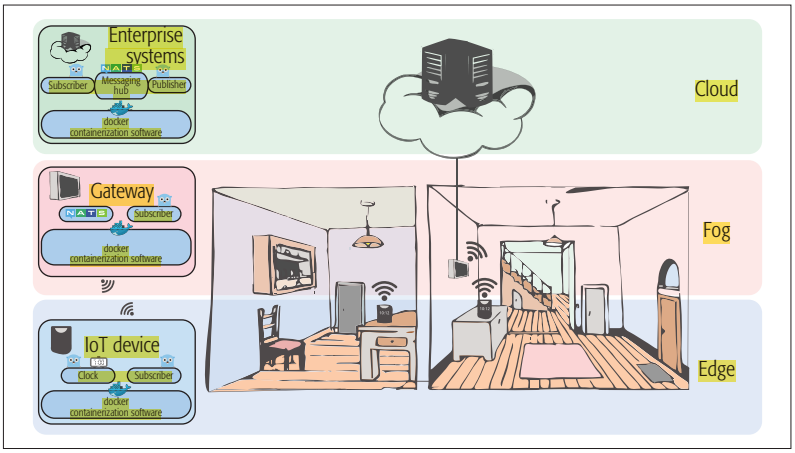

Figure 3. Test scenario for multi-layer orchestration.

For the entire experiment, Docker version 18.05.0-he was the chosen software for creating the cluster topology. Since version 1.12, Docker has an embedded orchestration tool, named Swarm, with two types of roles: workers and managers. A worker can only be used for hosting containers, while a manager can also terminate, deploy, update, and manage running containers in the cluster. Nodes joining the cluster were labeled according to their position in the architecture, i.e. the gateway as "FOG", the end devices as "EDGE," and the manager as "CLOUD."

The service used for this scenario is publish-based. It has three different roles: publishers, which publish data to channels; subscribers, which receive the published data from channels; and a messaging hub, which mediates the communication. The publisher transmits, in each message, the local epoch time in nanoseconds and the message number to a predefined channel. The messaging hub then broadcasts the data to each subscriber. The subscriber receives the data and presents it in the I2C display (in the console if one is not available). The behavior of the entire application is monitored through the transmissions sent to the messaging hub.

In order to reduce the size of the Docker images, and subsequently the download and transfer time between layers, we adopted the same programming language used for developing Docker, Golang. The images created are available online on Docker Hub as niplodim/subscriber, niplodim/publisher, and niplodim/nats. Both the subscriber and publisher images receive the configuration parameters as environment variables. The last image is a reduced version of the NATS messaging hub; specifically, the graphical user interface and encrypted channels were removed.

Results and Discussion

Having a centralized manager allows us to have fine-grained control over the cloud running services in terms of both orchestration [12] and monitoring [13]. Thus, this topology allows us to provide online service migration from layer to layer without downtime. In order to test this feature, a subscriber, a publisher, and a messaging hub were deployed in the cloud, and one publisher instance at one end device (with label EDGE). At the 10,000th transmission, the messaging hub is migrated to the gateway, and the transmission

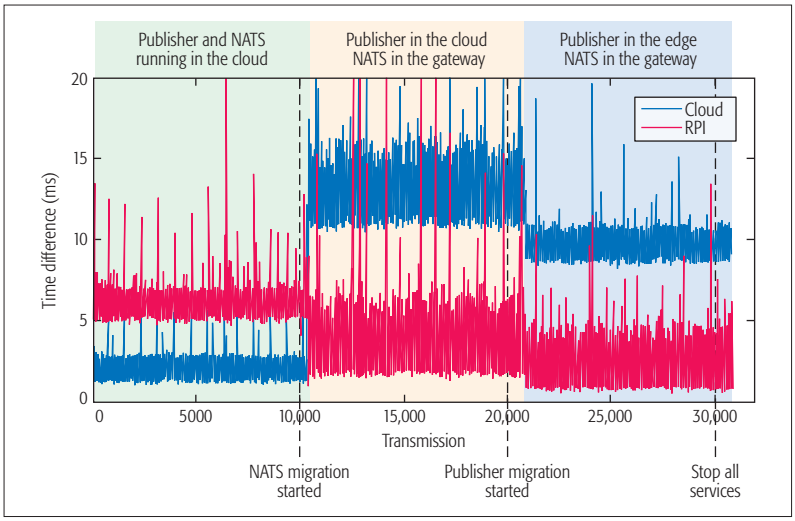

Figure 4. Communication delay with services in the cloud layer.

	Subscriber cloud			Subscriber edge		
Location	Average (μs)	Min (μs)	Max (μs)	Average (μs)	Min (μs)	Max (μs)
Cloud	2052.6	1029.9	8709.9	6198.7	4600.1	74,880.0
Fog	11,951.8	8668.9	225,009.6	2951.4	1155.8	21,644.8
Edge	9740.3	8248.3	19,628.0	2761.8	515.8	13,318.9

Table 1. Results summary.

counter is reset. After another 10,000 transmissions, the publisher is migrated from the cloud to the remaining edge device. The results are depicted in Fig. 4.

For this experiment, all the Docker images used were previously loaded in each node repository. Moreover, ptpd [14], an implementation of the Precision Time Protocol, was used to ensure that the clocks from all nodes were synced. Additionally, it is important to mention that the end-to-end time comparison is made before the update in the I2C displays. By comparing the different service logs, we can see the number of times data has been published and when it was published, and compare them to the time of reception.

Figure 4 presents the end-to-end service latencies per transmission. With both the publisher and messaging hub running in the cloud, the enterprise systems present the smaller latencies with an average of 2 ms in the cloud and 9 ms in the edge, as can be seen in Table 1. The cloud messaging hub is then stopped and the gateway starts mediating the communication between edges; this action takes 298 ms. With the data being published by the cloud to the gateway, the next phase presents the worst results of the experiment in terms of both latency and variance. It is important to note that the cloud is now subscribing to the same information it is publishing; therefore, it has the cost of traveling twice through the Internet backbone, with a resulting average of 12 ms in the cloud and 3 ms at the edge. The phase ends with the migration of the publisher instance to the empty edge device, which took 537 ms to perform. With both publisher and NATS running at the local systems, the average latency is reduced to 10 ms in the cloud and slightly reduces at the edge.

Compared to the average end-to-end round-trip time, measured with the ping Linux command, of 4 ms, the application does not bring additional burden to the communication. The results show that CC delivers a more stable solution with a smaller variance, but unfortunately comes up short on answering the ultra-low latency required by novel applications, such as augmented and virtual reality and the tactile Internet. The results also show that the orchestration brings no downtime to the service and little to no overhead to the system. This confirms that the architecture has the ability to aggregate storage resources, scale out the system across different layers, and manage the shared resources pool through a central administrative interface.

Conclusions

In this article, we present a layered and modular architecture that is running on cloud, fog, and edge devices, and offers containerized services and micro services. The proposed architecture has three main layers: sensing, mediation, and enterprise layers. The sensing layer is the lower layer that performs the sensing and operations (edge computing); the meditation layer represents the intermediate devices and operations (gateways, fog computing); and the upper layer is called the enterprise layer, which represents the cloud and operations such as long-term global storage. The proposed architecture makes sure that data gets collected and analyzed at the most efficient and logical places between the source and the cloud, balancing the load and pushing the computation and intelligence to the appropriate layers. The service can only be accessed through a dedicated channel, which allows the services to be small and loosely coupled across the whole system. The proposed architecture ensures higher reliability of the system by using orchestration rules that can achieve full service recovery in and during failures. In addition, the higher system resilience is achieved by introducing redundancy at different layers. The proposed architecture is tested for IoT deployment via a smart home use case in which real-time/time-sensitive application is tested using a publish/subscribe method. The results validate that the enterprise layer has management and control capabilities which ensure application deployment at different layers such as the enterprise layer and sensing layer (edge layer). This is mainly achieved by the application of orchestration tools. The orchestration ensures availability of service: the system was up and running, and no additional overhead was introduced. In addition, the results also prove that migrating services to the edge layer can improve the application latency while increasing its variance.

Acknowledgments

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