From the Sky to the Ground: Comparing Fog Computing with Related Distributed Paradigms

Joao Bachiega Jr.[1], Breno Costa[1], Leonardo R. Carvalho[1], Victor H. C. Oliveira[1], William X. Santos[1], Maria Clicia S. de Castro[2] and Aleteia Araujo[1]

[1]*Department of Computer Science, University of Brasília (UnB), Brazil*

[2]*Department of Infomatics and Computer Science, State University of Rio de Janeiro (UERJ), Rio de Janeiro, Brazil*

Keywords: Edge Computing, Fog Computing, Cloud Computing, Sky Computing.

Abstract: Fog computing is a paradigm that enables provisioning resources and services at the network edge, closer to end devices, complementing cloud computing and recently it's being embraced by sky computing. Beyond this computational paradigm, there are many other related technologies which also make use of distributed computing to improve the quality of service delivered to the end-users. The main contribution of this paper is to present a comparison between fog computing and nine other relevant related paradigms, namely Sky Computing, Cloud Computing, Edge Computing, Mobile Edge Computing, Mobile Cloud Computing, Mobile Ad hoc Cloud Computing, Mist Computing, Cloudlet Computing, and Dew Computing, highlighting the similarities and differences between them based on the main fog characteristics. A graphical characterization for each paradigm, highlighting its computational power, communication type and position in a three-layers architecture (Cloud-Fog-IoT) and some relevant challenges in this area are also presented.

1 INTRODUCTION

Over the years, computing paradigms have been evolving. Since the beginning of the modern computer era until about 1985, computers were large and expensive. Moreover, there was no connectivity between them and they operated independently of each other. With the development of powerful microprocessors and high-speed computer networks, it was possible to change this scenario (Tanenbaum and Van Steen, 2007).

After that, computing technologies evolved from distributed, parallel, clustering, peer-to-peer (P2P), and grid until the cloud computing. There is no doubt that cloud computing is one of the most important computational paradigms, playing an essential role in almost every aspect of our everyday life. It brought the impression of infinite computational resources (e.g. storage, processing) provided in a pay-per-use basis, allowing fast scalability at a reasonable cost. Nevertheless, as a centralized computing model, computation happens in the cloud data centers, located in specific places around the world, and far from the end-users (Mukherjee et al., 2018).

As in a cycle, nowadays is the time when distributed computing paradigms are back in the spotlight, aiming to overcome the limitations of centralized cloud computing processes. Internet of Things (IoT) development demands this (Yousefpour et al., 2019). Thus, new concepts were born ranging from *Sky Computing* (Keahey et al., 2009), which is a level above cloud computing and uses resources and services from several providers simultaneously, until *Fog Computing* (Bonomi et al., 2012), which is a cloud close to the ground, addressing several issues of connected devices, like high-bandwidth, geographical dispersion, and low latency needs. Fog is both complementary to, and an extension of, traditional cloud-based models.

Although fog computing is a recent paradigm, in the last 3 years it was the subject of approximately 20% of all publications related to computational paradigms, including Sky Computing, Edge Computing, Mobile Edge Computing, Mobile Cloud Computing, Mobile Ad hoc Cloud Computing, Mist Computing, Cloudlet Computing and Dew Computing.

The main contribution of this paper is to present a comparison between fog computing and other related paradigms, highlighting similarities and differences

Bachiega Jr., J., Costa, B., Carvalho, L., Oliveira, V., Santos, W., S. de Castro, M. and Araujo, A.
From the Sky to the Ground: Comparing Fog Computing with Related Distributed Paradigms.
DOI: 10.5220/0011033300003200
In *Proceedings of the 12th International Conference on Cloud Computing and Services Science (CLOSER 2022)*, pages 158-169
ISBN: 978-989-758-570-8; ISSN: 2184-5042

among them, based on the main fog characteristics. However, as some definitions are still imprecise, even nebulous, in the literature, we based our research on a qualitative bibliographic approach. To present a more accurate view of the whole computational spectrum, from the Sky to the ground, we also provide a graphical characterization for each paradigm, highlighting its computational power, communication type and position in the three-layers architecture (Cloud-Fog-IoT). Besides this, important challenges will be presented and discussed, giving to the researchers a comprehensive view of the subject.

For that, this paper is organized as follows. Sections 2 and 3 presents the sky and cloud computing concepts, respectively. In Section 4 the fog computing characteristics are presented. The related paradigms and technologies are described in Section 5, and a comparison is presented and analyzed in Section 6. The challenges in this area are presented in Section 7. Section 8 brings other papers related to this work. Finally, Section 9 concludes this paper.

2 SKY COMPUTING

The market for cloud providers has become more competitive over time. Currently, there is a profusion of services offered by different providers. Many of them offer similar products but using different approaches. In this scenario, a multicloud approach has grown within organizations, in which resources offered by different providers make up the technological support framework of these organizations.

This approach has been called Sky computing (Keahey et al., 2009) and can be defined as a level above cloud computing, since its resources are dynamically provisioned by different providers. It consists of a layer of cloud environments' management, offering variable storage capacity with dynamic support for real-time demands.

Sky computing can also be found under the denominations of multicloud (Kritikos and Plexousakis, 2015), cross-cloud (Elkhatib, 2016), federated clouds (Paraiso et al., 2012), or inter-clouds (Grozev and Buyya, 2014).This difference in nomenclature may be related to the way the architectures deal with the resource scheduler, since this component can be intrinsic to the provider, or an external service provided by a middleware, for example. There are also differences regarding the form of integration between the clouds participating in the sky computing layer, as well as regarding the knowledge of the existence of such layer by the resources in their respective providers.

An important characteristic of a sky computing environment is the consolidation of resources, whose purpose is to offer a single view of all elements of each cloud provider in the pool. To act in this continuous process of integration, discovery and consolidation of resources, it is possible to use tools called Cloud Orchestrators (de Carvalho and de Araujo, 2020) such as: Terraform (Shirinkin, 2017), Cloudify (Cloudify, 2021), and Heat (Michelino et al., 2013), for example. The sky computing characterization is presented in Figure 1.

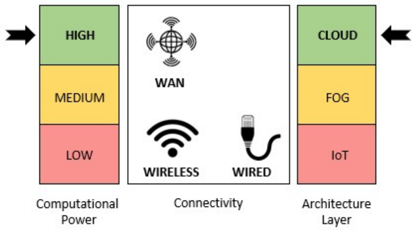

Figure 1: Sky Computing Characterization.

3 CLOUD COMPUTING

The underlying concept of cloud computing was introduced in 1961 by John McCarthy when he said that, in the future, computing could be organized as a public service, as it was the telephone system in those days (Foster et al., 2008). Computing and communication evolution allowed the cloud computing paradigm to expand and, nowadays, this platform is largely used by academia and industries. Cloud computing plays an important role as a computation infrastructure and impacts all other technologies and paradigms presented in this paper.

We have observed, over the last few decades, that computational resources, previously expensive and scarce, have now become cheap and abundant (Kushida et al., 2015). Cloud computing has emerged in this transition context, enabling the computing democratization. It has encompassed two important points: the illusion of infinite computing resources, and to allow the radical computation acceleration. Cloud computing makes the concept of utility a reality.

In the literature, we can find in (Mell et al., 2011) that the five essential features for cloud computing environments are defined as on-demand self-service, broad network access, resource pooling, fast elasticity, and measured service. Therefore, the main advantages of cloud computing are the availability of high computational power and large storage, paying only for what is used. The elasticity has a fundamental function in this context, allowing the growth or the decrease of resources dynamically. But cloud computing also has some constraints. The fundamental limitation is the connectivity between the cloud and the end devices and users, because public cloud providers are supported by large data centers around the world, but not close enough to the end-user, resulting in Quality-of-Service (QoS) degradation, which is not well-suited for time-critical service requests (Mukherjee et al., 2018).

Another relevant aspect is that the cloud computing paradigm is a centralized computing model, and most of the computations happen in the cloud. Although data processing speeds have risen rapidly, network bandwidth, even considering a high speed connection like 5G, is becoming the bottleneck of cloud computing for such a huge amount of data (Hu et al., 2017). Overcoming these limitations will benefit particular use cases as connected vehicles, smart cities, virtual reality and healthcare (Naha et al., 2018). The cloud computing characterization is showed in Figure 2.

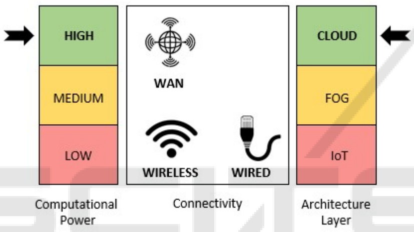

Figure 2: Cloud Computing Characterization.

4 FOG COMPUTING

Fog is a cloud close to the ground. Similarly the term fog computing refer to a computation that operates at the edge of the network, bringing cloud-like services to be executed close to the end-users. Furthermore, it provides computing resources for applications that cannot perform properly with the high latency provided by cloud-only environments (Naha et al., 2018).

Bonomi et al. (Bonomi et al., 2012) presented the first definition of fog computing saying that it is a highly virtualized platform that provides computing, storage, and networking services among many computing data centers or end-devices.

Various researchers have expanded and revised this initial definition of fog computing. Vaquero et al. (Vaquero and Rodero-Merino, 2014) and Yi et al. (Yi et al., 2015) consider fog computing as a scenario, composed of a high number of decentralized and heterogeneous devices, where they communicate and cooperate among themselves and with the network to perform data processing and storage without third-party interventions. Services, applications, or basic network functions that run in a sandboxed environment, can be supported by the data processing and storage.

In the definition presented by Dastjerdi et al. (Dastjerdi et al., 2016), fog computing is considered a distributed computing paradigm. In this paradigm the services provided by the cloud are essentially extended to the network edge. Fog computing addresses application requirements that need low latency with a huge and dense geographical distribution. Due to this, fog computing supports computing resources, different communication protocols, mobility, interface heterogeneity, integration with the cloud, and distributed data analytics.

For Naha et al. (Naha et al., 2018), fog computing is a distributed platform where the edge or end devices, that can be virtualized or not, will do most of the processing. It resides between the cloud and users and the cloud will do long-term storage and non-latency-dependent processing.

Finally, fog computing was defined in NIST (Iorga et al., 2018) as a layered model facilitating the deployment of applications and services that are latency-aware and distributed. This model enables ubiquitous access to shared devices of scalable computing resources that are not perceptibly different from each other, although the extremes are quite distinct. Therefore, fog computing provides, for the end-devices, local computing resources and network connectivity to centralized services, when needed, minimizing the request-response time.

In all definitions, it is possible to note that fog computing is tightly linked to the existence of a cloud since fog can never replace the cloud completely as we still need it to handle big or complex data problems (Gill et al., 2019). So, it is possible to state that fog computing is suitable to be used when the cloud does not meet the time limit, bandwidth limitations, or latency requirements.

Considering all concepts presented, the following fog computing definition is proposed: *Fog computing is a distributed architecture that uses the computational resources of devices located between end-users and the cloud to optimize the processing and to reduce applications' response times, meeting demands that until now were not possible.*

4.1 Fog Architecture

According to the NIST definition (Iorga et al., 2018), one fundamental component in fog architecture is the fog node. A fog node is any hardware device in a fog computing environment that has system and hardware resources added to high communication capability (Bachiega et al., 2021).

The fog environment can be based on a software-defined fog architecture and use Fog Radio Access Networks (F-RAN) (Mukherjee et al., 2018). However, layered (or hierarchical) representation is considered by Naha et al. (Naha et al., 2018) a better way to represent fog architecture. Although this topic has been largely researched in academia (Dastjerdi et al., 2016) and a three-tier architecture has been commonly used to represent a fog system (Mahmud and Buyya, 2016), it is possible to find proposals with four (Tang et al., 2015), five (Naas et al., 2017) or, even, six (Fan et al., 2018) layers, as presented in Figure 3. A comprehensive review of fog computing architectures can be found in (Habibi et al., 2020).

Figure 3 demonstrates that although there are variations in the number of layers in the existing architectures, it occurs only in the Fog Layer, with some components being more diluted and others being more concatenated. Another important point is that the End-users and Cloud layers are present in all architectures. Thereby, regardless of the number of layers being proposed, the architectures can be summarized in three essential layers: End-users, Fog, and Cloud. This three-layer architecture model will be used throughout this article to allow comparison with other computational paradigms.

The IoT/End-users Layer, at the base, represents all IoT devices. It is in this layer that end-users request services that will be processed in the Fog and the Cloud Layers. The Fog Layer acts as a link between IoT/End-users and the Cloud layers to provide the necessary extra functionalities for application-specific processing, as filtering and aggregation before transferring the data to the cloud (Al-Doghman et al., 2016). It is composed of fog nodes and this layer comprises 'intelligent' devices that are capable of computing, processing, and storing data in addition to routing and forwarding the data packets to the upper tier (Sarkar and Misra, 2016).

Finally, the Cloud Layer has powerful computational resources to process all requests and responses made by and sent to the Fog and IoT/End-users Layers directly. The Cloud Layer is a requirement in a fog system. Similar paradigms that enable application provisioning at the edge, as cloudlet (Satyanarayanan et al., 2009) or Mobile Edge Computing (MEC) (Beck et al., 2014) can operate in standalone mode.

4.2 Fog Characteristics

Bonomi et al. (Bonomi et al., 2012), writing for the first time about the fog computing paradigm, characterized it into ten items, namely location awareness and low latency; geographical distribution; large-scale sensor networks; large number of nodes; support for mobility; real-time interactions; predominance of wireless access; heterogeneity; interoperability and federation; and support for on-line analytics and interplay with the cloud.

Since then, the number of studies about fog computing has grown and revised these characteristics (Hu et al., 2017). Recently, NIST (Iorga et al., 2018) defined the following six characteristics that are considered essential in distinguishing fog computing from other computing paradigms:

- Low latency: offering the lowest possible latency due to the awareness of logical location and latency costs for communication between fog nodes in the context of the entire system;
- Geographical distribution: fog computing demands widely distributed deployments for services and applications;
- Heterogeneity: processing data acquired in different forms through multiple types of network communication capabilities;
- Interoperability: seamless support of certain services requires the cooperation of different providers;
- Real-time interactions: applications of fog computing involve real-time interactions rather than batch processing;
- Scalability: must be adaptive and support elastic computing, resource pooling, data-load changes, and network condition variations.

The fog computing conceptual model, proposed by NIST (Iorga et al., 2018), also defines the predominance of wireless access and support for mobility as additional characteristics often associated with fog computing. A fog computing characterization is showed in Figure 4. Considering these characteristics, some use-cases for fog computing include smart cars, traffic control, smart cities, smart buildings, surveillance and security. Furthermore, it is important to note that the sharp growth of 5G technology will leverage adoption of IoT-related services and fog computing is very appropriate to this scenario (Santos et al., 2018).

5 RELATED PARADIGMS AND TECHNOLOGIES

Apart from fog computing, there are other paradigms based on a close proximity to connected devices and

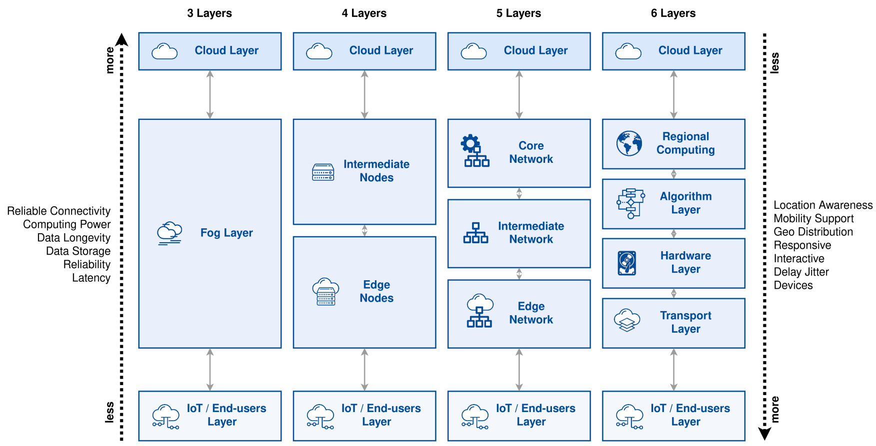

Figure 3: Variation in the number of layers in Fog Computing Architectures.

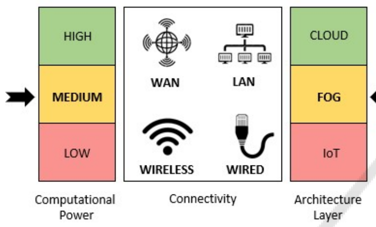

Figure 4: Fog Computing Characterization.

this causes confusion about their concepts and definitions. To avoid this confusion, next sections will present details about each related paradigm and compare them with the fog computing characteristics, as well as place them in the three-tier architecture presented in section 4.1 to clarify understanding.

5.1 Edge Computing

Fog computing is often erroneously confused with edge computing, but there are key differences between the two concepts. While fog computing runs applications in a multi-layer architecture, edge computing runs specific applications in a fixed location, that is, in the edge devices.

It can also be considered that the edge computing can be limited to a few number of end-user devices while fog computing has a bigger number of peripheral devices with hierarchical architecture. Therefore, it is possible to see that edge computing is more restricted than fog computing.

In edge computing the devices produce and consume data, participating in the processing. Data storage, computation offloading, processing, and caching will be done by an edge node. The edge device is also capable of distributing requests and providing cloud services to the users (Avasalcai et al., 2020).

Furthermore, in edge computing, the devices are not able to implement multiple IoT applications, since there are limited resources and this can result in resource contention and increase processing latency. On the other hand, fog computing can overcome these limitations by seamlessly integrating edge devices and cloud resources (Dastjerdi et al., 2016).

Finally, edge computing focuses on the end-devices level, while fog computing focuses on the infrastructure level (Shi et al., 2016). The edge computing characterization is presented in Figure 5.

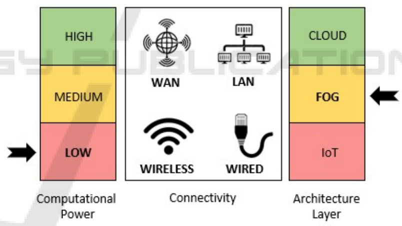

Figure 5: Edge Computing Characterization.

5.2 Multi-access Edge Computing (MEC)

Previously, also referenced by some authors as “Mobile Edge Computing”, MEC can be defined as an implementation of edge computing to bring computational and storage capacities to the edge of the network within the Radio Access Network (RAN) to reduce latency and improve context-awareness (Dolui and Datta, 2017).

According to Beck et al. (Beck et al., 2014), MEC is a proposal for co-locating, at the base stations of cellular networks, computing, and storage resources. MEC is the evolution of mobile base stations and collaborative deployment of telecommunication and IT networking. They operate on the edge of the Internet and remain functional even without Internet connectivity (Dolui and Datta, 2017). Figure 6 shows the MEC characterization.

The MEC computing paradigm can provide several services including IoT, location services, augmented reality, caching service, video analytics, and local content distribution. It can also provide low-latency access in real-time to local content or by caching the content at the MEC server. However, some restrictions cannot be ignored, such as the installation of the MEC server, which is specifically dedicated to them. The increase in resource demand over time also becomes a major scaling problem (Cui et al., 2021).

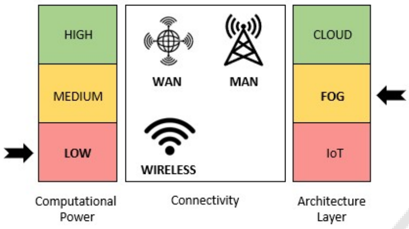

Figure 6: Mobile Edge Computing Characterization.

5.3 Mobile Cloud Computing (MCC)

The mobile computing concept proposed by Satyanarayanan in 1996 (Satyanarayanan, 1996) represents the computation performed via mobile, portable devices, such as laptops, tablets, or mobile phones. However, the evolving requirements of connected devices make mobile computing alone not enough to address some computing challenges of our days (Yousefpour et al., 2019).

Mobile computing has gained a valuable complement as cloud computing matured. This combination resulted in MCC, which is defined as an infrastructure where both data storage and data processing occur outside of the mobile device (Habibi et al., 2020).

The cloud computing, the mobile computing, and the wireless communication are combined to provide the MCC (Mahmud and Buyya, 2016), improving the Quality of Experience (QoE) of mobile users.

Mobile computing requires changes to some characteristics of cloud computing, like the existence of a low-latency intermediary tier, the optimization of cloud infrastructure for running mobile application, and the seamless offloading and remote execution. The viability of MCC is based on a reliable end-to-end network with high bandwidth and this can be achieved by using virtual machines and cloudlets that must be located closer to the mobile devices (Satyanarayanan, 1996). Figure 7 presents a characterization of MCC.

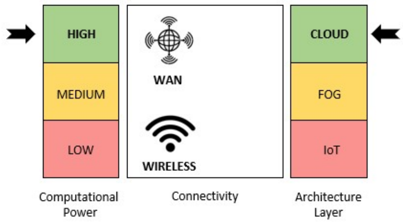

Figure 7: Mobile Cloud Computing Characterization.

5.4 Mobile Ad hoc Cloud Computing (MACC)

MCC has a pervasive nature, but there are scenarios where it is not suitable, for example where there is no centralized cloud, or the infrastructure is insufficient (Yousefpour et al., 2019). An Ad hoc mobile network consists of nodes that form a temporary, dynamic network through routing and transport protocols, building a decentralized form of network (Hubaux et al., 2001).

Therefore, MACC consists of a pool of devices with high computational capabilities that are closer to the user. This low-cost computational environment is deployed over a network where all nodes cooperatively maintain the network (Balasubramanian and Karmouch, 2017).

MACC's motivation is to address situations in MCC for which connectivity to cloud environments is not feasible, such as the absence of or an intermittent network connection (Yaqoob et al., 2016). Furthermore, the hardware used, the service access method, and the distance from users are also other differences between MACC and MCC. MACC's characterization is presented in Figure 8.

Finally, when compared with the fog computing, connected devices in MACC are more decentralized, and this allows the devices to form a more dynamic network in places of sparsely connected devices or a constantly changing network (Hubaux et al., 2001).

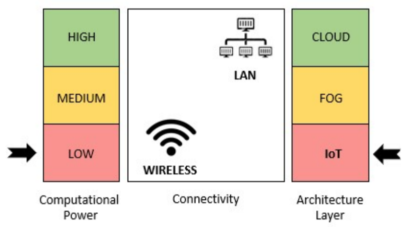

Figure 8: Mobile Ad hoc Cloud Computing Characterization.

5.5 Mist Computing

Mist computing can be defined as a lightweight and rudimentary form of fog computing (Ranaweera et al., 2021). It brings the fog computing layer closer to the smart end-devices, using microcomputers and microcontrollers to get it, beyond to reside directly within the network at the edge of the network (Iorga et al., 2018).

In the words of Yousefpour et al. (Yousefpour et al., 2019), Mist computing can be referenced as "IoT computing" or "things computing" and it could be seen as the first location where the computation takes place in the IoT-fog-cloud continuum.

The data transfer uses a lot of battery power and it is desirable that data can be processed, preconditioned, and optimized first before being stored. This fact results in a data transfer much smaller, consuming less power (Silva et al., 2017). The mist computing paradigm can increase the autonomy of solutions, and further decrease the latency period (Preden et al., 2015). The mist computing characterization is showed in Figure 9.

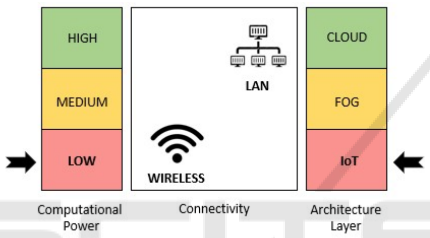

Figure 9: Mist Computing Characterization.

5.6 Cloudlet Computing

In 2009, Carnegie Mellon University introduced the "data center in a box" concept, named Cloudlet Computing (Satyanarayanan et al., 2009). Cloudlets are composed of decentralized and widely dispersed Internet infrastructure. Nearby mobile computers can leverage their compute cycles and storage resources. Cloudlets offer low latency for applications because they are provided over one-hop access with high bandwidth (Alli and Alam, 2020).

The mobile device, acting as a thin client, can offload computational tasks through a wireless network to a cloudlet, deployed one hop away (Riaz et al., 2019). However, a cloudlet's presence in mobile devices' proximity is necessary, as the end-to-end response time, when executing applications, must be smaller and predictable. If a device goes out of range of a cloudlet, then it should gracefully switch to the distant cloud, or worst-case scenario, rely solely on its resources (Bilal et al., 2018).

Another important characteristic of cloudlets is that they support local services for mobile clients by dividing tasks among cloudlet nodes near the mobile devices (Li and Wang, 2014). However, fog computing offers a more generic alternative that natively supports large amounts of traffic and allows resources to be anywhere along the thing-to-cloud continuum (Cui et al., 2017). Cloudlet characterization can be seen in Figure 10.

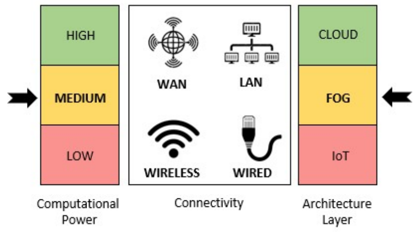

Figure 10: Cloudlet Computing Characterization.

5.7 Dew Computing

In the cloud computing spectrum, the on-premises computer software-hardware organization paradigm is known as Dew computing (Ray, 2017). In dew computing, the on-premises computational resources provide functionality which is independent, i.e. that works seamlessly without an internet connection, and also collaborative with cloud services, e.g. when an internet connection is available it can synchronize data and update a copy in the cloud.

So, dew computing intends to fully realize the potentials of on-premises computational resources and cloud services (Wang, 2016) acting together without a permanent connection. The nature of dew computing applications can be precisely described by the independence that indicates their applications are inherently distributed and the collaboration that indicates that the applications are inherently connected.

Dew computing takes the concepts of service, storage, and network, and goes further, defining a sub-platform, based on micro-services and distributing vertically its computing hierarchy (Wang, 2015). The dew computing paradigm makes the use of hardware resources easier since they are connected to a network, covering a broad range of ad-hoc-based networking technologies (Skala et al., 2015). Figure 11 shows the characterization of dew computing.

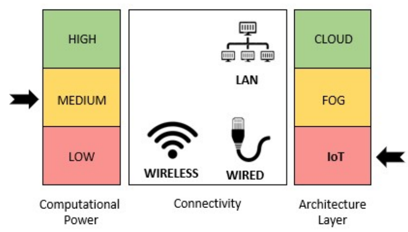

Figure 11: Dew Computing Characterization.

6 FOG COMPUTING AND RELATED PARADIGMS COMPARISON

Based on the main fog characteristics presented in Section 4.2, a comparison of aforementioned paradigms is presented in Table 1. The idea is to highlight the differences and similarities between the paradigms and help clarify the way they compare to fog computing.

Table 1: Fog computing and related paradigms comparison.

Paradigms	Low Latency	Geo-Distribution	Heterogeneity	Interoperability	Real-time	Scalability
Sky	-	-	✓	✓	-	✓
Cloud	-	-	✓	✓	-	✓
Fog	✓	✓	✓	✓	✓	✓
Edge	✓	✓	✓	✓	✓	✓
MEC	✓	✓	-	✓	✓	-
MCC	-	-	✓	✓	-	-
MACC	-	✓	-	✓	-	-
Mist	-	✓	✓	-	✓	-
Cloudlet	✓	✓	-	✓	✓	✓
Dew	-	-	-	✓	✓	-

Analyzing Table 1, it is possible to notice that edge computing is the paradigm closer to fog computing. On the opposite side, MCC, MACC and dew computing share few characteristics of fog computing, moving away from the scope of this paradigm.

Finally, Figure 12 shows the position of each analyzed paradigm on the IoT-Cloud continuum. Fog computing is located between cloud and IoT/end-users and, although the other described paradigms are suitable for some specific use cases, fog computing has been seen as a more general form of computing due to its comprehensive definition scope (Yousefpour et al., 2019).

7 CHALLENGES

Fog is a distributed paradigm that extends cloud computing to the network edge, providing services closer to end users. But the end users can be distributed and connected to the network by different ways and means, according to the use case they are executing: health monitoring use cases, industrial IoT (IIoT), Smart Power Grid, Smart Cities among others (Avasalcai et al., 2020). Each use case can have specific requirements and all of them together create a range of options and needs that must be considered on the same fog environment, or on a federation of fog environments. In such a scenario, there could be no need to consider mobility and the connection to the fog can be considered as reliable. A much more different scenario is a vehicular application connected to a fog node located as a Road Side Unit (RSU), where mobility and wireless communication are fundamental characteristics. Although the communication architecture can be the same between these two use cases, in a 3-tier architecture as presented on Section 4.1, the functionalities' set needed by each of them, as well as the options for privacy, security, fault tolerance, for instance, are different and must be provided by the fog computing environment accordingly.

A relevant challenge of fog computing is related to security and privacy warranty. Heterogeneity of user-equipment and access network makes it difficult and complex to implement security and privacy defense features (Ranaweera et al., 2021). Moreover, once the features are deployed, there is a trade-off between the functionalities running on the user device and energy consumption. For example, the stronger the key and the encryption process used, more energy from user's device will be consumed. Also, the fewer resources the device has available to run these security processes, the longer it takes to run them, increasing the response time of an application or service being executed and causing a worse QoE (Mahmud et al., 2018). According to privacy and security solutions in place, a minimum resource specification must be guaranteed by the service orchestrator when allocating a fog node to run a service.

Low latency is a requirement to run real time services on fog infrastructures. To meet this requirement, the service is placed closer to the user and, in case of user mobility, e.g., a mobile phone inside a moving car, the service could be migrated to another fog node that is located closer to the user's new place from time to time. Service migration is also used as a strategy of offloading services to a resource richer node and in case of node failure. The challenge is to guarantee the SLA/QoE while providing a secure communication channel between fog nodes (Ranaweera et al., 2021).

Finally, from the resource's management perspective, a wide-open issue must be improved. Although the virtual machine concept is extensively in use on cloud computing architectures and still being used in fog environments, recent works indicate that the use of containers, a standard unit of software that packages up code and all its dependencies (Yin et al.,

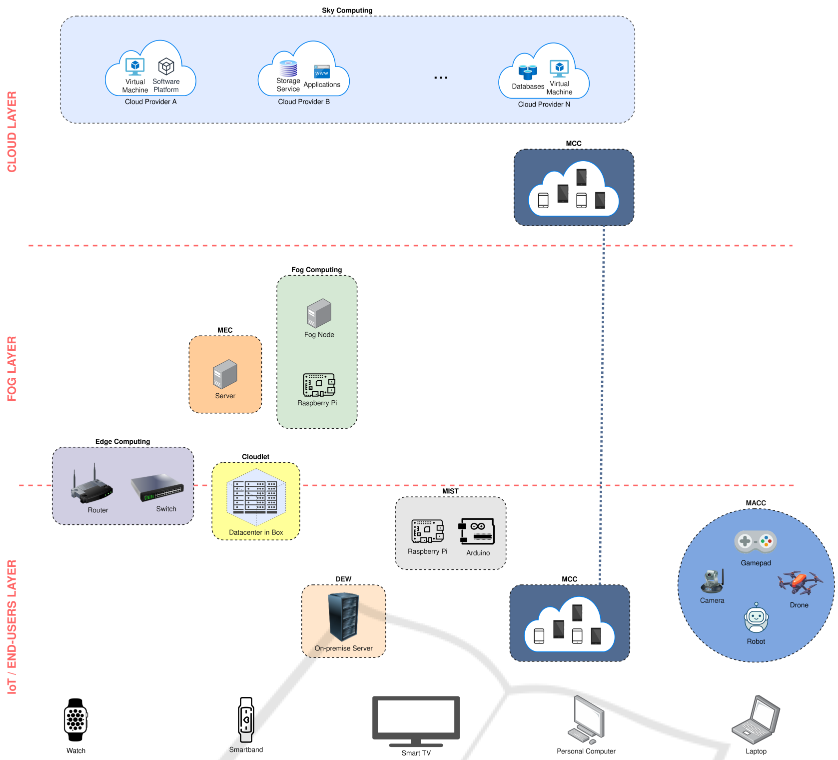

Figure 12: Position of computing paradigms on IoT-Cloud continuum.

2018), is more appropriate for fog features and needs. The use of federation, a set of public and private providers connected through the Internet, is widely adopted on cloud computing (Rosa et al., 2018). The development of a federation for fog computing is needed to ensure a greater computational capacity for this technology. Scalability may also depend on such a federation. Fog nodes help IoT devices lessening their load and providing fast response. This allows a higher number of devices to connect to the environment without overloading cloud network. But the challenge is to recognize when the number of devices connected directly to a fog node has reached a threshold in which may overload the node itself (Fersi, 2021), therefore requests must be redirected to other available fog nodes, including the federated ones. Automatic service orchestration and resource management are also needed (Costa et al., 2022).

8 RELATED WORK

In recent years, an increasing number of studies have been done about fog computing and related paradigms and technologies. Most of them, as in (Javed and Mahmood, 2021) and (Fersi, 2021), comparing these paradigms to cloud computing.

In Hu et al. (Hu et al., 2017), a study about fog computing presents a comparison between fog, edge, and cloud computing concepts. Some contextualization about the fog architecture, characteristics, and applications is presented.

Yousefpour et al. (Yousefpour et al., 2019) present similarities and differences between fog computing and the following paradigms: cloud computing, mobile computing, edge computing, mobile cloud computing, multi-access edge computing, mobile ad hoc cloud computing, and mist computing.

A comparison between fog computing, multi-access edge computing, and cloudlet is presented by Mouradian et al. (Mouradian et al., 2018) and (Ranaweera et al., 2021). In Bilal et al. (Bilal et al., 2018) the micro data center concept is compared to fog computing. In Naha et al. (Naha et al., 2018) the fog concept is compared with dew computing. Fog, edge, and mist Computing are compared in (Alli and Alam, 2020).

Gill et al. (Gill et al., 2019) presents three emerging paradigms, blockchain, IoT, and artificial intelligence, exploring how they will transform cloud computing to solve complex problems of next-generation computing. A complete study of related paradigms was done by the authors, including fog computing.

Habbib et al. (Habibi et al., 2020) present a com-

Table 2: Related work.

Paper	**Sky**	**Cloud**	**Fog**	**Edge**	**MEC**	**MCC**	**MACC**	**Mist**	**Cloudlet**	**Dew**
(Hu et al., 2017)		✓	✓	✓						
(Mouradian et al., 2018)			✓		✓				✓	
(Bilal et al., 2018)		✓	✓						✓	
(Naha et al., 2018)		✓								✓
(Yousefpour et al., 2019)		✓	✓	✓	✓	✓	✓	✓		
(Gill et al., 2019)		✓								
(Habibi et al., 2020)		✓		✓	✓					
(Alli and Alam, 2020)		✓	✓	✓				✓		
(Javed and Mahmood, 2021)		✓	✓							
(Ranaweera et al., 2021)			✓		✓	✓			✓	
(Fersi, 2021)		✓	✓							
(Ogundoyin and Kamil, 2021)		✓	✓	✓	✓	✓	✓	✓	✓	✓
This paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

prehensive survey addressing the fog architectural concepts, reviewing distinctions between cloud, edge, mobile edge, and fog, and proposing a taxonomy for architectural, algorithmic, and technological aspects of fog computing. An evaluation of the current state of the technology and identification of the potential future direction was also presented.

Finally, the article (Ogundoyin and Kamil, 2021) comments on the possible methods for optimizing fog computing and brings its applications, making metrics of its research in the literature and testing different algorithms for solutions in various environments and bringing with it proposals for future trends for optimization of computing in fog.

Table 2 summarizes the computational paradigms that were compared in each related work presented in this section, ordered considering the year of each publication. All papers analyzed in this section compare the fog computing concept with few other paradigms. In contrast, this paper shows a comparison between fog and all other relevant related paradigms, presenting the main differences and similarities. Furthermore, this paper is the only one that brings the concepts of the Sky Computing.

9 CONCLUSIONS

The distance of cloud computing data centers from the end-user's devices prompt the increase of computational technologies that solve this issue. In this paper, we present concepts, similarities, and differences of nine computational paradigms and technologies that fill in the gap between cloud computing and the edges.

Among the compared technologies in this paper, fog computing proved to be one of the most promising to be used closer to end-users, complementing the services offered by cloud computing and also by sky computing. It is a decentralized computing infrastructure that considers the best place between data source and cloud to distribute storage, computation, and applications.

Furthermore, the concatenated three-tier fog computing architecture with the related paradigms presented in Figure 12, helps understanding the position and characterization of each analyzed paradigm. Just like any emerging technology, these computational paradigms have some challenges to overcome, as standardization, security, resource management, QoS, and fault tolerance.

Unlike other related computational paradigms, fog computing is both complementary to and an extension of traditional cloud-based models, being suitable to support many use-cases, mainly accelerated by the increase of the 5G technology with IoT perspectives.

Just as it was done for sky computing paradigm, keeping up with the development of emergent computational paradigms and new technologies may be considered for future works to overcome the evolving of the computation challenges.

REFERENCES

Al-Doghman, F., Chaczko, Z., Ajayan, A. R., and Klempous, R. (2016). A review on fog computing technology. In *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 001525–001530. IEEE.

Alli, A. A. and Alam, M. M. (2020). The fog cloud of things: A survey on concepts, architecture, standards, tools, and applications. *Internet of Things*, 9:100177.

Avasalcai, C., Murturi, I., and Dustdar, S. (2020). Edge and fog: A survey, use cases, and future challenges. *Fog Computing: Theory and Practice*, pages 43–65.

Bachiega, J., da Costa, B. G. S., and Araujo, A. P. F. (2021). Computational perspective of the fog node. *22nd International Conference on Internet Computing & IoT*.

Balasubramanian, V. and Karmouch, A. (2017). An infrastructure as a service for mobile ad-hoc cloud. In *IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC)*, pages 1–7.

Beck, M. T., Werner, M., Feld, S., and Schimper, S. (2014). Mobile edge computing: A taxonomy. In *Proc. of the Sixth International Conference on Advances in Future Internet*, pages 48–55. Citeseer.

Bilal, K., Khalid, O., Erbad, A., and Khan, S. U. (2018). Potentials, trends, and prospects in edge technologies: Fog, cloudlet, mobile edge, and micro data centers. *Computer Networks*, 130(2018):94–120.

Bonomi, F., Milito, R., Zhu, J., and Addepalli, S. (2012). Fog computing and its role in the internet of things. In *Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing*, MCC '12, pages 13–16.

Cloudify (2021). Getting started.

Costa, B., Bachiega, J., de Carvalho, L. R., and Araujo, A. P. F. (2022). Orchestration in fog computing: A comprehensive survey. *ACM Comput. Surv.*, 55(2).

Cui, M., Fei, Y., and Liu, Y. (2021). A survey on secure deployment of mobile services in edge computing. *Security and Communication Networks*, 2021.

Cui, Y., Song, J., Ren, K., Li, M., Li, Z., Ren, Q., and Zhang, Y. (2017). Software defined cooperative offloading for mobile cloudlets. *IEEE/ACM Transactions on Networking (TON)*, 25(3):1746–1760.

Dastjerdi, A. V., Gupta, H., Calheiros, R. N., Ghosh, S. K., and Buyya, R. (2016). Fog Computing: Principles, architectures, and applications. *Internet of Things: Principles and Paradigms*, pages 61–75.

de Carvalho, L. R. and de Araujo, A. P. F. (2020). Performance comparison of terraform and cloudify as multicloud orchestrators. In *2020 20th IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing (CCGRID)*, pages 380–389. IEEE.

Dolui, K. and Datta, S. K. (2017). Comparison of edge computing implementations: Fog computing, cloudlet and mobile edge computing. *GIoTS 2017 - Global Internet of Things Summit, Proceedings*.

Elkhatib, Y. (2016). Defining cross-cloud systems. *CoRR*, abs/1602.02698.

Fan, Y., Zhu, Q., and Liu, Y. (2018). Cloud/fog computing system architecture and key technologies for south-north water transfer project safety. *Wireless Communications and Mobile Computing*, 2018.

Fersi, G. (2021). Fog computing and internet of things in one building block: a survey and an overview of interacting technologies. *Cluster Computing*, pages 1–31.

Foster, I., Zhao, Y., Raicu, I., and Lu, S. (2008). Cloud computing and grid computing 360-degree compared. *arXiv preprint arXiv:0901.0131*.

Gill, S. S., Tuli, S., Xu, M., Singh, I., Singh, K. V., Lindsay, D., Tuli, S., Smirnova, D., Singh, M., Jain, U., et al. (2019). Transformative effects of iot, blockchain and artificial intelligence on cloud computing: Evolution, vision, trends and open challenges. *Internet of Things*, 8:100118.

Grozev, N. and Buyya, R. (2014). Inter-cloud architectures and application brokering: taxonomy and survey. *Software: Practice and Experience*, 44(3):369–390.

Habibi, P., Farhoudi, M., Kazemian, S., Khorsandi, S., and Leon-garcia, A. (2020). Fog Computing : A Comprehensive Architectural Survey. *IEEE Access*, PP:1.

Hu, P., Dhelim, S., Ning, H., and Qiu, T. (2017). Survey on fog computing: architecture, key technologies, applications and open issues. *Journal of Network and Computer Applications*, 98(April):27–42.

Hubaux, J.-P., Gross, T., Le Boudec, J.-Y., and Vetterli, M. (2001). Toward self-organized mobile ad hoc networks: the terminodes project. *IEEE Communications Magazine*, 39(1):118–124.

Iorga, M., Feldman, L., Barton, R., Martin, M., Goren, N., and Mahmoudi, C. (2018). The nist definition of fog computing. Technical report, National Institute of Standards and Technology.

Javed, Z. and Mahmood, W. (2021). A survey based study on fog computing awareness. *International Journal of Information Technology and Computer Science (IJITCS)*, 13(2):49–62.

Keahey, K., Tsugawa, M., Matsunaga, A., and Fortes, J. A. B. (2009). Sky computing. In *IEEE Internet Computing*, page 43–51. IEEE Computer Society.

Kritikos, K. and Plexousakis, D. (2015). Multi-cloud application design through cloud service composition. In *2015 IEEE 8th Int. Conf. on Cloud Computing*, pages 686–693.

Kushida, K. E., Murray, J., and Zysman, J. (2015). Cloud computing: From scarcity to abundance. *Journal of Industry, Competition and Trade*, 15(1):5–19.

Li, Y. and Wang, W. (2014). Can mobile cloudlets support mobile applications? In *IEEE INFOCOM 2014-IEEE Conference on Computer Communications*, pages 1060–1068. IEEE.

Mahmud, M. and Buyya, R. (2016). *Fog Computing: A Taxonomy, Survey and Future Directions*.

Mahmud, R., Kotagiri, R., and Buyya, R. (2018). Fog computing: A taxonomy, survey and future directions. In *Internet of everything*, pages 103–130. Springer.

Mell, P., Grance, T., et al. (2011). The NIST definition of cloud computing.

Michelino, D., Leon, J. C., and Alvarez, L. F. (2013). Implementation and testing of openstack heat.

Mouradian, C., Naboulsi, D., Yangui, S., Glitho, R. H., Morrow, M. J., and Polakos, P. A. (2018). A Comprehensive Survey on Fog Computing: State-of-the-Art and Research Challenges. *IEEE Communications Surveys and Tutorials*, 20(1):416–464.

Mukherjee, M., Shu, L., and Wang, D. (2018). Survey of fog computing: Fundamental, network applications, and research challenges. *IEEE Communications Surveys and Tutorials*, 20(3):1826–1857.

Naas, M. I., Parvedy, P. R., Boukhobza, J., and Lemarchand, L. (2017). IFogStor: An IoT Data Placement

Strategy for Fog Infrastructure. *Proceedings - 2017 IEEE 1st International Conference on Fog and Edge Computing, ICFEC 2017*, (May 2018):97–104.

Naha, R. K., Garg, S., Georgakopoulos, D., Jayaraman, P. P., Gao, L., Xiang, Y., and Ranjan, R. (2018). Fog computing: Survey of trends, architectures, requirements, and research directions. *IEEE Access*, 6:47980–48009.

Ogundoyin, S. O. and Kamil, I. A. (2021). Optimization techniques and applications in fog computing: An exhaustive survey. *Swarm and Evolutionary Computation*, 66:100937.

Paraiso, F., Haderer, N., Merle, P., Rouvoy, R., and Seinturier, L. (2012). A federated multi-cloud paas infrastructure. In *2012 IEEE Fifth Int. Conf. on Cloud Computing*, pages 392–399.

Preden, J. S., Tammemäe, K., Jantsch, A., Leier, M., Riid, A., and Calis, E. (2015). The benefits of self-awareness and attention in fog and mist computing. *Computer*, 48(7):37–45.

Ranaweera, P., Jurcut, A. D., and Liyanage, M. (2021). Survey on multi-access edge computing security and privacy. *IEEE Communications Surveys & Tutorials*, 23(2):1078–1124.

Ray, P. P. (2017). An introduction to dew computing: Definition, concept and implications. *IEEE Access*, 6:723–737.

Riaz, N., Qaisar, S., Ali, M., and Naeem, M. (2019). Node selection and utility maximization for mobile edge computing–driven iot. *Transactions on Emerging Telecommunications Technologies*, page e3704.

Rosa, M. J., Araüjo, A. P., and Mendes, F. L. (2018). Cost and time prediction for efficient execution of bioinformatics workflows in federated cloud. In *2018 IEEE International Conference on Bioinformatics and Biomedicine (BIBM)*, pages 1703–1710. IEEE.

Santos, J., Wauters, T., Volckaert, B., and De Turck, F. (2018). Fog computing: Enabling the management and orchestration of smart city applications in 5g networks. *Entropy*, 20(1):4.

Sarkar, S. and Misra, S. (2016). Theoretical modelling of fog computing: a green computing paradigm to support iot applications. *Iet Networks*, 5(2):23–29.

Satyanarayanan, M. (1996). Fundamental challenges in mobile computing. *Proceedings of the Annual ACM Symposium on Principles of Distributed Computing*, pages 1–7.

Satyanarayanan, M., Bahl, V., Caceres, R., and Davies, N. (2009). The case for vm-based cloudlets in mobile computing. *IEEE pervasive Computing*.

Shi, W., Cao, J., Zhang, Q., Li, Y., and Xu, L. (2016). Edge computing: Vision and challenges. *IEEE internet of things journal*, 3(5):637–646.

Shirinkin, K. (2017). *Getting Started with Terraform*. Packt Publishing Ltd.

Silva, P. M. P., Rodrigues, J., Silva, J., Martins, R., Lopes, L., and Silva, F. (2017). Using edge-clouds to reduce load on traditional wifi infrastructures and improve quality of experience. In *2017 IEEE 1st International Conference on Fog and Edge Computing (ICFEC)*, pages 61–67. IEEE.

Skala, K., Davidovic, D., Afgan, E., Sovic, I., and Sojat, Z. (2015). Scalable distributed computing hierarchy: Cloud, fog and dew computing. *Open Journal of Cloud Computing (OJCC)*, 2(1):16–24.

Tanenbaum, A. S. and Van Steen, M. (2007). *Distributed systems: principles and paradigms*. Prentice-Hall.

Tang, B., Chen, Z., Hefferman, G., Wei, T., He, H., and Yang, Q. (2015). A Hierarchical Distributed Fog Computing Architecture for Big Data Analysis in Smart Cities. *Proceedings of the ASE BigData & SocialInformatics 2015*, (October):28.

Vaquero, L. M. and Rodero-Merino, L. (2014). Finding your way in the fog: Towards a comprehensive definition of fog computing. *SIGCOMM Comput. Commun. Rev.*, 44(5):27–32.

Wang, Y. (2015). Cloud-dew architecture. *International Journal of Cloud Computing*, 4(3):199–210.

Wang, Y. (2016). Definition and categorization of dew computing. *Open Journal of Cloud Computing (OJCC)*, 3(1):1–7.

Yaqoob, I., Ahmed, E., Gani, A., Mokhtar, S., Imran, M., and Guizani, S. (2016). Mobile ad hoc cloud: A survey. *Wireless Communications and Mobile Computing*, 16(16):2572–2589.

Yi, S., Li, C., and Li, Q. (2015). A Survey of Fog Computing. *Proceedings of the 2015 Workshop on Mobile Big Data - Mobidata '15*, pages 37–42.

Yin, L., Luo, J., and Luo, H. (2018). Tasks scheduling and resource allocation in fog computing based on containers for smart manufacturing. *IEEE Transactions on Industrial Informatics*, 14(10):4712–4721.

Yousefpour, A., Fung, C., Nguyen, T., Kadiyala, K., Jalali, F., Niakanlahiji, A., Kong, J., and Jue, J. P. (2019). All one needs to know about fog computing and related edge computing paradigms: A complete survey. *Journal of Systems Architecture*, (December 2018).