Fog computing: Data Analytics and Cloud Distributed Processing on the Network Edges

Nelson Mimura Gonzalez, Walter Akio Goya,
Rosangela de Fátima Pereira, Karen Langona,
Erico Augusto Silva, Tereza Cristina Melo de Brito Carvalho
Escola Politécnica, University of São Paulo, Brazil
{nmimura, wgoya, rpereira, langona, erico, carvalho}@larc.usp.br

Charles Christian Miers
Santa Catarina State University, Joinville, SC, Brazil
charles.miers@udesc.br

Jan-Erik Mångs and Azimeh Sefidcon
Ericsson Research, Stockholm, Sweden
{jan-erik.mangs, azimeh.sefidcon}@ericsson.com

***Abstract*—The term fog computing was coined in 2012. However, the concept of pushing data and application logic to the network edges is not a novelty. Similar proposals were observed with edge computing, from the early 2000s, and cloudlets, from 2009. In fact, the cloudlet concept is a subset of edge computing applied to mobile networks and the fog concept is a subset of edge computing applied to Internet of Things (IoT). This paper demystifies these concepts and provides a comprehensive survey of references from academia and industry. It analyzes the terminology and dimensions of performance, security, and governance, based on a taxonomy proposed and presented in the paper. In addition we provide a thorough analysis of related topics, identifying the main research areas correlated to edge computing. Finally, we draw conclusions regarding the state of the art and the future of edge computing.**

***Index Terms*—Fog computing; edge computing; cloudlet; data analytics; distributed processing; mobile networks.**

I. Introduction

Fog computing is a term that was coined in 2012 by Bonomi et al. in the paper ”Fog Computing and Its Role in the Internet of Things” [1]. The word ”fog” was chosen because fog is a cloud close to the ground. That reflects the core idea proposed by the authors: the need for a platform able to meet the requirements of latency-sensitive applications. In this sense, the fog would be a solution able to deliver results with lower latency by offering cloud resources closer to where the demand and the data sources are.

However, the idea of pushing application logic and data to the edge of the network in order to improve availability and scalability is not a novelty. Pang and Tan in 2004 [2] and Margulius in 2002 [3] already stated similar concepts: *“by caching application logic and data closer to the edge, you can perform routing and load balancing more efficiently, thereby serving applications and data faster and more reliably to end-users. (...) What’s different about edge computing is that a thin layer of business logic and intelligence has already started moving out toward the edges of the network, including logic for doing content delivery and data transformations, message routing, and other functions required by an increasingly edge-oriented computing world.”* Cloudlets also are another related concept proposed by Satyanarayanan in 2009 [4], defined as *“a trusted, resource-rich computer or cluster of computers that is well-connected to the Internet and is available for use by nearby mobile devices”*. Based on these observations, fog computing is closely related to other previously envisioned ideas and it is part of a framework focused on agile service delivery. The association of this framework with cloud computing leverages its characteristics, such as resource pooling and scalability, to the agility of edge computing. Fog computing enables a new breed of applications and services based on the interaction between fog and cloud [1], [5], [6]

The objective of this paper is to explore the state of the art of fog computing and its predecessors. We analyze how each of these concepts and ideas evolved, what are the interrelations between them, and what is the role of cloud technology in edge computing. We first propose a method to analyze the publications related to these subjects, leading to the creation of a taxonomy. Then we apply this taxonomy to a survey of publications both from academia and industry in order to analyze the trends, main concerns, and main solutions regarding the studied topics. Finally, we provide an analysis of the results, identifying the areas being covered by current research and others which demand further effort to improve feasibility and robustness of the technology.

The paper is organized as follows. Section II presents a study of edge computing and the related topics identified during the survey. Section III presents the taxonomy proposed and used to analyze the gathered references. Section IV presents the research method used to find the publications of interest, the results of the survey, and the analysis of its results. Finally, Section V presents the conclusion of this work.

II. Contextualization

A. Fog Computing

“Fog computing extends the cloud computing paradigm to the edge of the network, enabling a new breed of applications and services” [1]. This is the definition of fog computing proposed by Bonomi et al. The authors also define ten characteristics of fog computing, which we present and discuss in the following items.

978-1-5090-3339-3/16/$31.00

1) **Edge location, location awareness, and low latency.** The key point of fog computing is that the resources are located in the network edges, thus being closer to sources and consumers of data. The fog can be used to provide additional intelligence to solutions and to deliver a faster response than a traditional centralized cloud solution. Figure 1 illustrates this characteristic.

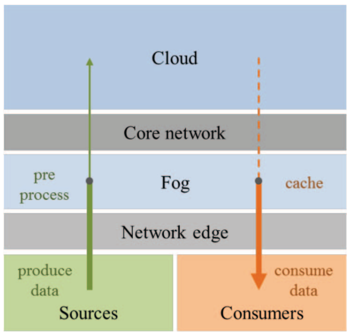

Figure 1. Fog basic architecture, with sources and consumers connected to the cloud through the network edge, the fog, and the core network.

The fog can be used to pre-process and cache data to reduce traffic in the core network This increases infrastructural efficiency and allows more users to be served with better quality of service and experience.

2) **Geographical distribution.** Cloud resources are distributed via virtualized infrastructures. However, in terms of geographical distribution these resources usually are concentrated in a data center. In contrast, the resources of a fog are inherently distributed across a larger geographical domain. This enables the deployment of services that explore this characteristic as a strategic advantage.

3) **Distributed computing and storage resources.** Scenarios such as large-scale sensor networks and Smart Grid environments require highly distributed resources available to process and store data. The fog is a set of pools of resources composed of a combination of virtualized components and distributed across the edges of the network.

4) **Very larger number of nodes.** The processing power of each fog node is less important than the number of nodes, as the objective of the fog is to reduce latency and reduce network traffic in the core network [7]. Usually the fog performs simple tasks for a large number of simultaneous users, instead of expensive tasks over a small amount of data. If a more expensive task has to be executed it should be sent to the central cloud.

5) **Support for mobility.** It is important to decouple the communication mechanisms from the applications and services running in the fog [8]. In a mobile network there are several smaller access points or base stations that receive connections from end users. These smaller access points are connected to a main base station, which has a robust link to the core network.

6) **Real-time interactions.** The strategic position of the fog allows the implementation of real-time decisions and processes [9]. This leads to lower latency and enables a variety of services and business models to be offered and explored. Interactions are performed in real-time, as data is either produced by end users and devices or consumed by them [10].

7) **Predominance of wireless access.** Recent reports from Ericsson [11], [12] state that smartphones are quickly replacing desktops and laptops to perform online activities. The number of worldwide LTE (4G) subscriptions reached 1 billion in Q4 2015. Mobile traffic from Q4 2014 to Q4 2015 grew 45%. 9.1 billion of mobile subscribers (4.1 billion being LTE) are expected by the end of 2021 [12]. Traffic is mainly represented by video (50% in 2015, 70% expected for 2021). Most of the services accessed by mobile devices are deployed in clouds. The fog can be an aggregator, responsible for receiving this traffic, performing local operations, and relaying information to a central server. Moreover, the combination of fog computing with LTE/5G small cells will contribute even more to reduce latency and jitter [13].

8) **Heterogeneity.** The fog is a border between end users and the core network. The fog has to support a multitude of applications developed using different communication, storage, and processing technologies. Consequently, the fog must cope with heterogeneity not only considering the devices it interacts with, but also how it internally operates.

9) **Interoperability and federation.** Fogs must be able to communicate among themselves in order to exchange information and perform load balancing and resource orchestration operations. Each fog can be specialized for a specific operation, such as caching or real-time analytics [9]. In this sense, tasks can be internally coordinated to be sent to the adequate specialized fog.

10) **Support for online analytics and interplay with the cloud.** Fog computing implies communication between fogs and traditional clouds. The fog acts as an additional layer providing intelligence on the edges while the cloud is the central powerhouse in the network hierarchy. Fogs and clouds must be orchestrated considering their strengths and weaknesses For example, the fog can implement a first round of real-time analytics to reduce core network traffic, then the cloud implements the final processing and long-term storage.

In a nutshell, the fog is a small cloud on the edge of the network. Location is its main strategic characteristic, enabling an abundance of applications to be developed. Although it might be less powerful than a traditional cloud or data center, the fog is closer to the elements that produce or consume data in the ecosystem. This allows the introduction of data-centric logic and intelligence, reducing response time and network resources consumption, particularly in the core network. This represents efficiency, as more data sources and consumers can be supported by the same infrastructure.

On the other hand, the fog is not a substitute for the cloud. Mims [14] correctly states that *"whereas the cloud is (...) distant and remote and deliberately abstracted, the fog is close to the ground, right where things are getting done. It consists not of powerful servers, but weaker and more dispersed computers"*. The notion of the fog as a strategic replacement for the cloud is not accurate, as they are complementary infrastructures.

B. Edge computing

Margulius [3] presented the concept of edge computing in 2002.The proposed architecture was a logical extension of content delivery networks (CDN), caching application logic and data closer to the edge in order to perform routing and load balancing more efficiently. Challenges related to security, manageability, and appropriateness for transactional applications, are similar to the ones found in other distributed architectures. The author also states that moving application logic towards the edge makes even more sense with the advent of Web services, as these services could become a service layer to the edge. Moreover, 80% to 90% of all edge devices would be wireless, meeting the characteristic observed in fog computing nowadays.

Regarding the evolution of the concept, Desertot et al. [15] focused on offering Web cache servers over ISP backbones. For the authors the benefits of edge computing are the on-demand performance scalability and quality of service. Additionally, the proximity of the servers to the clients decreases response time [16], [17]. The edge servers are managed by the Internet Service Providers (ISPs), reducing the computation needs and infrastructure costs from the Application Service Providers (ASPs).

Davis et al. [18] stated that edge computing is a *natural evolution of the CDNs*. They define two types of software components: an *edge component*, deployed on the edges of the network, and an *origin component*, deployed in the traditional manner within the data center. This was used to implement content aggregation, static databases (run entirely on the edge), data collection, two-way data exchange, and complex applications (e.g. e-commerce engines and online banking). Technical challenges include security (especially isolation and protection against buggy code), load balancing, resource management, monitoring, and debugging [19], [20].

Grieco et al. [21] presented a scalable infrastructure for developing and deploying edge computing services. They refer to the concept as *value-added proxy services infrastructures*, offering efficient and intelligent services as close as possible to the end users.

Tatemura [22] proposed an edge architecture for cache-friendly e-commerce applications. He claims that latency is caused not only by the network but also by the backend application execution time. Consequently, offloading processing from the backend is important to provide service scalability (a point also mentioned by [23]). The performance gains were verified through an Amazon Web Services based testbed.

Choy et al. [24] proposed a hybrid edge-cloud architecture for reducing online gaming latency. Clouds are about resource consolidation, lowering costs, and high throughput. The authors investigated the effectiveness of using this infrastructure for serving latency-sensitive multimedia applications and then compared it to edge servers. They concluded that a hybrid infrastructure (combining both approaches) significantly improves the number of end-users served, while a pure cloud infrastructure is unable to cope with the requirements.

C. Cloudlet

The concept of cloudlet proposed by Satyanarayanan et al. in 2009 [4] refers to a trusted resource-rich cluster available for use by nearby mobile devices. Cloud computing is limited by latency and delay, both with high impact on real-time applications. Moreover, these limitations are unlikely to improve, as the focus of researches regarding WANs are on bandwidth, security, energy efficiency, and manageability. Latency, on the other hand, might even get worse. In this context, instead of relying on distant clouds, mobile devices can use resources from a much closer cloudlet, which is a few hops away from it [25], [26], [27], [28], [29].

In 2012 an enhancement of the original cloudlet model was proposed by [30]. The authors proposed a more dynamic cloudlet in which all devices in the LAN network can cooperate. They also enhanced the granularity of the unit distribution, from virtual machines in the original model to application components. An Execution Environment (EE) is responsible for starting and stopping components, as well as resolving dependencies and exposing interfaces.

In 2014 [31] stated that one of the cloudlet challenges is to prove that code offloading actually offers a better performance than processing in the cloud. The balance between what should be offloaded and what should run using the mobile device or the cloud is another concern [32]. Challenges also include trusting the cloudlets to offload data and logic [33]. Mechanisms for attestation and integrity, such as Trusted Platform Module (TPM), might help to mitigate risks and reduce any suspicions when adopting cloudlets. Nevertheless, interactive applications based on code offloading can benefit from the latency reduction, enabling new applications to be developed [34].

III. Classification

The classification of papers and references on fog computing and its related topics was based on the taxonomy presented in Figure 2. The taxonomy is organized in three main categories:

- **Terminology**: Category composed by the terms fog computing, edge computing, and cloudlets. This category was used to determine which terms each paper uses.
- **Related topics**: Technologies related to fog computing, or technologies which use the infrastructure and the features from fog computing to deliver a better solution. For example, peer-to-peer applications that use the fog to perform rapid processing of user requests and content finding operations. Another example are Internet of Things solutions that use the fog to achieve faster response times and to reduce the amount of network resources consumed in the core network. This paper does not aim to provide an extensive comparison of these related topics with fog computing, but rather analyze how they are combined throughout references from academia and industry.
- **Dimensions**: Three dimensions were analyzed for each reference. The first one, Performance, was divided in

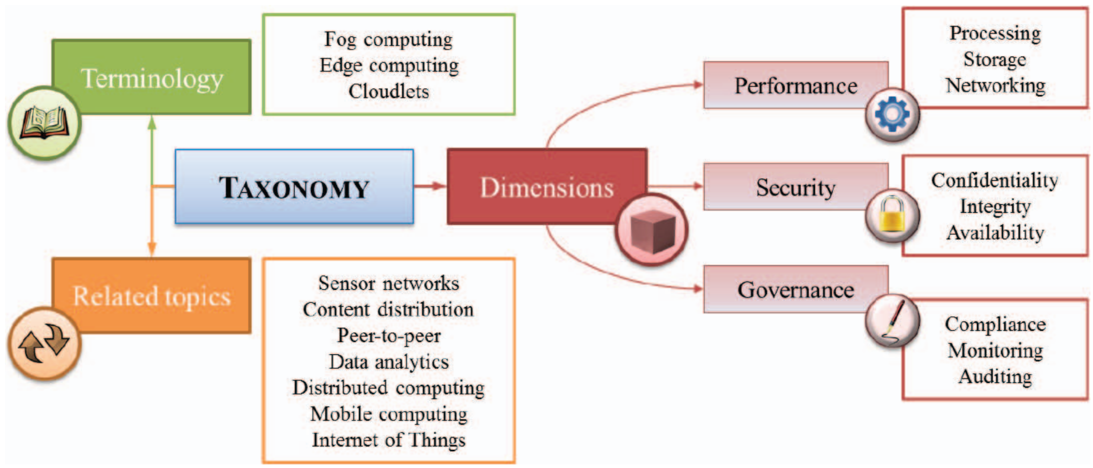

Figure 2. Taxonomy used in the classification of the references.

Processing, Storage, and Networking. The second one, Security, was divided in Confidentiality, Integrity, and Availability (following the CIA security model [35]). The third one, Governance, was divided into Compliance, Monitoring, and Auditing.

These three main categories represent the core aspects analyzed in the references found. The terminology analysis allows the identification of the main terms used to refer to the edge computing technology, and how often these terms are identified. The related topics analysis allows the identification of the main topics which are closely related to this technology, and it also revealed how the technology is used in concrete scenarios. Finally, the dimensions analysis allows the identification of the coverage of aspects such as performance, security, and governance.

IV. Survey

A. Research method

1) **Keywords and techniques**. Our objective with this survey was to broadly investigate publications, including scientific papers from the academia and white papers and other publications from the industry. The searches were based on combinations of the main keywords *fog computing*, *edge computing*, and *cloudlet*, to all the terms derived from the taxonomy. This produced 48 combinations of keywords plus the original 3 main terms, resulting in 51 queries for each search engine. Besides the combination of keywords, we also used other strategies to find papers. For example, both fog computing and cloudlets concepts have a main representative paper: [1] for fog, and [4] for cloudlets. Thus, we also looked for papers that cited these two, allowing us to find most of the papers which used these concepts.

2) **Search engines**. The main engine used to find academia papers was Google Scholar. We also used other engines to find academia papers, such as: IEEE Xplore, ACM Digital Library; ScienceDirect, Scopus, and CAPES (www.periodicos.capes.gov.br). These other engines were used to complement the results from Google Scholar. For industry publications, such as white papers, blog posts, news, and other media, we opted for simple Google searches using the same search terms presented before. This led to the identification of papers from several companies and institutions, such as Ericsson, Microsoft, IBM, Cisco, and many others.

3) **Selection and filtering**. For Google Scholar each page with search results contains 10 results. For each search results were analyzed up to the tenth page, leading to 100 results. Two rounds of searches were performed. The first one used default parameters, including any date range and sorting results by relevance. The second focused on more recent publications, obtaining results from 2013 or later.

Each query might produce repeated results that must be discarded. The queries might also produce unrelated results – results that contain the keywords but the subject is not relevant to our research. These results have to be filtered and discarded if necessary. After a first round of searches, applying those initial filters, we found over 500 references from academia and industry. This first round of filtering was performed using two software tools internally developed. The first tool is able to read the references and identify the keywords of interest. The second tool is able not only to identify the keywords, but also display the content surrounding the keyword. With both tools it was possible to easily and quickly analyze the papers, looking for what could be characterized as false positives. After applying a first round of filtering we narrowed down the results to 300 references. The second round of filtering was performed using the same tools from the first round. We identified the most interesting papers, which were elected as the main references for this survey and which were directly cited in this text. The other references served as complementary sources.

B. Results

After the consolidation of the references the results were grouped and organized. Considering the **terminology** aspect defined in the taxonomy, the results of the analysis are presented in Figure 3. In this graph and all subsequent ones, the X axis represents the concept or keyword used in the search, and the Y axis represents the number of papers (citations) found for that particular search. For this particular graph the term

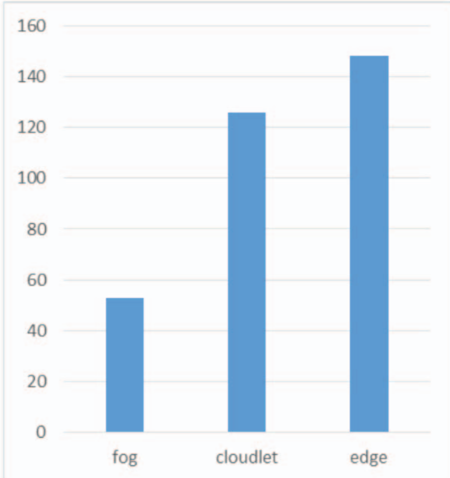

Figure 3. Number of references that uses each of the different terms selected to refer to the edge computing technology.

”edge computing” appeared in 148 references (from a total of 300), which is approximately 50% of the selected references. The second most used term is ”cloudlets”, most of them with direct citation to [4], with 126 appearances – around 42% of the references. The least used term in this context is ”fog computing”, with 53 references citing it. This low number can be related to the relative novelty of the term.This first analysis summarizes what was discussed before: the notion of bringing data and applications closer to the edges is not a novelty, although Cisco’s approach to it has shown relative success.

Considering the **performance** aspect defined in the taxonomy, we searched for the specific terms that have been defined for this dimension, which are processing, storage, and networking. We also looked for references mentioning performance in a broader way (not specifically one of the three terms defined beforehand). The results are observed in Figure 4.

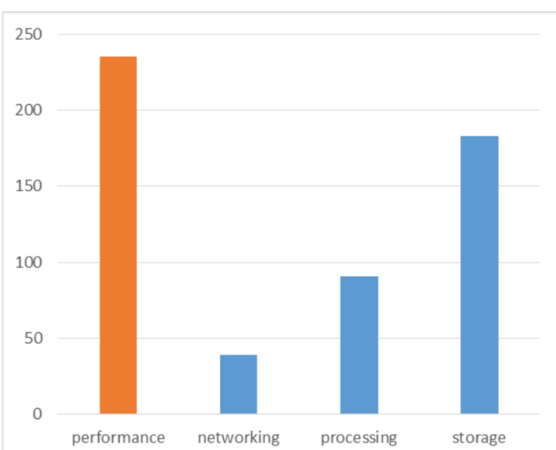

Figure 4. Number of references that either mentioned any of the terms from the performance dimension or referred to this dimension in a general way.

The first term is ”storage”, with 183 references using it (61% of the total). Then we have processing, with 91 references (around 30% of the total). And finally, networking, with 39 references (13% of the total). For each term this evaluation represents the number of references which mentioned problems and solutions for storage, processing and networking related to edge computing technologies. The storage sub-dimension is closely related to the deployment of caches and backup strategies using the edge as strategic advantage. Processing is related to distributed computing using the edges of the network to obtain faster response or implementing real-time (or near real-time) analytics, such as processing data from a sensor network. Networking is related to saving resources and reducing latency, especially for hosted content and Web pages.

Considering the **security** aspect defined in the taxonomy, we searched for the terms confidentiality, integrity, and availability (the CIA security triad). We also looked for other terms that are related to security but not specific to these three concepts. The results are observed in Figure 5. The sub-dimension with most citations is ”availability”, with 112 references using it (around 37% of the total). The second is ”integrity”, with 35 references (around 12%). And the last is ”confidentiality”, with only 9 references (3% of the total).

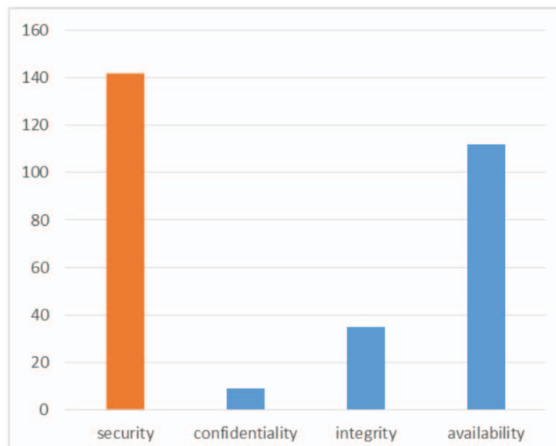

Figure 5. Number of references that either mentioned any of the terms from the security dimension or referred to this dimension in a general way.

Two observations are made regarding these results. The first is related to the massive difference between availability and the other security concerns. Most of the edge computing references that propose solutions focus on having mechanisms to guarantee the availability of the service, related to uptime requirements and backup and replication strategies. This is a reflection of how security concerns are addressed in cloud computing in a general way. The second observation regards the alarmingly small number of references addressing confidentiality issues, which are related to the protection of data and logic against attackers. This is a consequence not from the novelty of the concept, but the lack of maturity from it. One of the most expressive and mature use cases of pushing data to the edges are the content delivery networks (CDNs), mainly used to distribute video and other multimedia content. This type of use case cares less about security and confidentiality and focuses more on delivering the service under certain performance constraints, such as latency and bandwidth restrictions. Adding security features would only jeopardize these aspects. In conclusion, the most mature and well established use cases are the ones that do not care about security, especially confidentiality. However, as the technology is used in other scenarios, such as analytics of sensitive data on the edges, new security mechanisms will have to be proposed in order to guarantee a minimum confidentiality level. Security is one of the main aspects why cloud computing still is not widely adopted by enterprises. Pushing sensitive data to the cloud raises many concerns related to the communication channels and the privilege that a cloud provider has over data and resources.

Considering the **governance** aspect of the taxonomy, the results are observed in Figure 6. The main topic addressed by the references is ”monitoring”, with 74 citations (almost 25% of the total). The second topic is ”auditing”, with 15 citations (5% of the total). And the least addressed topic is ”compliance”, with only 9 citations (3% of the total).

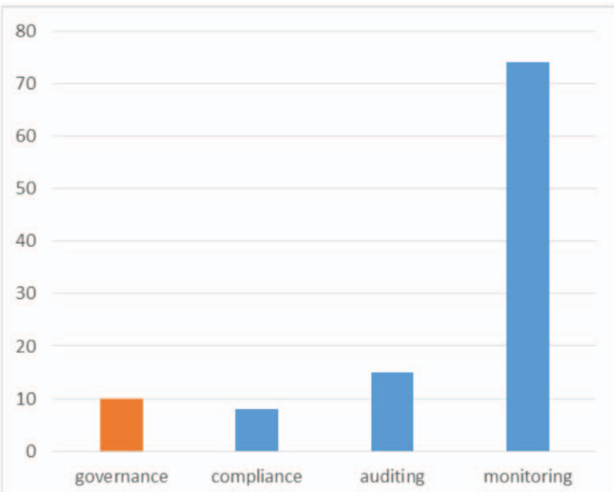

Figure 6. Number of references that either mentioned any of the terms from the governance dimension or referred to this dimension in a general way.

Two observations are made related to these results. The first is related to the huge chasm between monitoring and the other terms. Monitoring is a fundamental aspect to implement load balancing mechanisms and the interplay among fogs and clouds. Moreover, in cloud computing, auditing and compliance are topics usually relegated to secondary status in favor of performance and availability concerns, and it could not be different in the fog. Again, this represents the lack of maturity of the technology, and the lack of consolidated scenarios and products using it, especially for the less explored use cases, such as Internet of Things. The second observation is the overall low number of references mentioning governance related terms. This is a reflection of what is the focus of current edge computing researches: performance aspects and integration to specific use cases, such as mobile networks and Internet of Things. Governance still is not the main concern.

Considering the **related topics** analysis defined in the taxonomy, the results are observed in Figure 7. The dominance of the mobility topic is clear, including mobile networks [36] and code offloading [37], with 209 references mentioning it (almost 70% of the total).

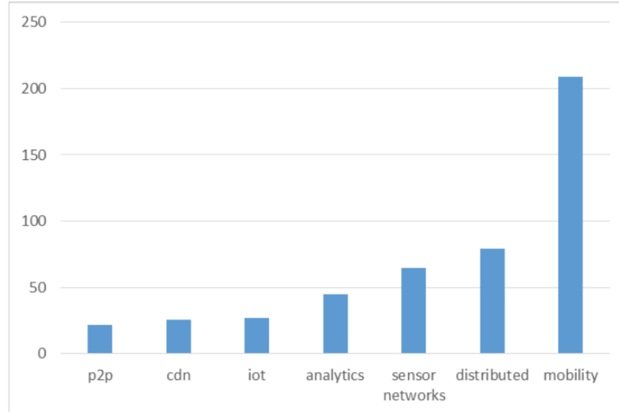

Figure 7. Number of references that are related to one of the related topics from the taxonomy.

Distributed computing, sensor networks, and data analytics are the next related topics, with 79, 65, and 45 references mentioning each (26%, 22%, and 15%, respectively). The topics with least citations are Internet of Things, content delivery networks, and peer-to-peer solutions, with 27, 26, and 22 references each (9% for the IoT and CDN, and 7% for P2P). However, in most papers the concept of mobility is closely related to IoT, so the percentage of references that mention IoT (directly or indirectly) should be higher. Nevertheless, it is clear that mobility currently drives research and industry hype surrounding fog computing. Edge computing and the fog computing term coined by Cisco focus on serving users close to the edge. The majority of devices connected to this edge is expected to be mobile (using wireless communication technologies). The second tier of use cases (distributed computing, sensor networks, and data analytics) heavily relies on processing on the edge. In this case the objective is to offer real-time results while reducing latency and saving network resources in the core network [38]. CDNs and P2P technology are well established and consolidated technologies, thus the amount of references is naturally lower if compared to other subjects which are much closer to the fog hype. However, edge computing is seen as a natural evolution of CDN [18], [39]. CDN is a use case for edge computing, and researches focused on applying the concept to other use cases will take advantage of the techniques already deployed in the CDNs to implement new edge solutions.

C. Analysis

After observing the results for each dimension and category from the proposed taxonomy, it is possible to draw some conclusions regarding the state of the art of edge computing researches. First, the **terminology** analysis. Edge computing and cloudlet terms still are more common than fog, although its recent hype especially in the industry [40], [41], [42]. The fact is that fog and edge are interchangeable terms, as pointed out by some authors [43], [44], [45]. Finally, the term fog has been pointed out as an industry strategy to sell an existing idea with a new name, which is somewhat similar to what happened to cloud some years ago. Cloud computing is based on the concept of utility computing, a term first coined in the 60s [46], [47]. Fog computing is based on edge computing, from the early 2000s. However, it is the technological advancement that has enabled the development of both cloud computing and now the notion of edge computing applied to data analytics, real-time processing, big data storage, and intelligent networking. In other words, if on one side the terms do not represent a novelty, on the other these new terms represent the evolution of the technology, enabling new models for service development and deployment, establishing new business models and mechanisms to offer computing. In the end, these are the the main concerns of every research in computer science and engineering – not the terminology issue.

A second analysis is regarding the **dimensions**: performance, security, and governance. It is clear that performance is the main topic addressed by the references. These references provide an accurate statistical representation of the state of the art of the technology. Thus, we conclude that due to the relative immaturity of the technology, the focus now is on the primary needs: faster response, lower resource consumption. These objectives are not achieved by offering security or governance mechanisms – they are achieved by offering robust and efficient solutions to process, store, and deliver data through the network. As the technology matures and these primary needs are satisfied, the natural evolution of the technology is to embrace the other concerns. Security is key for a wider adoption of cloud technology and the fog can be perceived as a sub-dimension of the cloud. There is also the interplay between fogs and clouds, raising new security concerns that have not been addressed before. Finally, there are specificities related to pushing data and logic to the edge of the network and the security implications of that approach. Data and logic will be stored and processed by third-party equipment, so it is necessary to consider a new party in the cloud ecosystem: the *fog provider*.

Finally, the **related topics** analysis investigates how edge computing is being related to other topics, such as data analytics, Internet of Things, and mobile networks. Due to the characteristics defined for fog (which can be extended to edge computing), it is clear that mobile networks are the main use cases for the technology. Wireless devices are expected to be the main elements using fog resources. Techniques such as code offloading [48], caching, and real-time processing [9] are fundamental for the development of solutions in this context. Cloudlets have been proposed as cyber-foraging sites for cloud offload [49]. Distributed processing is the second main related topic, including data analytics and processing data from sensor networks. Finally, technologies such as CDN and P2P represent existing and well established use cases of computing in the edge of the network (CDNs mainly with caching and P2P with collaboration between users and devices that are even beyond the edge of the network).

V. Conclusion

Edge computing is a term coined in the early 2000s envisioned as a technology to be deployed alongside grid computing, peer-to-peer architectures, and Web services. It would extend the concept of the CDNs by pushing both data and applications to the edges.

A first conclusion of this work is that fog computing is quickly moving towards mobile networks and mobile technologies. Wireless devices are expected to be the main drivers of the fog revolution, followed by Internet of Things. Differently from cloud computing, where the resource pools are organized in centralized data centers, fogs are sparsely distributed. They are less powerful than clouds but able to deliver results with lower latency [50], [51] while saving network resources. A conceptual view of the fog reveals that it enhances the efficiency of the cloud. If a fog is able to reduce the traffic of data to a central cloud by 50%, this means that the same cloud will be able to serve twice the number of current users. Moreover, due to its strategic location, fogs can implement specific logic and intelligence that would not be valid for the central cloud. Therefore, location is the fundamental concept of the fog.

A final conclusion is regarding the future of the fog. Edge computing has two very distinct facets. One, represented by use cases such as CDN and P2P, is a mature version of edge computing, with a lot of research and several existing products (Akamai, numerous P2P applications for content distribution). The other facet, represented by use cases such as Internet of Things and data analytics, reveals a lot of immaturity, with the focus on performance and availability. Concerns related to the security, especially confidentiality, have little research or solutions. This is a reflection of the main technological inheritance from cloudlets and fog: cloud computing. Security is still an issue in cloud computing, and it could not be different with cloudlets and fogs. Moreover, with the addition of the fog, there is a new party that adds complexity to the already complex cloud environment: the fog provider. The interactions among end users, mobile devices, traditional data center providers, cloud providers, and fog providers, is a research area that still has to produce a lot of results. While this maturation does not happen, fog computing will face the same obstacles that cloud computing has been facing over the years.

In fog computing, security concerns still remain in the dark, and governance concerns have not been addressed yet. Users are able to move data and logic to the cloud, but also take advantage of the fog. However, the infrastructures from cloud provider and fog provider are not the same, probably not even managed by the same entity. This raises the concern of provider privilege to another level – and not for the good. The question is whether academia and industry will be able to produce solutions adequately addressing performance, security, and governance needs. Otherwise, fog computing will evolve as cloud computing did, with several solutions emerging without clear definition of security and governance concerns and solutions. This led to the uncertainty and skepticism that still surround cloud.

Acknowledgment

This work has been supported by the Research and Development Centre, Ericsson Brazil.

References

[1] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the internet of things," in *Proc. 1st MCC Workshop on Mobile Cloud Computing*, ser. MCC '12. ACM, 2012, pp. 13–16.

[2] H. H. Pang and K. L. Tan, "Authenticating query results in edge computing," in *Proc. 20th International Conference on Data Engineering*, March 2004, pp. 560–571.

[3] D. L. Margulius, "Apps on the edge," may 2002. [Online]. Available: http://www.computerworld.com.au/article/21708/apps_edge/

[4] M. Satyanarayanan, P. Bahl, R. Caceres, and N. Davies, "The case for vm-based cloudlets in mobile computing," *IEEE Pervasive Computing*, vol. 8, no. 4, pp. 14–23, Oct 2009.

[5] S. Yi, C. Li, and Q. Li, "A survey of fog computing: Concepts, applications and issues," in *Proceedings of the 2015 Workshop on Mobile Big Data*, ser. Mobidata '15. ACM, 2015, pp. 37–42.

[6] C. L. Shanhe Yi, "A Survey of Fog Computing: Concepts, Applications, and Issues," *International Journal of Innovative Research in Computer and Communication Engineering*, vol. 4, no. 4, pp. 37–42, 2015.

[7] D. Hamilton, "Fog Computing Presents a New Way of Powering the Internet of Things," may 2014. [Online]. Available: http://www.thewhir.com/web-hosting-news/fog-computing-presents-new-way-providing-computing-power-needed

[8] J. B. Abdo, J. Demerjian, H. Chaouchi, K. Barbar, and G. Pujolle, "Single-sign-on in operator centric mobile cloud architecture," in *17th IEEE Mediterranean Electrotechnical Conference*, Apr 2014, pp. 151–155.

[9] R. A. Ali, I. Gerostathopoulos, I. Gonzalez-Herrera, A. Juan-Verdejo, M. Kit, and B. Surajbali, "An Architecture-Based Approach for Compute-Intensive Pervasive Systems in Dynamic Environments," mar 2014. [Online]. Available: https://hal.inria.fr/hal-01091541/document

[10] D. Fesehaye, Y. Gao, K. Nahrstedt, and G. Wang, "Impact of cloudlets on interactive mobile cloud applications," in *Enterprise Distributed Object Computing Conference (EDOC), IEEE 16th International*, Sept 2012, pp. 123–132.

[11] Ericsson, "10 Hot Consumer Trends 2014," Tech. Rep., 2014. [Online]. Available: http://www.ericsson.com/res/docs/2013/consumerlab/10-hot-consumer-trends-report-2014.pdf

[12] ——, "Ericsson Mobility Report," Tech. Rep., nov 2015. [Online]. Available: http://www.ericsson.com/res/docs/2015/ericsson-mobility-report-november-2015.pdf

[13] S. Agarwal, M. Philipose, and P. Bahl, "Vision: The case for cellular small cells for cloudlets," in *Proc. 5th International Workshop on Mobile Cloud Computing & Services*, ser. MCS '14. ACM, 2014, pp. 1–5.

[14] C. Mims, "Forget 'the Cloud'; 'the Fog' Is Tech's Future," *Wall Street Journal*, may 2014. [Online]. Available: http://www.wsj.com/articles/SB10001424052702304908304579566662320279406

[15] M. Desertot, C. Escoffier, and D. Donsez, "Towards an Autonomic Approach for Edge Computing: Research Articles," *Concurr. Comput. : Pract. Exper.*, vol. 19, no. 14, pp. 1901–1916, sep 2007.

[16] M. Desertot, C. Escoffier, P. Lalanda, and D. Donsez, "Autonomic Management of Edge Servers," in *Proc. 1st Int. Conf., and Proc. 3rd Int. Conf on New Trends in Network Architectures and Services Conference on Self-Organising Systems*. Springer-Verlag, 2006, pp. 216–229.

[17] C. P. Gavalda, P. G. Lopez, and R. M. Andreu, "Deploying Wide-Area Applications Is a Snap," *IEEE Internet Computing*, vol. 11, no. 2, pp. 72–79, mar 2007.

[18] A. Davis, J. Parikh, and W. E. Weihl, "Edgecomputing: Extending Enterprise Applications to the Edge of the Internet," in *Proc. 13th International World Wide Web Conference on Alternate Track Papers & Posters*, ser. WWW Alt. '04. ACM, 2004, pp. 180–187.

[19] A. C. Donald, S. A. Oli, and L. Arockian, "Mobile cloud security issues and challenges: A perspective," *International Journal of Engineering and Innovative Technology (IJEIT)*, vol. 3, no. 1, pp. 401–406, aug 2013.

[20] M. R. Ebling, E. d. Lara, A. Wolman, and A. Gavrilovska, "The Edge of the Cloud," *IEEE Pervasive Computing*, vol. 12, no. 4, pp. 17–19, oct 2013.

[21] R. Grieco, D. Malandrino, and V. Scarano, "SEcS: Scalable Edge-computing Services," in *Proc. 2005 ACM Symposium on Applied Computing*, ser. SAC '05. ACM, 2005, pp. 1709–1713.

[22] J. Tatemura, "Web service decomposition: edge computing architecture for cache-friendly e-commerce applications," in *International Workshop on Data Engineering Issues in E-Commerce*, apr 2005, pp. 81–87.

[23] N. Aminzadeh, Z. Sanaei, and S. H. A. Hamid, "Mobile storage augmentation in mobile cloud computing: Taxonomy, approaches, and open issues," *Simulation Modelling Practice and Theory*, vol. 50, pp. 96 – 108, 2015, special Issue on Resource Management in Mobile Clouds.

[24] S. Choy, B. Wong, G. Simon, and C. Rosenberg, "A Hybrid Edge-cloud Architecture for Reducing On-demand Gaming Latency," *Multimedia Syst.*, vol. 20, no. 5, pp. 503–519, oct 2014.

[25] S. Abolfazli, Z. Sanaei, A. Gani, F. Xia, and L. T. Yang, "Review: Rich Mobile Applications: Genesis, Taxonomy, and Open Issues," *J. Netw. Comput. Appl.*, vol. 40, pp. 345–362, apr 2014.

[26] H. T. Dinh, C. Lee, D. Niyato, and P. Wang, "A survey of mobile cloud computing: architecture, applications, and approaches," *Wireless Communications and Mobile Computing*, vol. 13, no. 18, pp. 1587–1611, dec 2013.

[27] S. Giordano and D. Puccinelli, "The human element as the key enabler of pervasiveness," in *Ad Hoc Networking Workshop (Med-Hoc-Net), 2011 The 10th IFIP Annual Mediterranean*, jun 2011, pp. 150–156.

[28] Y. Guo, L. Zhang, J. Kong, J. Sun, T. Feng, and X. Chen, "Jupiter: Transparent Augmentation of Smartphone Capabilities Through Cloud Computing," in *Proceedings of the 3rd ACM SOSP Workshop on Networking, Systems, and Applications on Mobile Handhelds*, ser. MobiHeld '11. New York, NY, USA: ACM, 2011, pp. 2:1–2:6.

[29] D. T. Hoang, D. Niyato, and P. Wang, "Optimal admission control policy for mobile cloud computing hotspot with cloudlet," in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, apr 2012, pp. 3145–3149.

[30] T. Verbelen, P. Simoens, F. De Turck, and B. Dhoedt, "Cloudlets: Bringing the Cloud to the Mobile User," in *Proc. 3rd ACM Workshop on Mobile Cloud Computing and Services*, ser. MCS '12. New York, NY, USA: ACM, 2012, pp. 29–36.

[31] A. Bahtovski and M. Gusev, "Cloudlet Challenges," ser. 24th DAAAM International Symposium on Intelligent Manufacturing and Automation, 2013, vol. 69, 2014, pp. 704–711.

[32] N. I. M. Enzai and M. Tang, "A Taxonomy of Computation Offloading in Mobile Cloud Computing," in *Proc. 2nd IEEE International Conference on Mobile Cloud Computing, Services, and Engineering*. Washington, DC, USA: IEEE Computer Society, 2014, pp. 19–28.

[33] A. Gember, C. Dragga, and A. Akella, "ECOS: Leveraging Software-defined Networks to Support Mobile Application Offloading," in *Proc. 8th ACM/IEEE Symposium on Architectures for Networking and Communications Systems*, ser. ANCS '12. ACM, 2012, pp. 199–210.

[34] A. Banerjee, A. Mukherjee, H. S. Paul, and S. Dey, "Offloading Work to Mobile Devices: An Availability-aware Data Partitioning Approach," in *Proc. 1st International Workshop on Middleware for Cloud-enabled Sensing*, ser. MCS '13. New York, NY, USA: ACM, 2013, pp. 4:1–4:6.

[35] Y. Cherdantseva and J. Hilton, "A Reference Model of Information Assurance amp; Security," in *8th International Conference on Availability, Reliability and Security (ARES)*, sep 2013, pp. 546–555.

[36] S. P. Ahuja and A. C. Rolli, "Exploring the Convergence of Mobile Computing with Cloud Computing," *Network and Communication Technologies*, vol. 1, no. 1, may 2012.

[37] S. Abolfazli, Z. Sanaei, E. Ahmed, A. Gani, and R. Buyya, "Cloud-Based Augmentation for Mobile Devices: Motivation, Taxonomies, and Open Challenges," *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 337–368, 2014.

[38] K. Ha, P. Pillai, G. Lewis, S. Simanta, S. Clinch, N. Davies, and M. Satyanarayanan, "The Impact of Mobile Multimedia Applications on Data Center Consolidation," in *IEEE International Conference on Cloud Engineering (IC2E)*, mar 2013, pp. 166–176.

[39] M. Rabinovich, Z. Xiao, and A. Aggarwal, "Computing on the Edge: A Platform for Replicating Internet Applications," in *Web Content Caching and Distribution*, F. Douglis and B. D. Davison, Eds. Springer Netherlands, 2004, pp. 57–77, dOI: 10.1007/1-4020-2258-1_4.

[40] Broyer, "The Foggy Future of Cloud (or Edge) Computing," aug 2013. [Online]. Available: http://blog.venyu.com/2013/08/28/the-foggy-future-of-cloud-or-edge-computing

[41] J. Burt, "Cisco Moving Apps to the Network Edge for Internet of Things," jan 2014. [Online]. Available: http://www.eweek.com/networking/cisco-moving-apps-to-the-network-edge-for-internet-of-things.html

[42] K. Bent, “Cisco Launches ’Fog Computing’ Platform For Internet Of Things,” feb 2014. [Online]. Available: http://www.crn.com/news/networking/240165897/cisco-launches-fog-computing-platform-for-internet-of-things.htm

[43] J. G., “FOG Computing (EDGE Computing) And Its Applications In Internet Of Things,” feb 2015. [Online]. Available: http://a4academics.com/be-seminar-topics/17-be-it-cse-computer-science-seminar-topics/558-fog-computing

[44] J. Markert, “How Fog Computing Could Power The Internet Of Things,” jun 2014. [Online]. Available: https://curiousmatic.com/efficient-decentralized-iot-computing-future-may-fog/

[45] O. Ferrer-Roca, “FOG computing in HEALTH 4.0,” may 2014. [Online]. Available: http://catai.net/blog/2014/05/fog-computing-in-health-4-0/

[46] M. Greenberer, “The Computers of Tomorrow by Martin Greenberger,” may 1964. [Online]. Available: http://www.theatlantic.com/past/docs/unbound/flashbks/computer/greenbf.htm

[47] J. McCarthy and A. Schurr, “Five myths of cloud computing,” HP, Business white paper, may 2011. [Online]. Available: http://www.hp.com/hpinfo/newsroom/presskits/2011/HPDiscover2011/DISCOVER5MythsofCloudComputing.pdf

[48] S. Abolfazli, Z. Sanaei, M. Alizadeh, A. Gani, and F. Xia, “An experimental analysis on cloud-based mobile augmentation in mobile cloud computing,” *IEEE Transactions on Consumer Electronics*, vol. 60, no. 1, pp. 146–154, feb 2014.

[49] K. Ha, P. Pillai, W. Richter, Y. Abe, and M. Satyanarayanan, “Just-in-time Provisioning for Cyber Foraging,” in *Proc. 11th International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys ’13. New York, NY, USA: ACM, 2013, pp. 153–166.

[50] S. Abolfazli, Z. Sanaei, M. Shiraz, and A. Gani, “MOMCC: Market-oriented architecture for Mobile Cloud Computing based on Service Oriented Architecture,” in *2012 1st IEEE International Conference on Communications in China Workshops (ICCC)*, aug 2012, pp. 8–13.

[51] P. Datta, S. Dey, H. S. Paul, and A. Mukherjee, “ANGELS: A framework for mobile grids,” in *Applications and Innovations in Mobile Computing (AIMoC), 2014*, feb 2014, pp. 15–20.