A Preliminary Roadmap for Dependability Research in Fog Computing

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ABSTRACT

Fog computing aims to support novel real-time applications by extending cloud resources to the network edge. This technology is highly heterogeneous and comprises a wide variety of devices interconnected through the so-called fog layer. Compared to traditional cloud infrastructure, fog presents more varied reliability challenges, due to its constrained resources and mobility of nodes. This paper summarizes current research efforts on fault tolerance and dependability in fog computing and identifies less investigated open problems, which constitute interesting research directions to make fogs more dependable.

CCS CONCEPTS

• Computer systems organization → Reliability; Availability; Redundancy;

KEYWORDS


1 INTRODUCTION

Fog computing is a recent computational paradigm, first introduced by Cisco, to extend cloud computing computational resources, closer to the edge of the network [7, 19]. Fog is a middle layer between the cloud and the devices to have more efficient data processing, effective analysis and storage scalability. It also reduces the amount of data transmitted to the cloud [14]. There is a general understanding that this technology is suitable for Cyber-Physical Systems, IoT and Industrial IoT (IloT) in different application areas. For instance, smart cities, agriculture domains, vehicular systems, industrial automation, health-care and robotics. It is also claimed that fog represents a solution to improve latency for distributed control systems in general.

According to Bonomi et al. [7] fog computing has the following characteristics, a) Low latency and location awareness; b) Supports geographic distribution; c) End device mobility; d) Capacity of processing with a high number of nodes; e) Wireless access; f) Real-time applications and g) Heterogeneity. These characteristics make fog computing a suitable solution for overcoming problems manifested by the use of traditional cloud computing in Internet of Things (IoT), like high mobility and low latency, but they also give rise to new dependability challenges. Note that each of the factors mentioned above represents a difficulty for achieving dependability, so the combination of all of them makes the whole undertaking even more challenging.

Dependability is the ability of a system to supply trusted and available services. A dependable system is a system which is able to avoid service failures that are more frequent and more severe than is acceptable. There are many dimensions that should be considered to analyze whether a fog-based solution is dependable, such as availability, reliability, performability, maintainability; which are well-known dependability attributes (or requirements) [4]. At the same time, there are different ways to implement a dependable system, for instance using fault tolerance algorithms and redundancy techniques. Given the interest in fog computing and the difficulties it introduces in terms of dependability, it is important to understand how dependability and fault tolerance are addressed in the literature on fog computing.

This paper summarizes fog computing dependability requirements and discusses the gap, in terms of dependability, of the existing solutions with respect to the desired dependability requirements. After presenting a basic hierarchical structure of fog architecture, in this paper we will 1) identify and classify current research approaches for dependability in fog computing, 2) compare different proposed solutions considering traditional dependability notions for critical systems, and 3) discuss research gaps related to fog computing dependability. We realized that there is a range of terms alternatively used for fog computing by authors in the literature. For instance edge clouds, cloudlets, mobile edge computing, etc. We considered these terms as related technologies to fog computing in our study. The remainder of this paper is organized as follows. In Section 2 we present the fog computing architecture. In Section 3, we review current approaches for dependability solutions in fog
computing. In Section 4 we discuss the gaps between current
research approaches and fog computing dependability requirements
and finally we conclude our work in Section 5.

2 FOG COMPUTING ARCHITECTURE

Fog computing is a highly virtualized platform that provides stor-
age, communication, computation, controlling, machine learning
services in a decentralized network closer to devices [1, 15]. To the
best of our knowledge, there is no reference architecture for fog
computing, however, there are basic architectures for fog proposed
in the literature, like [15, 21, 25]. The proposed architectures are
mostly constituted by a three-layer structure, as depicted in Figure
1, which includes a layer between cloud and devices, known as fog
layer. This fog layer carries out the task of computation from clouds
closer to the network edge.

![Figure 1: The basic hierarchical architecture of fog computing.](image)

There is a somehow diffuse border between fog computing and
the paradigm called edge computing, but there is an important
difference that we will apply in this work: edge computing does not
preclude the existence of a cloud to which the intermediate nodes
are connected. However, whenever edge is used in combination
with cloud, one can arguably say that both paradigms are equivalent.
For this reason, we also investigated systems introduced as edge
computing but have considered them as instances of fog.

In the following we will describe each layer of the hierarchical
fog computing architecture:

2.1 Cloud Layer

This layer consists of multiple, powerful computational resources,
storage and servers, which are capable of processing, analyzing and
storing large amounts of data. Cloud computing provides services
for different application domains, for instance, vehicular systems,
smart cities, smart factories, health-care, etc. [25]. The clouds are
efficiently managed and scheduled by some control strategies to im-
prove utilization of the cloud resources. Although cloud computing
is empowered by huge computational resources and storage capac-
ities, for certain tasks, e.g. those requiring low latency, it might be
better to release their execution to other parts of the system, closer
to the edge [27].

2.2 Fog Layer

According to the OpenFog consortium, the fog computing model
moves computation from the cloud closer to the network edge,
by placing geo-distributed computational resources between the
cloud and sensor layer [21]. The Fog computing layer is composed
of fog platforms (the fog nodes) which rely on highly virtualized
resources running under hypervisors. Fog platforms are constituted
by a large number of fog nodes consisting of routers, switches,
Wireless Access Points (WAP), Road Side Units (RSUs), gateways,
wireless set-top boxes, network bridges and cellular base stations
[6, 11].

These fog nodes, which can be fixed or mobile, are distributed
in different geographical locations to provide services in proximity
of edge devices. Given that the edge devices (Sensor layer) can
be mobile, the Fog layer should enable reallocation of tasks and
resources at runtime. In fact, the high mobility characteristic of
fog computing typically gives the impression that fog nodes enter
in and out the network, which may give rise to novel availability
issues. In terms of security, the existence of this intermediate level
also increases the attack surface of the system considerably.

2.3 Sensor Layer

This layer is bottom layer in the hierarchical architecture which
consists of devices, sensors, actuators in a physical environment;
for instance, vehicles, smart cards, IoT devices, etc. Devices in this
layer are geographically distributed, can be fixed or mobile, and re-
quire minimal computational resources, being typically very energy-
constrained. Usually utilized as smart sensing devices, they sense
data and gather information, and then send it to the upper layer for
processing, storage and distribution [2].
3 CURRENT DEPENDABILITY APPROACHES FOR FOG COMPUTING

Dependability approaches for fog computing are mainly proposed to address dependability objectives, redundancy models and fault management solutions. Figure 2 present a summary of the approaches in our literature review.

3.1 Dependability Objectives

Dependability requirements for fog computing are not clearly defined, as fog computing is a very recent technology. Our review of existing literature shows that authors differ significantly from each other in terms of the types of faults and errors they address, the method applied and even the dependability requirements themselves. Our study shows that the most common objectives are improving availability, reliability and Quality of Service (QoS). The ways to improve these attributes are typically based on redundancy models which are explained in the following subsection. Our study also shows that scalability, i.e. the ability to provide service for a large number of devices in the Sensor layer, is a crucial aspect of Fog. This can be related to the dependability attribute of performability.

3.2 Redundancy Models

Proposed redundancy models has been applied at different levels of the systems architecture: the communication links, the computing nodes and the application software. For instance, regarding network connectivity, Cau et al. used 5G communication to satisfy network reliability [10]. Wiss & Forsstrom. consider higher network connectivity as availability by using SCTP protocol instead of TCP [29].

Other works also consider the possibility of node failure. Itani et al. proposed dynamic failure recovery to improve node availability [16]. Zhou et al. used message broadcasting to check node availability for offloading tasks in case of fog node or link failures [33]. Okafor et al. proposed using of Spin-Leaf topology in fog network to ensure availability [20].

There is an interesting family of solutions that rely on software reallocation in order to increase service reliability/availability. Saqib & Hamid. proposed a task off-loading solution to ensure reliable computation in fog computing and IoT network [26]. Aral & Brandic. focused on QoS of VMs in an edge network infrastructure [3] and Osanaiye et al. proposed a live VM migration framework to increase QoS by improving availability of VM fog nodes [22]. Rimal et al. focused on improving system performance to promote QoS [24].

But, although authors allegedly address all these requirements, quantitative goals which would help us to define system thresholds are seldom or partially reported. In the scheme proposed in [9], authors considered strategies to minimize bandwidth and storage usage in which they reported percentage values of the gap between optimal scheme and practical measurements, lower than 6.2% and 30% for bandwidth and storage usage respectively.

Availability of replicated nodes or links are checked using different monitoring tools [17] or calculated via mathematical methods [9] or the use of machine learning algorithms [3].

With respect to the applied redundancy schemes, we found out that all types of redundancy have been used by different authors. It was observed that sometimes natural redundancy has been used for path redundancy, for instance as provided by wireless broadcast in [10]. The most common approach is Primary/Backup redundancy, with reconfiguration upon failure. Schemes relying both on Active replication (also known as Active/Active or Hot stand-by) and Passive replication (also known as Active/Passive or Cold stand-by) were found. For instance, Banson et al. proposed a dynamic path selection method based on Software defined networks (SDN), leveraging SDN monitoring tools to check the links availability status [5]. In another work [12] Maximum Distance Separable code (MDS) is used for dynamic clustering to find redundant nearby nodes. Although there are some approaches using dynamic redundancy, most often static allocation of redundancy is used. Cau et al. proposed static signal forwarding to available nodes in case of node failure in the network [10]. Other works also proposed passive replication in which virtual backup resources are pooled and shared across multiple virtual infrastructure [28, 31].

3.3 Fault Management Solutions

Solutions for fault management in fog computing proposed in the available publications on dependability and fog computing shows that authors have more importantly focused on these specific problems: a) Optimal allocation of redundancy, to reduce utilization. An instance is the work of Mennes et al. [18] which proposed an algorithm for optimal application placement; b) Techniques for error detection and reconfiguration upon failure, like e.g. Cher-vaykov et al. proposed a reconfigurable data storage system based on Redundant Residue Number System (RRNS) [13] and Xiao et
We have identified a number of research topics that seem to have ward (from sensors to fog) or internally cashed in fog node. All of (i.e. Stop failure semantics). However, more complicated failure are a number of papers dealing with security [8, 13, 20, 22], but comparing to cloud and traditional critical systems. this makes the fault-tolerant replication model more complicated, transmission, which can be upward (from clouds to fog), down-
tinction throughout the architecture, including data source and data
clarifying the interaction between application and data replica-
schemes have been proposed individually, and the potential inter-
ference between them has not been investigated. This also includes
clarifying the interaction between application and data replication through
out the architecture, including data source and data transmission, which can be upward (from clouds to fog), down-
ward (from sensors to fog) or internally cached in fog node. All of this
makes the fault-tolerant replication model more complicated, comparing to cloud and traditional critical systems.

Security issues aggravated by faults. We found out that there are a number of papers dealing with security [8, 13, 20, 22], but none of them addressed security for fog computing in the presence of unintentional faults. On the other hand, methods to achieving replication securely under differing threat models has not been specifically surveyed to provide secure redundancy techniques.

Error propagation through the fog structure. Uncontrolled error propagation is an important problem in any dependable sys-
tem. The usual way to handle this problem is by defining and substantiating appropriate error-containment regions. This work has not been done for existing fog computing architectures. This aspect is related to the security problems discussed above, since correct error-containment is a good support for security, but it also concerns non-malicious faults, which can spread as subsystem errors and cause unexpected failures in other parts of the system. In a highly-dynamic system like the fog, poor handling of error propagation might even lead to instability system-level problems. This also opens an opportunity to investigate novel methods for error forecasting and dynamic error containment.

Fault recovery and node reintegration. Current approaches studied in this work have investigated different methods for fault
detection, fault-tolerance, fault prevention and fault diagnostics. However, in a long-lifed system like the fog, it is also needed to
develop methods that allow faulty components to recover and be reintegrated in the system operation. This can prevent system failure or shut down caused by fast redundancy attrition.

Scalability concerns. Fog nodes should be able to provide ser-
vice for a large number of heterogeneous devices in different ap-
plication areas. These application domains can require large-scale deployment of nodes, also for safety-critical domains. For instance, firefighting, transportation systems and industrial robotics. When a fog node fails in such large-scale critical systems, it is usually difficult to coordinate the huge number of sensors and devices in the presence of faults or to recover from failures. Similar unknown risks, caused by the large system size and the massive number of components, might be found in future applications.

A comprehensive fault management framework is missing. A fault management framework is a part of large network man-
agement structure. This framework can address faults in a higher level as well as designing a high level management infrastructure for addressing faults in a system [23]. Although there are some frameworks proposed for Fog computing and fault tolerance in Fog networks, they do not address faults in all aspects. For instance, considering connection failure, node failure, application placement, task management, etc. combined in the same framework package. As indicated above, certain notions like fault diagnosis and fault treatment have received little attention, as well as the threats posed by malicious faults. All these aspects should also be integrated in this fault management framework. Similarly to other large-scale networked systems, the fog allows application of novel methods based on statistical learning, such as machine learning, in order to identify anomalies and forecast faults, but this type of work is still in its infancy. A suitable framework should include methods for data collection and a repository of considered faults and mitigation techniques.
5 CONCLUSION

This paper has reviewed the current state of the art regarding dependability and fog computing. We have summarized the current research efforts and discussed a list of open research problems.

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