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Review

Survey on fog computing: architecture, key technologies, applications and open issues

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A R T I C L E I N F O

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A B S T R A C T

The emergence of Internet of Things (IoT) has enabled the interconnection and intercommunication among massive ubiquitous things, which caused an unprecedented generation of huge and heterogeneous amount of data, known as data explosions. On the other hand, although that cloud computing has served as an efficient way to process and store these data, however, challenges, such as the increasing demands of real time or latency-sensitive applications and the limitation of network bandwidth, still cannot be solved by using only cloud computing. Therefore, a new computing paradigm, known as fog computing, has been proposed as a complement to the cloud solution. Fog computing extends the cloud services to the edge of network, and makes computation, communication and storage closer to edge devices and end-users, which aims to enhance low-latency, mobility, network bandwidth, security and privacy. In this paper, we will overview and summarize fog computing model architecture, key technologies, applications, challenges and open issues. Firstly, we will present the hierarchical architecture of fog computing and its characteristics, and compare it with cloud computing and edge computing to emphasize the similarities and differences. Then, the key technologies like computing, communication and storage technologies, naming, resource management, security and privacy protection are introduced to present how to support its deployment and application in a detailed manner. Several application cases like health care, augmented reality, brain machine interface and gaming, smart environments and vehicular fog computing are also presented to further explain fog computing application scenarios. Finally, based on the observation, we propose some challenges and open issues which are worth further in-depth study and research in fog computing development.

1. Introduction

With the development of Internet of Things (IoT), Cyber-Physical System (CPS) and Mobile Internet, various objects, including people, machines, things, are connected into information space in anywhere at any time (Atzori et al., 2010; Ning et al., 2016). The unprecedented amounts and varieties of data are being generated. According to the estimation and prediction of Cisco, there are more than 50 billion devices which will be connected to the Internet by 2020. And the data produced by people, machines, things and their interactions will reach 500 zettabytes, and 45% of IoT-created data will be processed, analyzed and stored at the edge of network by 2019 (Evans, 2011; Cisco, 2019). While the rapid growth in the amount of data, the speed of data generation is also increasing rapidly. A recent analysis of a healthcare-related IoT application show that 30 million users generate up to 25,000 tuples data per second (Cortes et al., 2015). The huge data volume result in that today's processing and storage capabilities cannot meet the demands (He et al., 2017). And it is difficult to be handled by traditional computing models, such as distributed computing, cloud computing, etc.

Cloud computing has been used as an efficient way to process data because of its high computation power and storage capability (Armbrust et al., 2010; Fernando et al., 2013). However, as cloud computing paradigm is a centralized computing model, most of the computations happen in the cloud. This means that all the data and requests need to be transmitted to centralized cloud. Although the data processing speed has risen rapidly, the network bandwidth has not increased appreciably. So the network bandwidth is becoming the bottleneck of cloud computing for such a huge amount of data. This may result in long latency. In some IoT applications, system might

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require a very short response time and mobility support, such as traffic light system in smart transportation, smart grids (Qiu et al., 2017b), smart healthcare (Cao et al., 2015; Stantchev et al., 2015), emergency response (Qiu et al., 2017a), and other latency-sensitive applications (Arkian et al., 2017). The delay caused by transferring data is unacceptable. Moreover, some decisions can be made locally, without having to be transmitted to cloud. Even if some decisions have to be done in the cloud, it is not necessary and inefficient to send all the data to cloud for processing and storing, because not all data is useful for decision making and analysis. In a word, these challenges which caused by the explosive growth of IoT, related to network bandwidth, latency, reliability and security, cannot be addressed only in dependence on cloud model.

To overcome these issues, cloudlet has been proposed to use the computing resources at the proximity to users for achieving local process and storage, and reducing the amount of network transmission and latency (Chen et al., 2015a). Combined with optimal offloading algorithm, cloudlet system can achieve low cost (e.g., computation and communication costs) (Zhang et al., 2015). However, cloudlet is accessed only through Wi-Fi access point, which results in the small coverage area (Ahmed and Ahmed, 2016). So it cannot support ubiquitous computing. Moreover, compared with cloud computing paradigm, cloudlet resource is constrained, which cannot support salable service and resource provisioning. In addition, mobile cloud computing (MCC) has also been proposed to provide the new models of services for mobile users and take full advantages of cloud computing (Dinh et al., 2013). It refers to an infrastructure where some processing and analytic tasks happen on the edge device while the Cloud is used for coordination and data archival. However, the MCC platform usually tends to be constrained devices, which battery or storage capacities often are the limiting factors. When the multiple IoT applications need to be handled, this will result in resource contention and increases processing latency (Dastjerdi and Buyya, 2016; Varshney and Simmhan, 2017).

Fog computing, which seamlessly integrates network edge devices and cloud center, is presented as a more effective solution to enable address these limitations. Fog computing is a geographically distributed computing architecture, which various heterogeneous devices at the edge of network are ubiquitously connected to collaboratively provide elastic computation, communication and storage services (Yi et al., 2015a). The most prominent characteristic of fog computing is the extension of the cloud service to the edge of network. It makes computation, communication, control and storage closer to end-users by pooling the local resources. Data is consumed by the geographically distributed network edge devices. Therefore, the data transfer time and the amount of network transmission are greatly reduced (Datta et al., 2015). The fog paradigm can effectively meet the demands of real-time or latency-sensitive applications, and notably ease network bandwidth bottlenecks.

Fog computing architecture adds an extra resource-rich layer between end devices and cloud to meet these challenges in the low latency, high reliability and security, high performance, mobility, and interoperability (Yi et al., 2015b; Stojmenovic and Wen, 2014). The fog platform is composed of a large number of fog nodes. Fog nodes include various network edge devices and management systems within these devices, even some virtualized edge data centers (Zhang et al., 2016). Fog computing bridges the edge users and cloud. On the one hand, fog nodes connect with end devices and users mainly by wireless connection mode, such as 4G, Bluetooth, or WiFi, to independently provide computing, computation, and storage services. On the other hand, fog nodes can also be connected with cloud by Internet in order to make full use of the rich computing and storage resources of cloud (Aazam and Huh, 2016). Fog computing paradigm will efficiently serve low-latency data analysis and decision making.

The fact needs to be emphasized that fog computing is the extension and expansion of cloud computing, rather than a substitute of cloud computing. Fog nodes process and store these data generated by sensors and edge devices. Then the remaining valuable data is transferred to the cloud server for storage or next processing. Through the collaboration with the traditional cloud computing model, fog computing will help cloud computing to play its value more efficiently and serve as a greener computing platform (Yannuzzi, 2014; Hajibaba and Gorgin, 2014).

In this paper, we will survey and summarize fog computing model from architecture, key technologies, applications, challenges and open issues. The main contributions are as follows:

- We present the hierarchical architecture of fog computing and its characteristics, then we compare fog computing with cloud computing and edge computing in similarity and differentiation.
- The key technologies like computing, communication and storage technologies, naming, resource management, security and privacy protection are introduced to present how to support its deployment and application in a detailed manner.
- Several application cases like health care, augmented reality, brain machine interface and gaming, smart environments, vehicular fog computing, IoT and cloud of things, smart energy grid, urgent computing and other applications are presented to further explain fog computing applications.
- Some challenges and open issues which are worth further study and research are presented, including security and privacy issues, control and management, programming platform, energy consumption.

The remainder parts of this paper are organized as follows. Section 2 summarizes the architecture and characteristics of fog computing, and the comparison with cloud computing and edge computing. Section 3 surveys the key technologies of fog computing paradigm. Section 4 shows some fog computing applications. Section 5 presents the possible challenges and open issues. Section 6 concludes this paper.

2. Architecture of fog computing

Fog computing is a new computational paradigm, which extends the traditional cloud computing and services to the edge of network. It provides the computation, communication, controlling, storage and services capabilities at the edge of network. The decentralized platform is different from other conventional computational model in architecture. In this section, we will summarize the architecture and characteristics of fog computing, and the comparison with cloud computing and edge computing.

2.1. The hierarchical architecture of fog computing

The reference model of fog computing architecture is a significant research topic. In recent years, a number of architectures have been proposed for fog computing. They are mostly derived from the fundamental three-layer structure. Fog computing extends cloud service to the network edge by introducing fog layer between end devices and cloud. Fig. 1 shows the hierarchical architecture of fog computing.

The hierarchical architecture is composed of the following three layers:

- *Terminal layer:* This is the layer closest to the end user and physical environment. It consists of various IoT devices, for example, sensors, mobile phones, smart vehicles, smart cards, readers, and so on. Specially, though the mobile phones and smart vehicles have the computing power, we only utilize them as the smart sensing devices here. These devices are widely geographically distributed in general. They are responsible for sensing the feature data of physical objects or events and transmitting these sensed data to upper layer

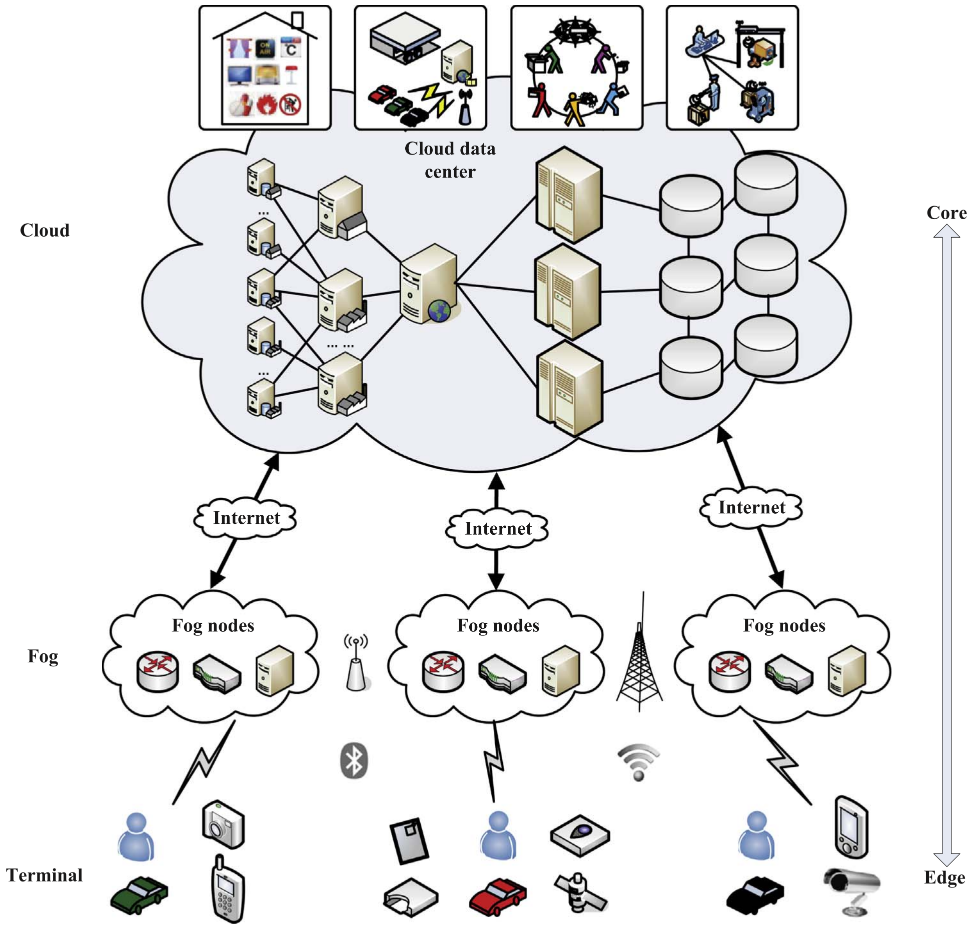

Fig. 1. The hierarchical architecture of fog computing.

for processing and storage.

- *Fog layer:* This layer is located on the edge of the network. Fog computing layer is composed of a large number of fog nodes, which generally including routers, gateways, switchers, access points, base stations, specific fog servers, etc. These fog nodes are widely distributed between the end devices and cloud, for example, cafes, shopping centers, bus terminals, streets, parks, etc. They can be static at a fixed location, or mobile on a moving carrier. The end devices can conveniently connect with fog nodes to obtain services. They have the capabilities to compute, transmit and temporarily store the received sensed data. The real-time analysis and latency-sensitive applications can be accomplished in fog layer. Moreover, the fog nodes are also connected with cloud data center by IP core network, and responsible for interaction and cooperation with cloud to obtain more powerful computing and storage capabilities.
- *Cloud layer:* The cloud computing layer consists of multiple high-performance servers and storage devices, and provides various application services, such as smart home, smart transportation, smart factory, etc. It has powerful computing and storage capabilities to support for extensive computation analysis and permanently storage of an enormous amount of data. However, different from traditional cloud computing architecture, not all computing and storage tasks go through the cloud. According to the demand-load, the cloud core modules are efficiently managed and scheduled by some control strategies to improve utilization of the cloud resources (Sarkar and Misra, 2016).

In this architecture, each end device or smart object is connected with one of the fog nodes by wireless access technologies (mainly including Wireless Local Area Network (WLAN), WiFi, 3G, 4G, ZigBee, Bluetooth, etc.) or wired connection. The fog nodes can be interconnected and intercommunicated by wired or wireless communication technologies. And each of fog nodes is linked into the cloud by IP core network.

This architecture can provide the technical support for the IoT, CPS and Mobile Internet to provide efficient data processing and storing services. Especially for CPS, which combines the capabilities of computing, communications and storage in order to monitor or control the entities and objects that exist in the physical world (Shi et al., 2011), fog computing can improve the efficiency and quality of service(QoS) in the case of data explosion currently. However, current research works on fog computing have not presented a unified architecture which can be reused in different application scenarios.

The cloud processing might take a long time depending on the network speed and server loads. Especially for mobile devices, the delays might be even longer because the bandwidth of wireless network is relatively low. In order to support the ubiquitous mobile devices, some researchers have proposed the mobile fog computing architecture.

This computing model enhances the performance and reduces the energy consumption in mobile environment. Mobile fog computing is the complementary of fog computing to provide low-latency mobile services.

Alam et al. (2016) introduced a mobile cloud computing service delivery architecture based on the fog computing. The access point (AP) and access point controller (APC) units were used as the fog nodes of mobile fog. The evolved Packet Data Gateway (ePDG) is responsible for inter fog communication. The AP is not only responsible for the connections between mobile devices and IP networks, but also providing sufficient computing, networking and storage capabilities to support mobile applications.

Hong et al. (2013) proposed a mobile fog programming model for the geospatially distributed, large-scale, and latency-sensitive IoT applications. The mobile fog computing not only provided a high-level programming model to simplify the development of a large number of distributed heterogeneous devices, but also allowed the applications to dynamically use the resource in the fog and cloud based on their workload and demands.

2.2. The characteristics of fog computing

Fog computing carries out the tasks of computation, communication and storage on near-user network edge devices. Its service capabilities are proximity to end users. This is the most basic characteristic of fog computing and the most significant advantage compared with other traditional computing models. Furthermore, there are some characteristics and advantages listed as follows:

1) Low latency and real time interactions

Fog nodes at the network edge locally acquire the data generated by sensors and devices, process and store data by network edge devices in local area network. It significantly reduces data movement across the Internet and provides speedy high-quality localized services supported by endpoints. Therefore, it enables low latency and meets the demand of real time interactions, especially for latency-sensitive or time-sensitive applications (Bonomi et al., 2012).

Sarkar and Misra (2016) proved that the service latency for a system associated with fog computing was significantly lower than that with cloud computing by theoretical modeling of the fog computing architecture. Hu et al. (2017a) applied fog computing model into face identification and resolution field, and indicated that the system response time significantly less than that with cloud computing by experiment.

2) Save bandwidth

Fog computing extends the computation and storage capabilities to the network edge to perform data processing and storing between the end nodes and traditional cloud. Some computation tasks, for example, data preprocessing, redundancy removing, data cleaning and filtering, valuable information extraction, are performed locally. Only part of useful data is transmitted to the cloud, and most of the data don't need to be transmitted over the Internet. For example, Hu et al. (2017a) proposed a fog computing based face identification and resolution scheme, where fog nodes transmitted only the face identifiers to cloud. Compared with the traditional cloud computing based scheme which needs to transmitted the raw face images to cloud, fog computing could effectively reduce the amount of network transmission and save bandwidth. Furthermore, in some application scenarios, decision making is locally realized in the fog nodes, rather than completed by cloud. In this way, fog computing model saves the bandwidth effectively. This advantage will become more and more significant along with the increasing of the amount of data in current big data era.

3) Support for mobility

In fog computing scenarios, there are various mobile devices (e.g., smart phones, vehicles, and smart watch) so that the spatial mobility at the terminal layer is frequent, while there are also some end devices remained static, such as traffic cameras. Similarly, fog node in fog layer can also be a mobile or static computing resource platform. It can be deployed in airport and coffee shop, or on the mobile vehicles and trains (Varshney and Simmhan, 2017; Luan et al., 2015; Hossain and Atiquzzaman, 2013).

It is essential for fog computing to communicate directly with mobile devices. Moreover, various mobile devices can also communicate directly to each other. The data does not have to be transmitted to the cloud or even the base station. End device itself or intermediate devices process the massive data generated by the Internet of things, and truly realizing mobile data analysis. So it can provide services for more extensive nodes.

By using the routing, communication or addressing protocol, fog applications can interact and communicate directly with users and mobile devices. For example, Locator/ID separation protocol of mobile node (LISP-MN) decouple host identity from location identity and require a distributed directory system to support mobility techniques (Natal et al., 2013; Natraj, 2016). Moreover, the access of mobile devices is based on physical proximity by some communication technologies, such as Bluetooth, Near Field Communication (NFC) or Millimeter Wave communication. This way can avoid the intermittent network connectivity caused by mobility (Vaquero and RoderoMerino, 2014). Furthermore, by using the idea of "Data Sherpa", the data from a static sensor (edge) can be transferred to a mobile smart phone (edge) with Bluetooth technology when they are proximity, and then smart phone transmit the data to fog or cloud (Varshney and Simmhan, 2017; Shi et al., 2012).

Fog computing architecture supports location-based mobility demands and enables administrators to control where users and mobile devices are coming in and how they access the information (Hassan et al., 2015). This improves the performance of system and quality of service.

4) Geographical distribution and decentralized data analytic

Compared with the more centralized cloud computing, the services and application of fog computing advocate geographical distributed deployment. It consists of large number of widely distributed nodes, which have the ability to track and derive the locations of end devices in order to support the mobility. Instead of processing and storing information in centralized data center far away from end-user, the decentralized architecture of fog computing ensures the proximity of data analytics to the customer. This characteristic can support faster analysis of big data, better location-based services, and more powerful capabilities of real-time decision making.

In IoT and ubiquitous computing environment, the goal is to achieve the interconnection and interworking among ubiquitous things. These things are not only huge in number, but also widely distributed. The characteristic of geographical distribution and decentralized data analytics can effectively meet the above demands. For example, in the application of Internet of Vehicles (IoV), fog computing can provide a wealth of IoV services (including traffic security and data analysis, urban and road conditions, entertainment information,etc.) based on the connection and interaction of vehicle to vehicle, vehicle to access points (Kang et al., 2016).

5) Heterogeneity

In general, fog nodes come in different form factors and are deployed in a wide variety of environment in the form of physical node or virtual node (Kang et al., 2016). They usually range from high-performance servers, edge routers, gateways, access points, base stations, etc. These hardware platforms have varying levels of computation and storage capabilities, run various kinds of operating system (OS), and load different software applications. Fog computing is a highly virtualized platform, so some virtual nodes, for example, virtual computing nodes and virtual network nodes, can be also used as fog nodes (Aazam and Huh, 2016). Therefore, fog nodes are heterogeneous.

Moreover, the network infrastructure of fog computing is also heterogeneous, which includes not only high-speed links connecting to data center, but also wireless access technologies (for example, WLAN, WiFi, 3G, 4G, ZigBee, etc.) connecting to the edge devices (Bonomi et al., 2014).

The fog computing platform is organized by a multi-tiered hierarchical architecture from the edge to the core. In various IoT applications (including intelligent transportation, smart home, Internet of Vehicles, etc.), the resources and service interfaces of fog nodes are highly dynamic and heterogeneous at different levels of architecture hierarchy to address the requirements of widely distributed applications that need low latency (Hong et al., 2013).

6) Interoperability

Due to their heterogeneous nature, fog nodes and end devices come from different providers and are usually deployed in the various environments. Fog computing must be able to interoperate and cooperate with different providers to cope with wide range of services and seamlessly support certain services (Kang et al., 2016). For example, streaming service supported by fog computing requires the cooperation of different providers, in which services are federated across domains (Bonomi et al., 2012).

Taking the smart transportation system based on fog computing as an example, real-time data analysis is required along with the dynamic information transmission among the smart vehicles, traffic lights, fog nodes and fog applications. In order to realize the complex collaboration and data sharing, a policy-based management scheme of resources is proposed to ensure interoperability and secure collaboration among the different user-requested resources in fog computing (Bonomi et al., 2014; Dsouza et al., 2015). The policy specifications are defined to support the policy requirements (including operational requirements, network requirements, and security requirements) and ensure that a uniform yet secure collaboration is maintained when communication happen in a dynamic and distributed environment. By this way, fog computing realizes the interconnection, interworking and interoperation of heterogeneous devices and resources.

7) Data security and privacy protection

Fog computing hosts services closed to end-users. So it has particular advantages in data security and privacy protection. Firstly, it can protect data by encryption and isolation. Fog nodes provide access control policy, encryption schemes, integrity check and isolation measures to protect the security of sensitive privacy data. Secondly, it can avoid the risks caused by system upgrade. The remote upgrade of traditional devices is low efficiency, and there are disadvantages such as firmware upgrade lost contact. Fog computing does not need Over-the-Air Technology (OTA) firmware upgrade of system, only update the algorithms and micro applications in the fog end.

8) Low energy consumption

In the fog computing architecture, fog nodes are dispersed geographically. So it will not generate a lot of heat due to concentration, and need not additional cooling system. In addition, short range communication mode and some optimal energy Management Policies of mobile nodes evidently reduce communication energy consumption (Zhang et al., 2016). This will lead to reducing power consumption, saving energy and decreasing the cost. Fog computing provides a greener computing paradigm.

Sarkar and Misra (2016) demonstrated that fog computing served as a greener computing platform by theoretical modeling of the fog computing architecture. The experimental results indicated that the average energy consumption for fog computing architecture is 40.48% less than the conventional cloud computing model. Jalali et al. (2016) proposed and adopted flow-based and time-based energy consumption models to compared the energy consumption of a service provided by using nano data centers (nDCs) used in fog computing with using centralized data centers (DCs) in cloud computing. The results revealed that the applications offloaded source of data from centralized DCs to nDCs could effectively save energy.

2.3. The comparison with cloud computing and edge computing

Many computing modes have been proposed, including cloud computing, edge computing, grid computing, jungle computing, cluster computing, etc. They have their own advantages for meeting the requirements of computing tasks in specific scenarios. In this section, fog computing is compared with some typical computing modes in order to presenting its properties.

2.3.1. Cloud computing

Cloud computing technology is proposed to offer on-demand and scalable processing and storage services for various applications. It consists of a shared pool of virtualized resources (e.g. computation, communication, storage, application, and service) in the centralized large-scale data centers. These resources can be rapidly provisioned and released with minimal management effort according to different task (Khan et al., 2014; Alam et al., 2015). Because computing power in the cloud is more powerful than in the network edge devices, moving the computing tasks to the cloud has become an efficient way.

However, the rapid development of IoT, CPS and Mobile Internet generate unprecedented amounts and variety of data (Botta et al., 2015). It is almost impossible to send all the data to the cloud for processing and storing, as the network bandwidth is becoming the bottleneck of cloud computing. The increasing of data volume contributes to high network latency. So the work pattern that transfers data to cloud and back to the client is unacceptable for latency-sensitive and real-time applications, such as health-monitoring (Cortes et al., 2015), emergency-response, etc. Moreover, cloud computing depends on the support of great infrastructures which mainly includes large data centers comprising thousands of server units and other supporting equipment, for example, cooling system. The energy consumption of these infrastructures will be enormous (Mastelic et al., 2015).

Fog computing properly addresses these issues. It emphasizes the full use of the computation and storage capabilities of devices at the network edge. It makes the computation and storage services closer to end users. The data generated by end sensors can be processed and stored locally, which need not to transfer all the data to cloud. This will reduce the amount of network transmission, save bandwidth, as well as accelerate data analysis and decision making (Dastjerdi and Buyya, 2016). Moreover, when resource-constrained devices are to be offloaded frequently, fog computing is a more appropriate solution, rather than the cloud, as fog is easier to access.

Cloud computing and fog computing are different in concept and architecture. But they are all concern about the computation, communication and storage resources. They balance the deployment of these resources from different emphasis.

Considering some researcher surveys (Kang et al., 2016; Dastjerdi and Buyya, 2016; Luan et al., 2015; Madsen et al., 2013), the comparison of cloud computing and fog computing is summarized and shown in Table 1.

In the support of location awareness, cloud computing locates in a centralized place and serves as a centralized global information portal, so it is often lack of location awareness. While Fog computing extends cloud to the proximity to network edge and provides localized service applications (Luan et al., 2015). And in the requirement of mobility, cloud computing is limited, while fog computing is supported. For fog computing, there are a large number of network edge devices which are used as fog nodes to provide services. The number of fog nodes will dwarf the number of cloud data centers, even if not their computing and storage capacities (Varshney and Simmhan, 2017). The service location of fog computing is the proximity to edge devices which is single network hop or few network hops away from the edge. While cloud computing usually locates in a centralized data center which far away from edge devices. Therefore, the communication mode of cloud computing mainly depends on IP networks, while fog computing depends on wireless communication (e.g., WLAN, WiFi, 3G, 4G, ZigBee, etc) or wired communication (part of the IP networks). In the dependence on the quality of core network, cloud computing is stronger than fog computing. By the characteristics of two computing architectures, the bandwidth cost of cloud computing is higher, and the computation and storage capabilities of cloud computing are stronger.

Cloud computing and fog computing have their respective advantages. In many actually use cases, they need to cooperate with each other actively. This is also the cooperation between edge and core. While fog nodes provide localization, cloud provides global centralization for big data analytics (Alsaffar et al., 2016). Masip-Bruin et al. (2016) introduced a layered fog-to-cloud (F2C) architecture, which meets the real need for coordinated management of F2C computing

Table 1
Comparison of cloud computing and fog computing.

	Cloud computing	Fog computing
Latency	High	Low
Real time interactions	Supported	Supported
Mobility	Limited	Supported
Location awareness	Partially supported	Supported
Number of server nodes	Few	Large
Geographical distribution	Centralized	Decentralized and distributed
Distance to end devices	Far (multiple network hops)	Near (single network hop or few network hops)
Location of service	Within the Internet	At the edge of the local network
Working environment	Specific data center building with air conditioning systems	Outdoor (streets,base stations, etc.) or indoor (houses, cafes, etc.)
Communication mode	IP network	Wireless communication: WLAN, WiFi, 3G, 4G, ZigBee, etc. or wired communication (part of the IP networks)
Dependence on the quality of core network	Strong	Weak
Bandwidth costs	High	Low
Computation and storage capabilities	Strong	Weak
Energy consumption	High (especially the energy consumption of data center coolant system)	Low

systems. It coordinates the difference between cloud and fog components by defining a comprehensive control and management strategy. This architecture can improve the performance, such as execution time, parallel execution, edge processing, low resource utilization, high energy efficiency, etc.

2.3.2. Edge computing

Edge computing is also a computing model that extends cloud service to the edge devices. It refers to the enabling technologies which allow computation and storage to be performed on edge devices (Ahmed and Ahmed, 2016; Beck et al., 2016). That is to say, computing and storing happens near things and data sources (Beck et al., 2014). Fig. 2 shows the architecture of edge computing. The edge nodes and devices with computing capacity perform a large number of computing tasks (e.g., data processing, temporarily storing, devices management, decision making, and privacy protection) to reduce the network latency and traffic between end devices and cloud (Shi et al., 2016). These edge nodes can be composed of smart sensors, smart phones, and smart vehicles, even a special edge servers. They can interconnect and intercommunicate in the local to form an edge network. Moreover, edge devices connect with cloud data center by core network. Edge computing provides edge intelligence services nearby to meet the critical demands of the digital industry in agile connection, real-time services, data optimization, application intelligence, security and privacy protection.

In the context of IoT, low power consumption, large connection, low latency and high reliability are the main challenges. Edge computing solves these problems properly. The core of IoT is to realize the intelligent connection and operation of each object, while edge computing realizes the sensing, interaction and control among objects

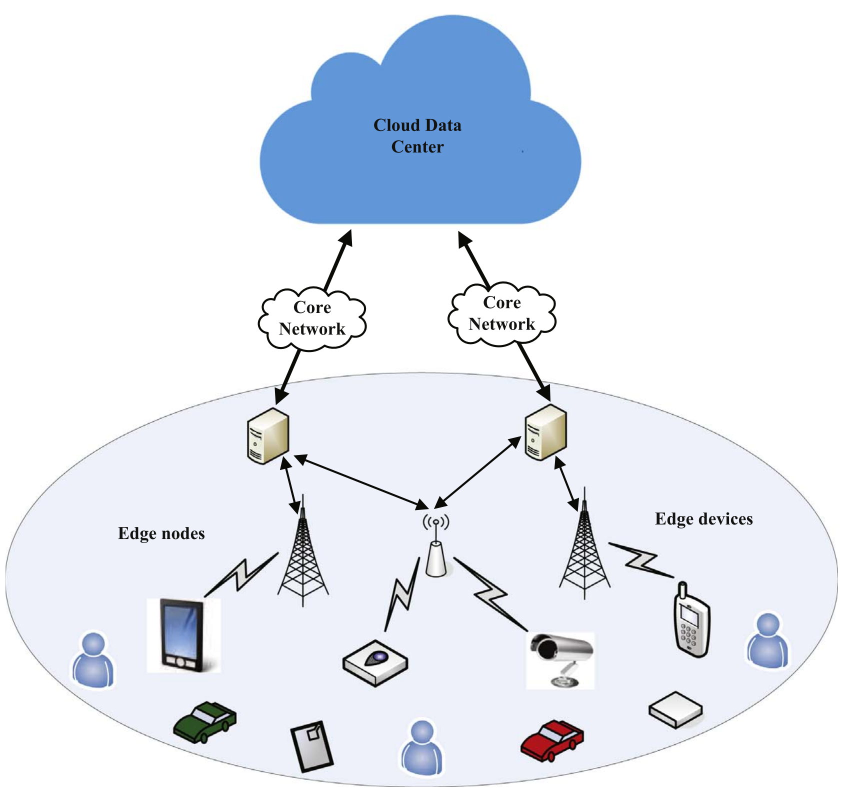

Fig. 2. The architecture of edge computing.

Table 2
The similarities of edge computing and fog computing.

	Edge computing	Fog computing
Architecture	Hierarchical, decentralized, distributed	Hierarchical, decentralized, distributed
Proximity to end devices	Located in end devices	Near (single network hop or few network hops)
Latency	Low	Low
Bandwidth costs	Low	Low
Resource	More limited	Limited
Computation and storage capabilities	More limited	Limited
Mobility	Supported	Supported
Scalability	High	High
Service	Virtualization	Virtualization

by data analysis and processing. In edge computing, the end devices act as not only data consumers but also data producers. And these devices not only request services from the cloud but also provide services to the cloud, instead of just requesting from the cloud traditionally (Shi and Dustdar, 2016).

The prime objectives of edge computing and fog computing are similar. Both of them bring cloud computing-like capabilities to the edge of network. They enable the computation and storage capacities within the close proximity of end users to reduce service latency and save network bandwidth for delay sensitive applications (Khan, 2016). In some paper, the fog computing is known as edge computing (Varghese et al., 2016). The similarities of edge computing and fog computing is summarized and shown in Table 2 (Shi et al., 2016; Shi and Dustdar, 2016; Pande et al., 2016; Dey and Mukherjee, 2016; Wang et al., 2017).

For edge computing and fog computing, their architectures are hierarchical, decentralized, and distributed, which is different from centralized cloud computing architecture. Their service locations are the proximity to end users. Edge computing is located in edge devices, while fog computing is located in network edge devices, which is single network hop or few network hops away from the edge. Their resources (e.g., computing, communication and storage resources) and computation and storage capabilities are limited by comparing with cloud computing, and edge computing is more limited than fog computing. Because the resources and service capabilities of network edge devices are relatively stronger than edge devices. Moreover, these two computing paradigm have mobility support for end users. Because most services are provided locally, it is essential to take the existence of mobile devices into consideration. They also support the scalability of the whole ecosystem. The reason is that a large number of wide-spread and geo-distributed nodes are available if the situation requires them, including the nodes located at a certain site, neighboring nodes, or even the nodes situated at more remote geographical locations (Roman et al.,). Furthermore, they are highly virtualized computing platforms. The nodes and networks are not always physical, while virtual sensor nodes and virtual sensor networks are also used for implementing various services (Aazam and Huh, 2014). The virtualized service mechanisms can be provided by them.

Obviously, even if they have the same goal, there are still some underlying differences between edge computing and fog computing. In edge computing, edge devices cannot implement multiple IoT applications, because the limited resources will result in resource contention and increase processing latency. While fog computing can overcome these limitations felicitously and avoid resource contention at the edge by seamlessly integrating edge devices and cloud resources. It coordinates the use of geographically distributed network edge devices and leverages the cloud resources to balance the use of resources and improve the utilization (Dastjerdi and Buyya, 2016). Furthermore, edge computing pays more attention to the things level, while fog computing focus more on the infrastructures level.

Table 3
The difference between edge computing and fog computing.

	Edge computing	Fog computing
Location of data collection, processing, storage	Network edge, edge devices	Near-edge and core networking, network edge devices and core networking devices
Handling multiple IoT applications	Unsupported	Supported
Resource contention	Serious	Slight
Focus	Things level	Infrastructures level

The differentiation of edge computing and fog computing is shown in Table 3 (Wang et al., 2017; Roman et al., 2016 ; Ahmed and Rehmani, 2017).

For edge computing and fog computing, their service locations are the proximity to end users. However, Edge computing is located in edge devices, while fog computing is located in network edge devices, which is single network hop or few network hops away from the edge. Edge computing platform usually tends to be constrained devices, which battery or storage capacities often are the limiting factors. When the multiple IoT applications need to be handled, this will result in resource contention and increases processing latency (Dastjerdi and Buyya, 2016). So the resource contention of edge computing is more serious than fog computing. Moreover, edge computing focus more on the things level, while fog computing focus more on the infrastructure level (Shi et al., 2016).

3. Key technologies for fog computing

Fog computing depends on some existing and common technologies to support its deployment and application. As is shown in the Fig. 3, they mainly include computing, communication and storage technologies, naming, resource management, security and privacy protection, etc. These key technologies fully consider the properties of fog computing to meet its application requirements. Based on them, fog computing provides more intelligent and adaptive services to users. In the following, we will survey and summarize these key technologies in fog computing paradigm.

3.1. Computing technologies

Fog computing is an intelligent computing system which fog node can autonomously and independently serve local computation and data processing requests for users. The intelligent and low-latency service capability needs to be supported by some computing technologies.

1) Computation offloading

Computation offloading mechanism can overcome the resource constraints on edge devices, especially for the computation-intensive tasks. It can help with improving performance and saving battery lifetime (Zheng et al., 2017). Chen et al. (2015) studied the multi-user computation offloading problem in mobile-edge cloud computing and proposed a distributed computational offloading model. This model adopted a game theoretic approach which the distributed computation offloading decision making problem was formulated as a multi-user computation offloading game. When multiple devices offloaded tasks to cloud simultaneously using same wireless channel, only the task which computation time was reduced and energy consumption was saved after offloading is offloaded. In a multi-channel wireless environment, the offloading decision of multi-user mainly depended on the total performance value.

For the computation offloading among the peers of fog nodes Gao (2014) proposed a probabilistic computation offloading framework

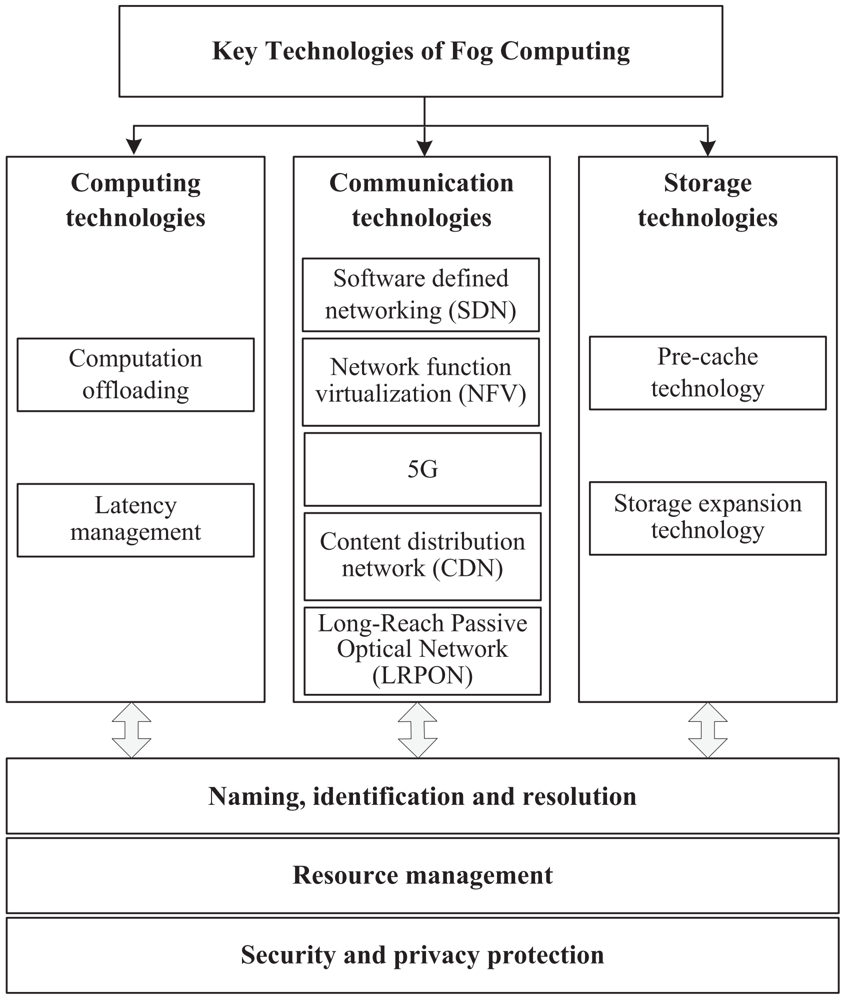

Fig. 3. The key technologies of fog computing.

which could offload part of tasks to the nearby nodes to reduce computational time and energy consumption. The offloading decision mainly depended on the computational power, energy level of the neighbor node and the probability of connection between them in the future. The task would be offloaded successfully to the nearby nodes if the time and energy consumption could be reduced after offloading and the new node could ensure to complete the task on time.

2) Latency management

The primary objective of latency management in fog computing is to limit the ultimate service response time within an acceptable threshold. This threshold is the maximum tolerable latency of a service request or applications quality of service (QoS) requirement. In order to realize latency management, Oueis et al. (2015) proposed an efficient initiation mechanism of nodes collaboration which computation tasks can be executed collaboratively by many nodes within the latency constraints. Zeng et al. (2016) researched the completion time minimization problem of service requests by considering task image placement and task scheduling jointly. The overall computation and transmission latency of all requests could be minimized by distributing computing tasks and balancing the workload on both client and fog nodes. And the task completion time minimization problem was converted into a mixed-integer nonlinear programming problem which solved by a low-complexity three-stage algorithm. In another work, Intharawijitr et al. (2016) proposed a low-latency fog computing architecture for latency management. To clarify the computing delay and communication delay, a mathematical model is defined, which can be used for guiding the selection of nodes in fog network to provides minimum delay.

3.2. Communication technologies

According to the fog computing architecture, fog node is the role of intermediate networking component which connects with end users and devices, other fog nodes and cloud. It contains three sorts of connections: 1) wireless connections between end devices and fog nodes; 2) wired/wireless connections among fog nodes; 3) wired/wireless connections between fog nodes and cloud data center. These common wireless communication technologies, includes 3G, 4G,WiFi, Wireless Local Area Networks (WLAN), ZigBee and Bluetooth, support the fog application, especially the mobile fog computing. Some other communication technologies are discussed in the following.

1) Software defined networking (SDN)

SDN is an emergent computing and networking paradigm, which is an implementation method of network virtualization. This architecture separates control plane and data plane to realize the flexible control of network traffic. Control is done by a centralized server, and communication path of node is also decided by the centralized server (Nunes et al., 2014). It has the characteristics of flexibility, scalability, programmability. There is no need to rely on the underlying network devices (e.g., routers, switches, firewalls), and the difference from the heterogeneous underlying networks devices can be eliminated. Users can define any network routing and transmission rules that they want to implement, thus making communication more flexible and intelligent (Kreutz et al., 2014).

In fog computing, SDN can help with the efficient management of heterogeneous fog networks (Kim and Feamster, 2013). SDN paradigm together with fog computing can solve some issues, such as irregular connectivity, collisions and high packet loss rate (Natraj, 2016). For example, in vehicular networks based on fog computing, SDN-based architecture can properly overcome above issues and satisfy the demands of future vehicular networks applications. Truong et al. (2015) proposed a new vehicular ad hoc networks architecture based SDN and fog computing (called FSDN)to resolve the main difficulties of poor connectivity, less scalability, less flexibility and less intelligence. Moreover, it can also optimize resources utility and reduce latency by integrating fog computing.

2) Network function virtualization (NFV)

The main idea of NFV is that the network function is decoupled from the dedicated physical network hardware by leveraging virtualization and device abstraction technology. This means that resources can be fully and flexibly shared to achieve the rapid development and deployment of new service. NFV technology notably improves the flexibility of telecommunication service provisioning (Mijumbi et al., 2015).

Fog computing will benefit from NFV in many aspects, for example, gateways, switches, and firewalls can be virtualized and placed on fog nodes. It can enable the seamless management of resources (e.g., computing, storage and communication) and orchestration of functionalities in the heterogeneous and widely geo-distributed fog network. The new application can be deployed automatically and expanded flexibly based on the actual requirements. For applying NFV in fog computing, the performance of virtualized network devices is the important concern. Virtualized network devices combine with efficient instantiation, placement and migration technologies to achieve low latency and high throughput (Han et al., 2015).

3) The fifth generation (5G) wireless communication system

5G is the new generation mobile communication technology with many unprecedented advantages, mainly including wide signal coverage, high network speed, high flux density, high mobility, and diversified applications, etc. Compared with the fourth generation (4G), 5G can achieve system capacity growth of 1000 times and end-to-end latency reduction of 5 times, provide energy efficiency growth of at least 10 times and the area throughput growth of at least 25 times (Peng et al., 2014).

This technology enables many challenging applications and services with resource limited mobile terminals (Chen et al., 2015b). For the fog computing, especially the mobile fog computing, 5G technology has the potential to overcome the bottleneck of resource limitation and provide more and more resource-intensive services for mobile users (Amendola et al., 2016). It can also meet the demands for high-speed data applications, high-quality wireless communication, and low-latency services.

Peng et al. (2015) proposed fog computing based radio access network, which incorporates fog computing into heterogeneous cloud radio access network, as a promising paradigm for 5G system to provide high spectral and energy efficiency. It properly solves the disadvantages of the traditional cloud radio access network in the constrained front haul and centralized baseband unit pool. This paradigm can provide real-time collaboration radio signal processing and flexible cooperative radio resource management at the edge devices.

4) Content distribution network (CDN)

CDN is the Internet-based cache network which deploys the CDN proxy servers at the edge of Internet. By comprehensive considering the information including connection status, load and user distance of each node, the CDN system distributes the related contents to the CDN proxy server close to the users. Users can obtain the required information and reduce the download delay of contents from remote sites and improve response speed (Papagianni et al., 2013; Coile and O'Mahony, 2015). According to the characteristics of fog computing, CDN technology can help with less bandwidth usage, reduced network congestion, higher content availability, and reduced costs. Especially integrated with context aware technology, CDN-based fog computing can rapidly provide the most desirable services to end users.

5) Long-Reach Passive Optical Network(LRPON)

Long-Reach Passive Optical Network (LRPON) is proposed to extend the network reach up to 100 km with a large number of optical network units. It covers a large area and simplifies network consolidation process (Davey et al., 2009). Furthermore, LRPON has been introduced into fog network to support latency-sensitive and bandwidth-intensive applications, for example, smart home and smart industry services.

Zhang et al. (2017) proposed the integration between fog computing and LRPON to optimize network design, and a near-optimal solution for the large scale fog network was obtained by developing an efficient heuristic algorithm.

3.3. Storage technologies

In order to meet the demands of low-latency property in fog computing, the pre-cache technology can be considered. Fog nodes predict the demand of user and proactively select the most desirable contents to cache in the geo-distributed nodes. By this way, the download delay of contents from remote datacenter can be reduced significantly, and fog applications can make full use of the storage resources to provide the most desirable services to users (Luan et al., 2015). Bastug et al. (2014) proposed the proactive caching paradigm in 5G wireless networks to proactively pre-cache the desirable information before users request it. The file popularity and correlations among user and file patterns were used as the basis for prediction. Moreover, social networks and device-to-device communications were leveraged to proactively cache strategic contents. The peak traffic demands can be substantially reduced by proactive predicting user demands and caching at base stations and edge devices. This framework and pre-cache strategy can be adopted and support for fog computing.

Moreover, the storage capabilities of edge devices usually are limited. So storage expansion technology is very influential for improving overall service capabilities of fog computing. Hassan et al. (2015) proposed a safe and efficient storage expansion method by utilizing the personal storage for mobile devices. It integrated all the personal storage space of a user together via fog networking to build-up a distributed storage service and augment storage capacity.

3.4. Naming, identification and resolution

In fog computing, there are a large number of things and devices. Based on fog paradigm, there are a lot of applications running and providing various services. Similar to the domain name system (DNS) of computer network, the naming, identification and resolution scheme in fog computing is very important for addressing, identity authentication, controlling and managing of objects, data communication, discovery of objects and services, etc.

A standardized and efficient naming mechanism is prerequisite for the communication and collaboration among heterogeneous things and devices. The traditional naming mechanisms, e.g., DNS and uniform resource identifier (URI), have been maturely and widely used in the current networks. In a part of fog computing scenarios, these naming schemes can still satisfy application requirements. However, most of the things and devices at edge are highly mobile and resource constrained. So these naming mechanisms are not flexible enough in some scenarios to serve the dynamic fog computing paradigm, and the universally used IP-based naming mechanism could be too heavy for supporting its cost.

In order to support the properties of fog computing, some new naming schemes are proposed, for example, named data networking(NDN) (Jaffri et al., 2013; Zhang et al., 2014) and MobilityFirst (Raychaudhuri et al., 2012).

- NDN: It is an evolution of the IP architecture that focuses on “What (the contents)" rather than "Where (the addresses)". NDN packets bring with the hierarchically structured data names instead of the source and destination address. It can name anything, such as sensors, computers, humans, books, etc. The objectives of this scheme are to improve the scalability, efficiency, security and robustness of current internet state for fitting fog and edge computing.

- MobilityFirst: It is proposed for addressing the challenges of mobility and wireless access to meet the requirements of naming mechanisms in current mobile Internet. It separates names from network addresses. The global unique identification (GUID) is adopted, and global name resolution service (GNRS) is used to dynamically bind names and addresses. In MobilityFirst, the service API is based on the names of source or destination network objects, rather than the network addresses. It uses hybrid name/address based routing to achieve scalability. This naming scheme is very efficient for serving fog paradigm in which things have high mobility.

For the identification technology of things, devices and applications in fog computing, it can be divided into three categories: physical object identification, communication identification and application identification.

- Physical object identification: It mainly is used for the identification of things and devices. This type of identification adopts ID code and natural property as identifier. The former is comprised of numbers or alphabets with certain rules, for example, electronic product code (EPC) (Brock, 2001), ubiquitous ID (uID) (Koshizuka and Sakamura, 2010), and European article number (EAN), etc. The latter is also called non-ID identification, which biometric, behavior characteristics, space-time information, or other characteristics are used as identifier (Hu et al., 2017c; Ning et al., 2015).
- Communication identification: It is used to identify the identity of network nodes or devices which have the communication ability. The familiar identification forms include IP address (Hong et al., 2010), MAC address, E.164 number, etc.
- Application identification: It is used to identify the various application services in fog paradigm, mainly including domain name, uniform resource locator (URL), etc.

For the resolution technology, the object name service (ONS) is a typical resolution model of ID code (Ning et al., 2012). It can realize the mapping from EPC to detailed identity information of physical object. This resolution model supports the mobility in fog computing paradigm. Furthermore, Hu et al. (2017a) proposed a fog computing based face identification and resolution framework. It not only realizes face based individuals identity identification and resolution, but also improves the processing efficiency and saves bandwidth. This scheme can also be used as a reference for other non-ID identification. For the communication identification, DNS resolution technology is still available in some fog computing scenarios with relatively powerful resources.

3.5. Resource management

In fog computing, resource management should be given high priority in provisioning fog resources and services. As edge devices and fog nodes are usually energy-constrained, the reasonable allocation and management of resource directly affects the lifetime and performance of fog network. To enable low-latency process and mobility in fog computing, some resource-management and scheduling techniques need to be investigated, including the placement, migration, and consolidation of edge devices, fog nodes, application modules, and tasks. These technologies significantly impact processing latency and decision-making times.

Resources virtualization of fog nodes is an effective management manner, which can be allocated to multiple users. Context-awareness technology can make contribution to efficient resource and service provisioning in fog computing. This contextual information includes environmental context, application context, user context, device context, network context, etc. The context-awareness based energy and resource management method can effectively improve the resource utilization and save energy (Sharma et al.,2017).

Resource discovery and sharing is critical for improving application performance in fog computing. Liu et al. (2014) proposed a dynamically adaptive method of resource discovery in mobile cloud computing. It can automatically transform between centralized and flooding strategies to save energy in heterogeneous networks. This method provides the reference for resource discovery in fog computing, however, more constraints need to be taken into consideration, for example, latency sensitivity, density and mobility of edge devices and fog nodes. For resource sharing, Nishio et al. (2013) proposed a service-oriented heterogeneous resource sharing framework in fog computing. It realized resource sharing by equivalent mapping all the heterogeneous resources (e.g., CPUs, bandwidth, and power) to time resource. Then the optimization problems of resource sharing were formulated for maximizing the sum and product of service-oriented utility functions by convex optimization approaches. This sharing strategy reduces service latencies effectively and achieves high energy efficiency.

3.6. Security and privacy protection

Being close to end users, fog node devices are usually deployed in some places where protection and surveillance are relatively weak. So they might encounter malicious attack (Hu et al., 2017b; Qiu et al., 2017c). For example, the man-in-the-middle attack is one of the potential data hijacks way (Lee et al., 2015). In this attack, fog node devices might be pretended or replaced by fraudulent ones. Encryption and decryption methods can be adopted to solve this problem.

Fog computing is a distributed platform, which edge devices generate large amounts of data which need to be transferred to fog nodes for computing and storing. And the fog nodes need to frequently communicate with edge devices and data centers in cloud computing. As a consequence, the confidentiality and integrity of data should be guaranteed. This problem can be solved by using light-weight encryption algorithms or masking techniques (Lee et al., 2015).

Furthermore, the situation of multi-level collaboration results in a large number of security and privacy problems, mainly including identity management, authentication and authorization, resource access control, securely distributed decision enforcement and collaboration, sharing policy of information, quality of security and service, etc. (Premarathne et al., 2015; Yaakob et al., 2015). For these issues, Dsouza et al. (2015) proposed policy-based resource management and access control in fog ecosystem to support secure collaboration and interoperability between heterogeneous user-requested resources.

4. Applications

Generally speaking the fog computing suits applications with low latency requirements (Aazam and Huh, 2016; Dastjerdi and Buyya, 2016), therefore fog computing has the potential to be used in any application that is latency sensitive, such as health care, urgent services and cyber-physical systems, here we list some of the applications of fog computing:

4.1. Health care

Fog computing applications on health care have attracted most of the literature works. A wide variety of works about monitoring, detection, diagnosis and visualization of health maladies have been proposed in recent years. Stantchev et al. (2015) and Shi et al. (2015)

Table 4
Comparison between different fog based health care systems.

Framework name	Monitored disease	Used technique	Devices software	Open source
FAST	Stroke (brain attack)	Fall detection	Smart phones, Cloud servers	Non
eWALL	COPD, Mild Dementia, diseases related to aging	Daily Activity Monitoring, Daily Functioning Monitoring	Sensors, Actuators, eWALL Cloud, Cloud Middleware	Non
Health Fog	Multi purposes	Activity recognition, Cloud access security broker	Smart phones, Smart home devices, Wearable sensors	Non
fHealth	Fitness	Activity tracking	Smart phones, Cloud servers	yes

discusses the characteristics of fog computing and services that fog computing can provide in the healthcare system and its prospect, Cao et al. (2015) proposed FAST, a fog computing assisted distributed analytics system to monitor fall for stroke mitigation, they have implemented fall detection algorithms and incorporated them into fog-based distributed fall detection system, which distribute the analytics throughout the network by splitting the detection task between the edge devices (smart phones attached to the users) and the server (servers in the cloud), while Kyriazakos et al. (2016) presented eWALL, an intelligent home environment offering personalized context-aware applications based on advanced sensing and fog computing on the front and cloud solutions on the back.

In Ahmad et al. (2016) Health Fog was presented, a framework where fog computing is used as an intermediary layer between the end users and the cloud. The design of Health Fog successfully reduces the extra communication cost that is usually high in similar systems. Grasshopper (2016) fHealth is an open source framework proposed as a use case of fog oriented health care applications. Table 4 present a comparison between these systems.

4.2. Augmented reality, brain machine interface and gaming

Many popular products and projects such as Microsoft HoloLens, Google Glass and Sony SmartEyeglass, can be used in augment reality (AR) applications; AR applications usually need high bandwidth for data transmission and high power computation to process video streaming, since a very small delay in the range of milliseconds can damage the user experience and leads to negative feedback, low latency is a prerequisite for augmented reality and brain related applications, therefore fog computing is the best paradigm that can fulfill such requirement, AR system supported by fog computing can reduce latency in both processing and transmission and maximize the throughput.

Zao et al. (2014) developed augmented brain computer interaction game based on fog computing and linked data, the data generated by EEG headset while a person is playing is used to detect the players brain state, as its time-consuming task to send the continues brain states to central servers for processing, the system leverages a combination of both fog and cloud servers, enabling continuous real-time processing and classification.

Ha et al. (2013) have designed and implemented a wearable cognitive assistance based on Google Glass and Cloudlet, which can offer the wearer hints for social interaction via real-time scene analysis. The system achieves tight end-to-end latency constraint by offloading computation-intensive task to nearby Cloudlet. Network failure and unavailability of distant Cloudlets are also considered and provided automatic degrade services.

4.3. Smart environments

Network is the basic component of smart living environments and IoT applications, the latter is composed out of smart objects and variety of processors, smart objects such as sensors, controllers, actuators and inter-connectors, and the processors are used to monitor, control and communicate with the smart objects in the network, Cloud computing paradigm is widely used in smart environment (e.g., smart city, smart home), in which the cloud servers are used for coordination and collaboration among smart objects. However smart objects are ubiquitously distributed, thus, data transmission latency between cloud and smart objects is a critical issue especially to the applications that have sensitive delay requirements. To address this problem, the fog computing paradigm is recently proposed by the industry, which further enables real-time interaction and location-based services. In particular, the local processing capability of fog computing significantly scales down the data volume towards the cloud.

Li et al. (2015) developed a data-centered fog platform to support smart living, in which implement and analyze the data flow of the same applications, EHOPES (smart energy, smart health, smart office, smart protection, smart entertainment and smart surroundings), they have compared the performance of the applications with different network topology, namely cloud based and fog based architectures, in which they have proved that fog based architecture has the upper hand in smart environment applications.

Yannuzzi (2014) argue that fog computing paradigm will be the most suitable architecture for the IoT, that is because the cloud architecture face complex challenges such as mobility, reliable control and scalability. The potential of using fog computing as a middleware between the cloud and the IoT objects, or even pure fog-IoT architecture have been discussed in many works (Aazam and Huh, 2016; Bonomi et al., 2012, 2014; Dastjerdi and Buyya, 2016).

4.4. Vehicular fog computing

Vehicular Ad-hoc Networks(VANET) are regarded as an important part of the promising Intelligent Transportation Systems(ITS). VANET ensure traffic efficiency, driving safety, and convenience by exchanging valuable information, they support various mobile services ranging from the content-sharing applications (e.g., advertisements and entertainments) to information-spreading services (e.g., emergency operations for natural disaster and terrorist attack) (Kang et al., 2016; Chen et al., 2017).

During the few years, with the emergence of new advanced technologies and equipments, such as cloud computing and 4G cellular networks, VANET and its related applications have been developed dramatically. As a consequence of this trend, a notable issue also appears, namely, the acute increases in the demand of both computational capability and data communication. New applications, such as augmented reality (AR) techniques, self-driving, etc., all deal with complex storing operations and data processing, which require higher level of data storage, computation, and communication. Therefore, the needs for a new computational paradigm to fulfill the requirements of these applications become indispensable.

To satisfy the demand of the above mentioned application with special requirements of mobility, location awareness, and low latency, a new computing paradigm known as Vehicular Fog Computing (VFC) have been proposed (Hou et al., 2016; Kang et al., 2016; Bonomi, 2011; Bonomi et al., 2012).

VFC employs vehicles as the infrastructures to make the best use of these vehicular computational and communication resources. VFC establishes highly virtualized communication and computing facilities

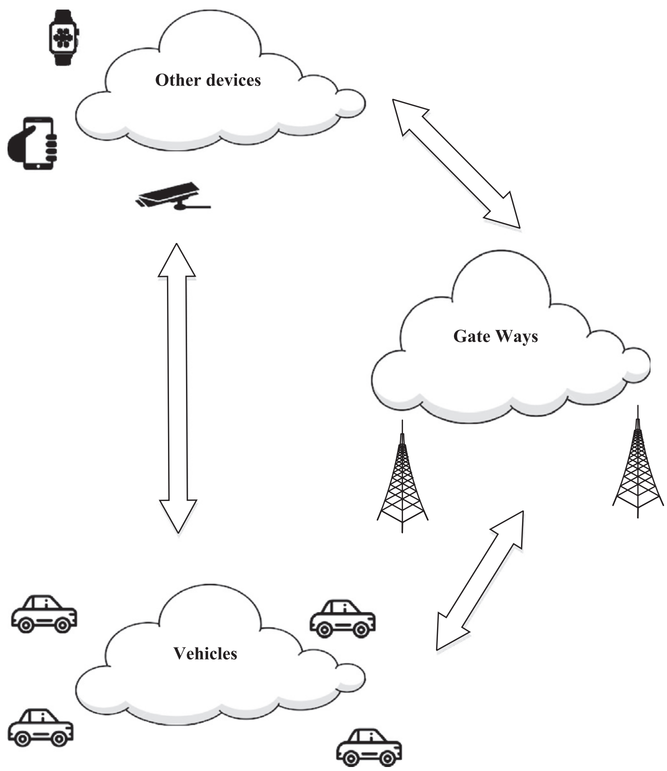

Fig. 4. Example of Vehicular Fog Network.

at the proximity of mobile vehicles in VANET. Specifically, VFC is an architecture that uses a collaborative multitude of end-user clients or near-user edge devices to carry out a substantial amount of communication and computation (Bonomi, 2011; Bonomi et al., 2012).

Besides the traditional cloud characteristics, such as computing, storage, and application as services to end users, VFC differentiates itself from existing techniques with its dense geographical distribution, support for mobility, and proximity to end users (Bonomi et al., 2012). An Example of VFC is shown in Fig. 4.

It is important to notice that key characteristics of the VFC differ from those of the vehicular cloud computing (VCC), in Table 5.

4.5. Fog in IoT and cloud of things

The emergence of IoT have made it difficult to deal with data in an effective and efficient way to create useful services.

Different devices generate different data types of with different frequencies and different size. Therefore, mixture of IoTs and cloud computing, termed as Cloud of Things (CoT) has emerged recently (Aazam and Huh, 2014).

CoT facilitate and ease the management of growing media content and other data. Besides this, features like: service discovery, resource provisioning, ubiquitous access and service creation play a significant role, which comes with CoT. Healthcare, emergency, and latency sensitive services require real-time response.

In addition, it is important to decide what type of data is to be uploaded in the cloud, without overloading the network bandwidth and the cloud. For this reason, Fog computing is expected to play an important role to accomplish this task. Fog resides between underlying the cloud and IoTs. Its job is to manage resources, preprocessing, data filtration, and security measures. For this purpose, Fog requires an effective and efficient resource management framework for IoTs. A typical application of Fog computing in the industrial internet of things (IIoT), where the machines and other sensors and actuators and gateways in a production site can be used as Fog network to increase the efficiency of the production (Zhu et al., 2017).

Table 5
Comparison between VCC and VFC.

Characteristic	VFC	VCC
Geo-distribution	Yes	NO
Communication type	Real-time	Bandwidth Constrained
Capacity of communication	Large	Medium
Deployment Cost	High	Low
Decision making	Local (in VANET)	Remote (in the cloud)

4.6. Smart energy grid

The energy grid is an electricity distribution network, that deploy smart meters at various locations to measure the real time status information, in terms of energy generating, energy delivery, energy consuming and billing. Smart energy refers to the use of networking technologies and IoT to dynamically distribute energy in order to minimize their cost as well as maximizes energy, which involves decision-making and action-taking subsystem.

A centralized server called supervisory control and data acquisition (SCADA) system gathers and analyzes the status information, and sends commands to respond to any demand change or emergency to stabilize the power grid. For example, the Los Angeles Smart Grid will serve over 4 Million customers in the largest public utility in the US (Varshney and Simmhan, 2017). Net-connected smart meters observe power demand at households and industries and report them periodically back to the utility every few minutes. With fog computing, the smart grid will turn into a multitier hierarchical system with the interplay between the fog and SCADA. In such system, a fog is in charge of a micro-grid and communicates with neighboring fogs and higher tiers. The higher the tier, the larger the latency, and the wider the geographical coverage.

4.7. Urgent computing and other applications

Fog computing is very suitable environment for Urgent computing. Applications that needs instant feedback and response such as disaster support applications. Brzoza-Woch et al. (2015) developed a flood decision support system uses fog nodes in order to process the acquired real data and trigger alarms in case of flood. Similarly, Aazam and Huh (2015) presented E-HAMC (Emergency Help Alert Mobile Cloud) program, which attempts to response promptly to a request of a user when there is an emergent situation.

Another application of fog computing is in web optimization (Zhu et al., 2013), since all web requests that the user makes first goes through the edge (or fog) servers, which subsequently obtain them from the core network where the web servers reside and potentially modify and locally cache these files. Fog devices have the potential to be used as local caching points.

5. Challenges and open issues

5.1. Security and privacy issues

Fog computing devices may face serious system security problems, because fog devices are usually deployed in places out of strict protection and surveillance, thus, become vulnerable to traditional attacks that may compromise the system of fog devices in order to realize malicious tasks such as data hijacking and eavesdropping.

There are many security solutions for cloud computing. However, these solutions may not work for fog computing because fog devices work at the edge of networks. The working surroundings of fog devices may face many threats which do not exist in cloud computing.

Here we list some of the prominent attacks that can be launched against fog computing:

- *Man in the middle:* The man-in-the-middle attack has a potential to become a typical attack in fog computing, as an intruder can sniff or interrupt the packets between fog devices, because these devices usually cannot implement secure communication protocols due to their lack of resources (Stojmenovic et al., 2015). The man-in-the-middle has been proven in other works to be stealthy attack against fog computing, and the definite solution still an open challenge.
- *Authentication:* Fog devices such as gateways may face many authentication and trust issues that do not exist with the could case, relying on the cloud central authentication servers is not a preferable choice because authentication have to continue to work in order to access personnel devices locally when remote authentication server communications are down. Some works have discussed the problem of authentication and trust in the fog however none of them have given a holistic solution (Yi et al., 2015c).
- *Distributed denial of service:* Distributed denial of service or DDOS is known as the most challenging security threat for websites and online services in the modern era. Fog nodes are resource constraint; it is very difficult for them to deal with large number of requests simultaneously, by launching a lot of irrelevant service requests concurrently, fog nodes may become busy for a long period of time. As a result, resources for hosting legitimate services become unavailable (see Fig. 5(A)). On the other hand, fog nodes themselves can be used to launch DDOS attack (see Fig. 5(B)). Recently hackers have been able to use internet-connected home devices, such as printers and Closed Circuit Television (CCTV) cameras, to perform DDOS attacks against popular websites, site like PayPal, Twitter, Spotify, Reddit, SoundCloud and several other sites have been affected by the attacks (BBC, 2016a, b). As the smart objects will have more computational capabilities and ability to perform tasks cooperatively in fog computing, DDOS attacks using fog devices will be more severe compare to traditional DDOS, the issue of DDOS needs to be well addressed in any future fog computing standardization.
- *Access control:* In fog computing, one can raise the question: how to design access control traverse client-fog-cloud, to meet the aims and resource constraints at different levels. Access control has been proven to be a reliable tool to ensure the security of systems. Access control of data owner can be expanded into the cloud; some works have achieved this by exploiting techniques of several encryption schemes together to build an efficient data access control in the context of Cloud Computing (Yu et al., 2010). Some other works such as Dsouza et al. (2015) proposed a policy-based resource access control in Fog computing. Even though, many works need to be done to develop more robust Access control techniques, aiming to support secure collaboration and interoperability between heterogeneous resources in Fog environment.
- *Fault tolerance:* Fog computing should still provide services normally when there is a failure individual sensors, networks, service platforms, and applications (Dastjerdi and Buyya, 2016). Because there are large numbers widely geographically distributed fog nodes, users should be able to quickly have turned to other adjacent nodes by corresponding mechanism when the service in an area is abnormal.

5.2. Control and management

5.2.1. Application-aware provisioning

Fog computing is expected to offer mobile crowd-sourcing/sensing applications by providing application-aware provisioning. In order to meet the QoS requirement of Fog, such as delay, a Fog network needs to do provisioning in order to prepare resources to provide service mobility. The challenge is that mobility of end nodes, since that metrics such as bandwidth, storage, computation and latency will be changed dynamically.

Fog must deal with mobile nodes and IoTs, which involves dealing with objects and devices of different types, having unstable connectivity. All such kinds of service customers have an unpredictable relinquish probability, since any device or object can quit resource utilization at any moment.

The authors of Aazam and Huh (2015) proposed a framework that covers the issues of resource prediction, customer type based resource reservation and estimation, advanced reservation, and pricing for new and existing IoT customers, on the basis of their characteristics. While the work in Dhelim et al. (2016) presented a framework the manage the spatial temporal attributes of smart objects using semantic web technologies. However, providing application-aware provisioning is still a big challenge in Fog computing.

5.2.2. Fog resource management

Fog computing is expected to extends the cloud computing paradigm to the edge of the network. Fog resource management, for example, sharing and discovery, is critical for application performance. In Fog computing, not only central data centers but also ubiquitous

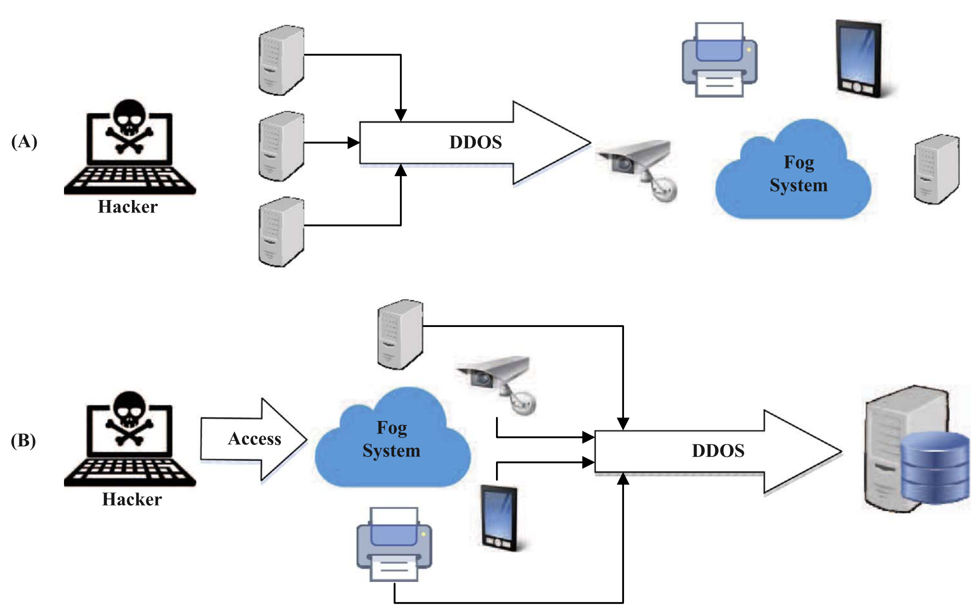

Fig. 5. (A) Launch DDOS attack against fog device to stop fog system; (B) Using fog devices to perform DDOS attack.

mobile devices share their heterogeneous resources (e. g. bandwidth, CPUs, data) and supported services (Nishio et al., 2013).

5.3. Programming platform

In cloud computing the infrastructure is transparent to the user, the computational work is done by program is written in specific programming language that runs in the cloud. However, in fog computing, the computation is to be done in the user end edge nodes which are most likely run heterogeneous platforms, and usually differ from each other, thus, programming in such heterogeneous platforms is a huge challenge. Therefore, the need for a unified development framework for fog computing has become indispensable.

Fog environments require the ability to dynamically add and remove nodes, because fog nodes are generally mobile devices that join and leave networks frequently, therefore most of the available stream-processing and data-processing frameworks such as S4 and Apache Storm, don't provide enough flexibility and scalability for fog computing, because the architecture of these frameworks is based on static configurations rather than dynamic one.

5.4. Energy management

Fog computing systems consist of many distributed nodes, thus energy consumption is expected to be higher than their cloud counterparts. Therefore, a lot of works need to be done in developing and optimizing new effective energy saving protocols and architectures in fog paradigm, for example, efficient communications protocols, computing and network resource optimization.

6. Conclusion

Fog computing is a high-potential computing model whose significance is growing rapidly due to the fast development of IoT, CPS and Mobile Internet. Through making full use of the geographically distributed network edge devices, the fog paradigm pushes more and more applications and services from cloud to the network edge. It greatly reduces the data transfer time and the amount of network transmission, and effectively meet the demands of real-time or latency-sensitive applications and ease network bandwidth bottlenecks. In this paper, we focus on the fog computing technology. The architecture, key technologies, applications, challenges and open issues are summarized and surveyed in detail. We review and present the hierarchical architecture of fog computing and its characteristics. And fog computing is compared with cloud computing and edge computing in similarity and differentiation. Then the key technologies, like computing, communication and storage technologies, naming, resource management, security and privacy protection are summarized to present how to support its deployment and application in a detailed manner. Several application cases like health care, augmented reality, brain machine interface and gaming, smart environments and IoT are presented to further explain fog computing applications. Finally, some challenges and open issues which are worth further study and research, including security and privacy, programming platform, energy consumption, are presented. Fog computing will serve as a more intelligent and greener computing model to promote the development of IoT and big data. This is a valuable research area which will influence future academia and industry.

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