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Post-Cloud Computing Paradigms: A Survey and Comparison

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Abstract: With the rapid development of pervasive intelligent devices and ubiquitous network technologies, new network applications are emerging, such as the Internet of Things, smart cities, smart grids, virtual/augmented reality, and unmanned vehicles. Cloud computing, which is characterized by centralized computation and storage, is having difficulty meeting the needs of these developing technologies and applications. In recent years, a variety of network computing paradigms, such as fog computing, mobile edge computing, and dew computing, have been proposed by the industrial and academic communities. Although they employ different terminologies, their basic concept is to extend cloud computing and move the computing infrastructure from remote data centers to edge routers, base stations, and local servers located closer to users, thereby overcoming the bottlenecks experienced by cloud computing and providing better performance and user experience. In this paper, we systematically summarize and analyze the post-cloud computing paradigms that have been proposed in recent years. First, we summarize the main bottlenecks of technology and application that cloud computing encounters. Next, we analyze and summarize several post-cloud computing paradigms, including fog computing, mobile edge computing, and dew computing. Then, we discuss the development opportunities of post-cloud computing via several examples. Finally, we note the future development prospects of post-cloud computing.

Key words: cloud computing; fog computing; edge computing; mobile edge computing; dew computing

1 Introduction

Cloud computing has been vigorously promoted by IBM, Google, Amazon, and Microsoft, as well as other large commercial companies, since it was first proposed by IBM in 2007[1]. In recent years, cloud computing and its services have been widely recognized and utilized in many areas and have developed significant commercial value. For example, Amazon's cloud computing revenues reached 12.2 billion in 2016[2]. Microsoft predicts that revenue for its cloud computing business will reach 20 billion by 2018[3]. In recent years, computer and communication technologies have flourished and developed rapidly, which has promoted the development of cloud computing. However, this development has also exposed some inherent flaws and deficiencies associated with cloud computing, which has prompted the consideration and examination of the network computing paradigm in the post-cloud computing era.

First, with the rapid technological development of pervasive intelligent devices, a variety of new smart devices have emerged and been widely applied. Taking intelligent mobile devices (e.g., smartphones) as an example, the global shipment of these devices has exceeded that of the Personal Computer (PC) since 2011. In 2016, the number of global mobile subscribers reached 7 billion[4] and China's mobile Internet users reached 0.9 billion[5]. Following Moore's law, the

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capabilities of these intelligent mobile devices are also growing rapidly. The CPU of the latest Huawei P10 smartphone has eight cores (four 2.4-GHz cores and four 1.8-GHz cores), which is more powerful than some PCs. Taking smart wearable devices as another example, smart watches, smart wristbands, and other smart wearable devices have also developed rapidly in recent years. Moreover, various intelligent or non-intelligent sensing devices of different sizes and capabilities, including radar, camera, and water/fire sensors, have been deployed in cities, communities, and even in mountain and lake regions. These pervasive intelligent or non-intelligent devices have significantly different abilities with respect to computation, storage, network connectivity, and energy consumption, and due to the characteristics of centralized computation and storage, it is very difficult for cloud computing to be adaptively applied to these mobile devices and sensors. Also, it is difficult to maximize the potential of these various types of devices using cloud computing.

Then, ubiquitous network technologies have been developed and deployed. 4G-LTE, LTE-A, WiFi, and other wireless broadband technologies are being widely used. Moreover, 5G network and D2D communication technologies are currently being developed and will be ready for commercial deployment in the coming years. The development of wireless broadband speeds up user access to cloud services and improves user experience. However, the potential access speed requirements and end-user demands have yet to be met. With respect to online video, mobile online video utilizes numerous network bandwidths. Moreover, network delay has a significant effect on user experience. Therefore, the development of 5G and D2D technologies has resulted in not only a new driving force but also a new challenge for cloud computing, i.e., how to further improve user experience by fully utilizing continuously updated network devices and technologies. Meanwhile, the development of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) technologies has enhanced the processing and storage capabilities of edge network routing devices such that their functions can now be extended and customized according to user requirements. However, the user requirements arising from the development of ubiquitous network technologies are inconsistent with the cloud computing concept because of its centralized processing, which poses major challenges to the continued development and application of cloud computing.

Furthermore, the rapid development of pervasive intelligent devices and ubiquitous networks has spawned a rich variety of new network applications and services. For instance, the Internet of Things (IoT), Internet of Vehicles (IoV), Internet of Everything (IoE), smart planet, smart city, smart grid, social networks, and content/media/service-oriented networks have gradually become familiar to the public. In recent years, virtual reality/Augmented Reality (AR), self-driving vehicles/Unmanned Aerial Vehicles (UAVs), and other new network applications and services have grown in popularity. This has brought yet another challenge for cloud computing—how to meet all the requirements associated with the rapid growth of these new network applications and services using a centralized computing paradigm.

In summary, with the rapid technological development of pervasive intelligent devices and ubiquitous networks, as well as the accompanying new network applications and services, it is difficult for the cloud computing paradigm with its centralized processing and storage model to adapt and be applied to various types of technologies and application scenarios. For this reason, since 2011, the industrial and academic communities have been exploring new network computing paradigms for the post-cloud computing era[6]. In the meantime, fog computing[7], Mobile Edge Computing (MEC)[8], dew computing[9], and other post-cloud computing paradigms have been proposed and developed. Since the investigation of these new network computing paradigms is critical to the development of the entire computer and communications industry, in this study, we analyze and summarize recently emerged network computing paradigms in the post-cloud computing era to promote continued research and development in this field.

This paper provides a detailed description of several post-cloud computing paradigms, including fog computing, MEC, and dew computing, to help readers understand the concepts associated with various post-cloud computing paradigms. These new paradigms have been brought forward by the Cisco Company, European Telecommunications Standards Institute (ETSI), and the academic community, respectively, and each has its own emphases due to their unique goals and targeted application areas.

Although these post-cloud computing paradigms differ in terms of their goals, technologies, and application areas, their fundamental concept is the same. That is, they attempt to physically or logically deploy cloud infrastructures closer to end users and their devices and then utilize the computation and storage resources in these local infrastructures to rapidly complete the required computation or storage tasks of the end users, thereby accelerating the processing and response time and improving user experience. To gain insight into the development and application of post-cloud computing paradigms and to understand the various characteristics of existing network computing paradigms, we conducted a comparative analysis of post-cloud computing paradigms to provide a detailed overview of their emphases and differences.

Whether or not a post-cloud computing paradigm that has been proposed by the industrial or academic community can be widely accepted and developed depends on the combined effects of many factors. At present, it is difficult to accurately predict which post-cloud computing paradigm will become dominant. However, we know that post-cloud computing paradigms will develop to a considerable degree in the near future in response to the clear opportunities they present. Therefore, we also conducted a primary analysis of the opportunities associated with post-cloud computing from a number of perspectives.

The rest of this paper is organized as follows. In Section 2, we present a brief analysis of the challenges encountered in the development of cloud computing. In Section 3, we introduce recently emerged post-cloud computing paradigms that attempt to solve the challenges faced by cloud computing. In Section 4, we present a detailed analysis and comparison of cloud computing and several post-cloud computing paradigms. In Section 5, we analyze the opportunities open to post-cloud computing, and finally, in Section 6, we draw our conclusions.

2 Development and Challenges of Cloud Computing

With the development of computer hardware, software, and network technology, the computing paradigm has also changed and evolved. Historically, the computing paradigm evolved from mainframes to PCs and then to network computing when networks became popular in the 1970s and 1980s. To date, cloud computing is widely recognized as the dominant paradigm in the network computing era. The mainframe is a kind of centralized computing paradigm, in which computation and storage are performed on the mainframe machine and the associated dumb or smart terminals perform only input and output functions involving human-computer interaction. In contrast, PC computing is a decentralized computing paradigm, in which computation and storage as well as human-computer interactions are performed independently on each PC. With the invention and development of computer networks, PCs began to be able to connect with each other with the help of various kinds of servers that perform specific functions for them, thus establishing a type of network computing paradigm. A number of network computing paradigms were proposed in the post-PC computing era, including grid computing[10], service computing[11], autonomic computing[12], transparent computing[13], and cloud computing[1]. Ultimately, cloud computing gained wide recognition and achieved considerable commercial success. The core characteristic of cloud computing is that all computation and storage are performed on servers located in a large data center. Therefore, in essence, cloud computing represents a historical and spiral regression to the centralized mainframe computing paradigm even if the modality and technology of cloud computing substantially differ.

From a historical perspective, centralized and decentralized computing paradigms have their own pros and cons. Each has become successful and dominant during specific historical periods based on the technology and requirements of that period, following a historical spiral pattern over the evolution of computing paradigms. Similarly, the inherent centralized premise of cloud computing is increasingly exposing its fundamental shortcomings and inevitable bottlenecks due to changing technologies and requirements. In the following subsections, we analyze and discuss the challenges faced by cloud computing.

2.1 Leveraging the capabilities of heterogeneous devices and edge equipment

First, with the rapid development of pervasive devices, a variety of heterogeneous intelligent or non-intelligent networked devices have emerged, including smart phones, smart wearable devices (e.g., watches, wristbands, and glasses), intelligent electric apparatus, intelligent instruments, intelligent sensors, and other devices. These devices differ in their sizes and shapes and have different levels of capabilities with respect to processing, storage, and networking. On one hand, Moore's law continues to prove true, with the computation, storage, and communication capabilities of end devices becoming stronger even as their sizes decrease. However, the capabilities of some devices are not fully utilized and are often idle due to the dynamic requirements of users and their immediate tasks. On the other hand, the computation, storage, or communication capabilities of other devices remain inadequate for meeting application requirements. For instance, several types of sensors and even some smart phones show obvious deficiencies in their computation, storage, or communication capabilities in specific application scenarios. In the centralized paradigm of cloud computing, the end terminals are used solely to enable the input and output of human-computer interactions. Consequently, the computation, storage, and communication resources of devices cannot be fully exploited in cloud computing, which is leading to wasted resources in end devices. Moreover, devices with insufficient capabilities cannot utilize the relative excess or spare computation, storage, and communication resources of other local devices to facilitate their own tasks. All these situations have led to the low utilization and efficiency of the computation, storage, and communication resources of devices and the cloud as a whole.

Second, most all existing intelligent devices, particularly intelligent mobile devices, are equipped with various types of sensors that can perceive their physical positions (e.g., GPS) or aspects of the surrounding environment. The collection of position or environmental information produces large quantities of sensing data. In cloud computing, it is very time-consuming and laborious to upload these super-large-scale volumes of data to a cloud data center for processing and analysis. Moreover, the significance of the uploaded data quickly becomes stale and useless if a processing or analysis result is not timely obtained.

Third, with the development of hardware technology, the capabilities of edge network equipment (e.g., routers, WiFi access points) become stronger and stronger. The enhancement of these capabilities enables end users to achieve their desired value-added services by utilizing the relatively rich resources of edge network equipment. For example, the capabilities of edge network equipment can be fully exploited with SDN and NFV technologies. In the 5G cellular network, the value-added services of the base station are further extended[14] and users can customize and realize desired functions or services by accessing the computation, storage, and communication resources provided by dedicated servers in the base station. However, it is difficult to provide this level of service capability in cloud computing.

2.2 Heterogeneous and long-distance network bottlenecks

With the development of the ubiquitous network technology, network bandwidth and speed have been significantly improved. To date, broadband wireless access is available almost anytime and anywhere. To some extent, the development of network technology has provided strong technical support and a guarantee of the application of cloud computing. However, due to the inherent centralized processing of cloud computing, the network bandwidth and speed still limit its performance and effectiveness, especially in some mission-critical applications.

First, with the rapid development of the mobile Internet, intelligent mobile devices and broadband wireless access have become popular. Because the original premise of cloud computing was based on the assumption of fixed computing devices and wired networks, it is not perfectly suitable for mobile Internet applications. With the recent development of the mobile Internet and IoT, mobile users and services have become mainstream, which is posing challenges to cloud computing. For example, mobile users may expect a seamless service access experience across different regions, time, and service providers. This is difficult to ensure in cloud computing, which lacks mobile and interoperational support between the various service providers.

Second, in cloud computing, end devices and large cloud data centers are connected via different types of networks. Generally, either a long-haul wide-area network or a wireless network is used in the majority of cases, which exhibit relatively poor performance. Related studies show that the performance improvement in terms of congestion, latency, jitter, and failure remains limited[15], although the bandwidths of long-haul wide-area and wireless networks have increased. For example, the typical network delay is currently approximately 33 to 100 ms. It may be that network latency, congestion, and other relative performance issues cannot be easily improved in the near or even long term due to the limitations of network routing, packet processing on intermediate network nodes, cross handling of different network service providers, and security monitoring. The quality of service in wireless networks is also difficult to ensure because of the radio broadcasting mechanisms, which can cause congestion at peak times and lead to network packet loss and jitter. All these factors serve to increase the response time of cloud applications and services, especially those that are interactive.

Previous studies have shown that users of interactive applications will become dissatisfied or bored if the response delay is more than 150 ms or 1 s, respectively[16]. Considering the inherent delay and congestion of long-haul and wireless networks, it is difficult to satisfy users who are running interactive applications in cloud computing. The current application scenarios of cloud computing may verify this statement. For common end users, cloud storage is the most-used application of cloud computing, such as the Baidu cloud disk, 360 cloud disk, and the Tencent microcloud. These applications store and share data or files for end users, and response delay is not the main concern. However, there are very few deployments and applications of the cloud desktop, for which the interactive response time is critical to the user experience. As such, the long-distance network bottleneck of cloud computing is limiting its application range and effectiveness.

2.3 Demand of new complex network application scenarios

With the development of the mobile Internet, wireless sensor networks, and pervasive heterogeneous devices, new network applications and services are being rapidly introduced. These newly emerging network applications and services are more complicated and diverse than previous technologies and vary with respect to device and network types and their processing and application requirements. These variations pose significant challenges to the centralized processing model of cloud computing. To clarify this challenge, we offer two typical application scenarios as examples that demonstrate the inadequacy of cloud computing.

The IoT, our first example of a complex application scenario, actually involves a series of applications and services, such as the IoV or connected vehicle, smart grid, smart city, and wide wireless sensor and actuator networks. It is not easy for cloud computing technology to meet IoT requirements, which include:

- Wireless and low-latency access. As mentioned above, the instability and high latency of wireless access make it difficult for cloud computing to satisfy end users of interactive applications that demand fast response times, such as gaming, video streaming, and AR.
- Mobile support and environmental awareness. In IoT applications, the node can move around and collect data and information. Thus, these applications must acquire location or environmental information to make timely and dynamic adjustments. If these applications are being run in the cloud center, the necessary location or environmental information is difficult to obtain.
- Timely and rapid processing of sensor data. In the IoT, such as the smart grid, a sensor network with large-scale sensing nodes and a wide geographical distribution is responsible for the collection of big data. These data must be handled in a timely and rapid manner that is beyond the capability of cloud computing.
- Node heterogeneity, interoperability, and collaboration. Some services provided by the IoT, such as video or data streaming, require seamless connectivity and migration between heterogeneous nodes and also require interoperability and collaboration between these nodes to provide better user experiences. However, for commercial reasons, it is difficult for cloud providers to cooperate in this way.
- Real-time processing. In IoT applications involving an actuator or controller, sensor data must be processed in real time for decision-making purposes or risk economic and social losses. Obviously, it is very difficult for cloud computing to meet this requirement.

The 5G network provides another example. There are several characteristics that differentiate the 5G network, including wide coverage, wide bandwidth (Gb), short delay (ms), software-defined radio, and D2D communications. Therefore, various types of applications can be well supported in the 5G network, including the IoT and IoE, mission-critical services, manufacturing, government decision-making, education, and e-health. However, the demands associated with these 5G application scenarios also bring challenges to cloud computing, including the following:

- Efficient distribution of content. Data distribution, particularly media content distribution, occupies most of the bandwidth of the Internet. However, the centralized distribution model of cloud computing could potentially cause a substantial waste of bandwidth because the same media content data must be transferred from the data center to end devices, and it is expensive to distribute high-resolution media data to a large number of users.
- Code/computation offloading. Intelligent mobile devices and wearable devices have limited computation, storage, and network capabilities. Therefore, it is very useful to help these low-resource devices by utilizing power and on-demand computation or storage resources provided by the cloud data center. However, the high latency associated with long-haul and wireless networks between end devices and the cloud center has postponed the deployment and application of code offloading in remote cloud centers.
- Data analysis of intelligent mobile devices. The massive use of intelligent mobile devices generates vast amounts of end-user usage data. The analysis of these big data can ensure the precise positioning of the enterprise market and products. Also, the traditional processing model of cloud computing inevitably leads to high bandwidth consumption when transferring data and high latency in their analysis.
- End-to-end collaboration. It is possible to provide direct, real-time communication and collaboration among end devices in the 5G network by leveraging the D2D functions, thereby making it more efficient and feasible for many applications, including proximity services, publication of warnings about road accidents, and emergency treatment.

The above analysis highlights the challenges faced by the centralized cloud computing paradigm in meeting the demands of the newly emerging applications and services, mostly due to the delay bottlenecks associated with long-haul and wireless networks. This trend makes it inevitable that alternative paradigms to cloud computing must be explored.

3 Post-Cloud Computing Paradigms

The inherent centralized processing characteristics of cloud computing cannot meet the requirements of rapidly changing pervasive devices, ubiquitous networks, and newly emerging network applications and services. To overcome the weakness of cloud computing, the industrial and academic communities have conducted a number of investigations of new network computing paradigms. Since the Cisco Company first put forward the concept of fog computing in 2011[6], similar computing paradigms have been proposed that employ different terminologies, such as MEC, edge computing, and dew computing. We collectively refer to these newly emerging computing paradigms as post-cloud computing paradigms.

Although the new post-cloud computing paradigms have been proposed by various organizations with different points of view, they share similar principles, ideas, and technological approaches. The basic principle of these paradigms is to locate the cloud closer to the ground. In essence, this means the extension of cloud computing from the data center to network edges that are closer to end users, thus overcoming the network bottlenecks associated with cloud computing and improving the processing speeds and efficiencies of user services. Technically, dedicated servers and equipment or small-scale data centers are deployed on network edges near end users to achieve small-scale centralized processing using technologies similar to those used in cloud computing. Obviously, these newly emerging post-cloud computing paradigms do not completely differ from cloud computing, but rather are a natural extension of cloud computing from centralized to small-scale centralization and distribution, which can be regarded as a historical regression to the PC distributed computing paradigm. In the following subsections, we provide a detailed overview of several typical post-cloud computing paradigms.

3.1 Fog computing

The concept of fog computing was first proposed by the network device manufacturer Cisco in 2011[6] and was explained in detail in a paper presented at the 2012 Mobile Cloud Computing Conference[7]. Fog computing is defined as follows.

Definition 1 Fog computing is a highly virtualized platform that provides computation, storage, and networking services between end devices and traditional cloud centers, usually but not exactly at the edge of networks.

The paper also provides the ideal information and computing architecture as well as the position of fog computing for IoT applications. As shown in Fig. 1, fog computing is a layer located between the IoT and cloud data centers. It is also pointed out in the paper that fog computing is an extension of cloud computing, but not a simple extension and application. Fog computing has its own properties and characteristics as follows: (1) locating on the edge of network and location awareness and low latency; (2) wide geographical distribution; (3) supporting large-scale sensor networks and smart grids that require distributed computation and storage resources internally; (4) supporting node heterogeneity and mobility; (5) supporting ultra-large-scale network nodes; (6) enabling real-time interactions; (7) wireless access oriented; (8) supporting interoperability and alliances of the service provider; and (10) supporting online analysis and integration with back-end cloud computing.

The previous description shows that the definition of fog computing initially proposed by the Cisco Company is still rudimentary. It only analyzes the challenges of cloud computing in the application of the IoT, and simply moves the virtualization platform of cloud computing to the edge of the network.

In November 2015, ARM, Cisco, Dell, Intel, Microsoft, and Princeton University Edge Computing Laboratory collaborated to establish an OpenFog Consortium to promote academic research and industrial development of fog computing[17]. To date, the consortium has 53 members from 15 countries. The OpenFog Consortium makes some update to the fog computing concept of Cisco. The definition of fog computing by OpenFog is as follows.

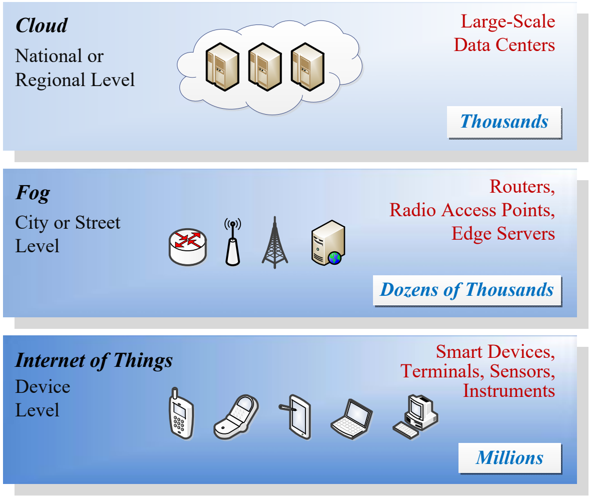


Fig. 1 Internet of things and fog computing.

Definition 2 Fog computing is a horizontal architecture. It deploys computation, storage, control, and network resources and services anywhere between the cloud and the smart thing.

Its main characteristics are as follows:

- Horizontal architecture. Supporting vertical and application areas of multiple industries to provide users and companies with intelligent services.
- Cloud-to-thing continuous service. Deploying services and applications closer to the thing anywhere between the back-end cloud and the smart thing
- System level. Crossing multiple protocol layers from the smart thing and the network edge to the back-end cloud. It is not only a wireless access system, protocol layer, and one part of an end-to-end system, but also spans things to clouds.

The above definition also mainly concerns the application of fog computing in the IoT or IoE. However, in this definition, the continuity of service provision is provided throughout the whole path between the end device and the back-end cloud.

As yet, there is no consensus regarding the definition of fog computing. The definition we provide here is consistent with the initial presentation of fog computing. Other researchers or organizations offer their own explanations or extensions of the meaning of fog computing. Due to the limitations of length, we do not cover these extended definitions here. Interested readers can refer to Refs. [18–20].

3.2 Mobile edge computing

The concept of MEC was first proposed by ETSI in September 2014[8]. Advocates of the ETSI Industry Specification Group (ISG) MEC include Nokia, Huawei, IBM, Intel, NTT DoCoMo, and Vodafone. Currently, there are 53 members of ETSI ISG MEC, including Huawei and ZTE. MEC differs from fog computing in that it is a post-cloud computing paradigm developed and advocated by communication equipment manufacturers. Therefore, this paradigm lays particular emphasis on support for communications and related applications. MEC was initially defined as follows.

Definition 3 MEC provides cloud computing capabilities and IT service environments for application developers and content providers at the edge of mobile networks. This environment is characterized by ultra-low latency and high bandwidth, and applications that can access wireless network information in real time.

The main characteristics with respect to its business aspect are the following:

- A new value chain and an energized ecosystem based on innovation and commercial value.
- Operators can authorize a third party to open their wireless access network edge to allow a third party to flexibly and rapidly deploy innovative applications and services.
- It can provide new and innovative applications and services to mobile users, enterprises, and vertical segment markets.

This definition by the ETSI ISG MEC mainly focuses on commerce and benefits and does not concern itself with the related technology. MEC was mainly proposed to address the demands associated with mobile communication scenarios. It combines communication with IT and adds IT and cloud computing capacities to the Radio Access Network to provide users with more value-added services.

On September 2016, the ETSI ISG MEC changed its group name from “Mobile Edge Computing” to “Multi-Access Edge Computing” to reflect its efforts to include WiFi and fixed-access technologies in its specifications[21, 22]. This term change allowed ETSI to retain the MEC acronym, which is widely recognized by stakeholders in the industry. More importantly, the terminology change also extends the scope of MEC as originally defined by ETSI. In this way, the operators of MEC are no longer restricted to cellular networks. MEC hosts owned by various operators can be deployed in many different types of networks, thus allowing MEC hosts to run edge applications collaboratively.

MEC services can be deployed in LTE macro base stations (eNBs), 3G radio network controllers (RNCs), WiFi access points, edge network routers, and enterprise edge servers. As a result, fast local services can be provided directly at the network edge and these services can be accessed by multiple-access technologies. More importantly, multiple-access technologies can be flexibly integrated to improve capacity, and applications can choose any access technology for uplinking/downlinking according to their needs. Figure 2 shows the high-level architecture of MEC[8, 23]. As demonstrated by ETSI[8, 14], various application scenarios, such as AR, the IoT, videos, and connected vehicles can benefit from MEC.

ETSI ISG MEC provides an initial reference architecture of the MEC server platform[8], which consists of an MEC hosting infrastructure and an MEC application platform. The MEC hosting infrastructure includes underlying hardware resources and a higher virtualization layer. The MEC application platform provides managed applications with various capabilities consisting of an application virtualization manager and application platform services. The application virtualization manager provides applications with flexible, efficient, multitenant, runtime, and managed environmental services via the infrastructure as an IaaS. The IaaS controller provides security and resource sandbox functions. The application is packed and sent to the IaaS as a virtual appliance through virtual machine images. Furthermore, a PaaS may also be supported to provide services in the future.

ETSI ISG MEC has also published various specifications for MEC[21], including the location API, radio network information API, and general principles for mobile edge service APIs. The location API specification gives the necessary API for mobile edge location services and details related application policy information. The network information API specification focuses on radio network information for

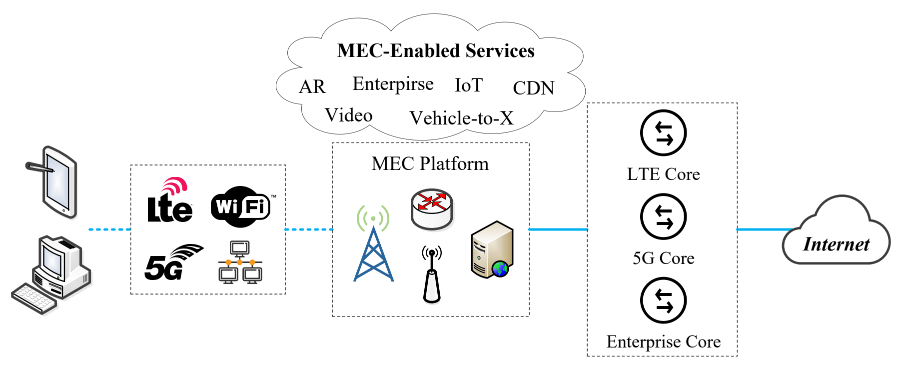


Fig. 2 MEC architecture.

mobile edge services. For more information regarding these specifications, readers can refer to the MEC website in ETSI[24].

3.3 Dew computing

Dew computing was introduced by the academic community in 2012[25] and the basic cloud-dew architecture was fully described in 2015[9]. Figure 3 shows a schematic diagram of the cloud-dew architecture, whose purpose is to ensure the availability of a website even when there are no Internet connections available. Compared with traditional client-server architecture, cloud-dew architecture has an additional dew server, which is a Web server deployed in a user's local computer. In cloud-dew architecture, the user's data are not only stored in the cloud, but also in the user's local computer. Therefore, cloud-dew architecture can help users access the Web without an Internet connection.

The typical routine followed by cloud-dew architecture is to distribute processing tasks between centralized servers and local computers. Dew computing is a realization of the generic cloud-dew architecture and its initial definition is as follows[26].

Definition 4 Dew computing is a software organization model for PCs in the cloud computing era, which strives to fully realize the potential of PCs and cloud computing services. In the dew computing paradigm, software is organized according to the cloud-dew architecture. Local computers can provide rich functionality independently of cloud services and can also collaborate with cloud services.

The authors in Ref. [27] further extended and revised this initial definition of dew computing, but there is little difference between the new and initial definitions, so we do not fully cite it here. In the new definition, the devices involved in dew computing range from PCs to more universal on-premise computers. Moreover, the new definition identifies two key features of dew computing, namely, independence and collaboration. The term independence indicates that on-premise computers can provide rich functionality independently of cloud services for which there are no Internet connections, and collaboration means that a dew computing application must automatically exchange information with a cloud service to realize the potential of the cloud service.

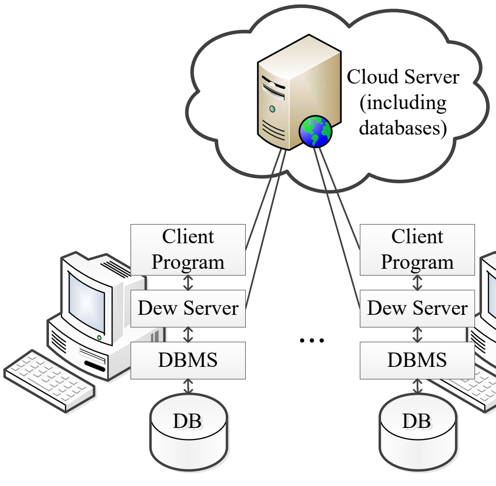


Fig. 3 Cloud-dew architecture.

Skala et al.[28] further extended the hierarchical architecture of dew computing based on the cloud-dew architecture. In the extended hierarchical architecture, dew computing is regarded as a new structural layer located at the ground layer under both the cloud computing and fog computing. Moreover, dew computing focuses on three content areas—information processing, high productivity regarding user requests, and high equipment efficiency.

Edge Computing (EC), another computing paradigm advocated by the academic community, was initially proposed by Carnegie Mellon University in June 2015 via the Open Edge Computing Initiative[29]. This Initiative provided EC with a wider description and broader meaning than fog computing[29, 30]. EC, which is based on fog computing and refers to and is included in the definition and categories of MEC, is a general term that covers both fog computing and MEC. As yet, however, there is no broad consensus on the concept of EC.

Mobile transparent computing is another computing paradigm developed by the academic community to overcome the limitations of cloud computing by extending the original concept of transparent computing from fixed desktops and wired networks to mobile devices and wireless networks[31–33]. By streaming and scheduling the codes related to the operating system or application program stored on the nearby servers, it can adaptively leverage resources from appropriate machines to execute computing tasks and achieve nearly optimal performance.

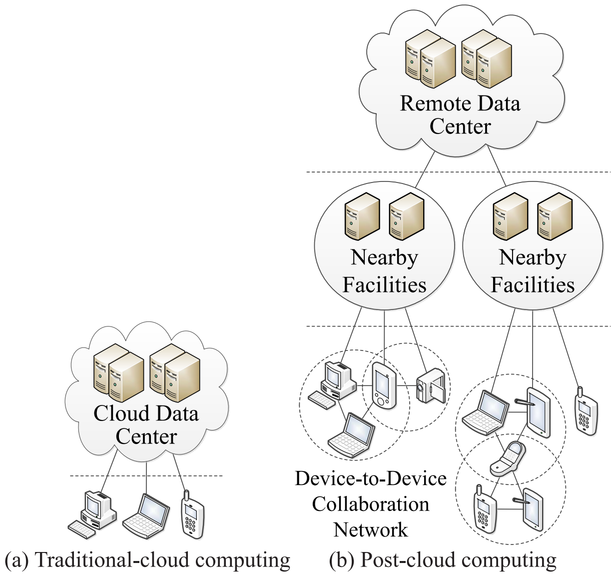
4 Comparative Analysis

In this section, we compare the cloud and post-cloud computing paradigms from different perspectives and analyze the differences between various post-cloud computing paradigms.

4.1 Cloud computing vs. post-cloud computing

To gain a more thorough and clear understanding of different computing paradigms that have different definitions and goals, we analyzed the characteristics and evolution of these computing paradigms by comparing them from several perspectives, including their architecture, computation and storage modes, place of execution, and execution time sequence. Table 1 shows a comparison of the mainframe, PC, cloud computing, and post-cloud computing paradigms with respect to the above aspects.

Figure 4 shows that cloud computing has a two-tier architecture consisting of the end device and cloud data center. Compared with cloud computing, post-cloud computing paradigms add one or more tiers of nearby facilities (e.g., edge network routers, cellular network base stations, nearby servers, etc.) located between the end device and a remote data center. Computation, storage, networking, and other tasks can be performed not only in the remote data center but also in nearby facilities. Moreover, a device-to-device and decentralized collaboration network can also be established between the device itself and devices adjacent to it to perform computation, storage, networking, and various other tasks. As such, the original two-tier cloud computing architecture is extended to a multi-tier one[34]. With respect to the execution time sequence, in cloud computing, all processing tasks are conducted in the data center and the end devices must wait for the processing results to be returned from the data center before performing the next step. However, in post-cloud computing paradigms, computation and storage can be performed in parallel at different locations due to the availability of different levels of processing capacity distributed in the multi-tier infrastructures.



(a) Traditional-cloud computing (b) Post-cloud computing

Fig. 4 Architecture of cloud computing and post-cloud computing.

To help readers better understand the differences between traditional cloud and post-cloud computing paradigms, Tables 2 and 3 summarize their differences with respect to their general characteristics and technical parameters[18, 35, 36].

The above comparison and summary show that post-cloud computing not only extends to the network edge, but also fundamentally differs from cloud computing in its architecture, computation, and storage execution mode, service control, availability, and other aspects. Post-cloud computing involves the comprehensive promotion and evolution of cloud computing and post-cloud computing paradigms offer significant development opportunities because of these fundamental differences. After briefly comparing several post-cloud computing paradigms, we offer a preliminary analysis of the opportunities associated with post-cloud computing to promote related research initiatives and applications in this field.

4.2 Comparison of post-cloud computing paradigms

In this section, we analyze the difference between cloud

Table 1 Simple comparison of different computing paradigms.

Computing paradigm	Architecture layer	Computation or storage models	Execution place of computation	Execution time sequence of computation
Mainframe	One layer	Centralized	Mainframe	Serial
PC	One layer	Decentralized	PC machines	Parallel
Cloud computing	Two layers	Centralized	Large data center	Serial
Post-cloud computing	Multiple layers	Small centralized or device-to-device	Network edge, adjacent device, device itself	Serial or parallel

Table 2 Simple comparison of cloud computing and post-cloud computing.

	Cloud computing	Post-cloud computing
Target user	Common Internet users	Mainly mobile users
Distance to users	Far from users	Physically close to users
Hardware resources	Rich and extensible storage space and computing capacities	Limited storage and computing capacities
Working environment	A warehouse-sized building equipped with an air conditioner	Outdoors or indoors
Geo-distribution	Centralized	Small centralized or distributed
Geographic coverage	Global	Local area or wider
Types of services	Information collected from the global scope	Local information services for a particular deployment environment
Location of service	Within the Internet	At the edge of local networks
Support company	Large Internet service company	Small operators and equipment manufacturers

Table 3 Comparison of technical parameters in cloud computing and post-cloud computing.

	Cloud computing	Post-cloud computing
Latency	High	Low
Delay jitter	High	Very low
Access network	Wired or wireless	Mainly wireless
Distance between client and server	Multiple hops	One or multiple hops
Location awareness	No	Yes
Mobility support	Limited	Supported
Control mode	Centralized/layering	Distributed/layering
Service access	Through the center	On the edge or handheld devices
Number of users/devices	Ten millions to billions	Ten billions
Number of server nodes	Few	Very large
Price of each device	1500–1300 US dollars	50–200 US dollars
Main content generator	Humans	Devices/sensors/humans
Content generation	Central location	Anywhere
Content consumption	End devices	Anywhere
Attack on data enroute	High probability	Very low probability
Availability	99.99%	Highly volatile/highly redundant

and post-cloud computing paradigms and then compare the various post-cloud computing paradigms.

To facilitate a clear understanding of the three post-cloud computing paradigms, Table 4 shows a preliminary comparison of their original proposer, supporting organization, motivation for development, and overall purpose. From this comparison, readers can readily grasp their underlying principles. Table 5 shows a detailed comparison of the similarities and differences of these three paradigms[37, 38].

This comprehensive comparison shows that although the names of these computing paradigms differ, they have similar features, including low latency and close to end users. They also have their own unique characteristics. Fog computing emphasizes the applications in the IoT, whereas MEC focuses on the wireless access network from the perspective of communication operators without regard to collaboration between end devices and cloud centers. Dew computing focuses on collaboration between the user device and cloud computing, disregarding the edge and wireless access network. As such, a general pattern of the post-cloud computing paradigm combines the collaboration of user devices and leverages the capabilities of facilities that are located near the end user. In the end, computation, storage, and networking service providers could choose the location at which these services are executed (e.g., the user device itself, adjacent user devices, nearby facilities, and remote data centers) and these services could also migrate on-demand from place to place.

Table 4 Basic comparison of typical post-cloud computing paradigms.

	Fog computing	MEC	Dew computing
Original proposer	Cisco[6]	A group of six companies who founded ETSI ISG MEC: Nokia, Huawei, IBM, Intel, NTT DoCoMo, Vodafone[8]	Wang[9]
Supporting organization	OpenFog Consortium[17]	ETSI ISG MEC[24]	/
Inspired drivers	IoT, wireless sensor, and actuator networks	Nokia liquid applications, 5G network services like content acceleration, augmented reality, etc.	Internet Web browsing
Purpose	Meet the requirements of low latency, location awareness, mobile support and geographical distribution of the IoT	Reduce latency by transferring computation and storage from the core network to the edge of wireless access network	Provide services for users using on-premise computers independent of and collaborating with cloud computing

Table 5 Detailed comparison of typical post-cloud computing paradigms.

	Fog computing	MEC	Dew computing
Users	Mainly mobile users	Mainly mobile users	Common Internet users (including mobile users)
Distance to users	Very close	Very close	Very close
Access network	Mainly wireless	Mainly wireless	Wireless and wired access
Network latency	Low	Low	Low
Distance between client and server	One or multiple hops	One hop	One or multiple hops
Deployed Hardware	Routers, switches, access points, gateways, etc.	Radio access points, base stations, etc.	On-premise computers
Deployment environment	Edge and near-edge	Network edge	User equipment
Usage of virtualized platforms	Yes	Yes	No
Usage of end device	Yes	No	Yes
Service type	Local service	Local service	Local service
Service access	Edge or user-handheld devices	Edge	User-handheld devices
Typical application scenarios	IoT, smart grid, Internet of vehicles	Augmented reality, intelligent video acceleration, IoT	Web browsing

5 Development Opportunities for Post-Cloud Computing

Post-cloud computing takes place closer to end devices by combining decentralized and centralized processing models. It also supports cooperation between end devices. Hence, post-cloud computing provides great development opportunities in the IoT, smart grid, IoV, UAVs, 5G, and other application areas. In the following subsections, we discuss the development opportunities of the post-cloud computing paradigm via several specific examples.

5.1 Internet of Things

The IoT is a network that connects various things to the Internet to perform information exchange and communications in accordance with an agreed protocol using information sensing equipment to achieve intelligent identification, location, tracking, monitoring, and management[39]. The core of the IoT is the information exchange between a thing and another thing and between a human and a thing. It extends the dimensions of information communication to any time and any place, and connects anyone to anything. Everything connects to the Internet to establish the IoT[40].

The application fields of the IoT are very extensive, including intelligent transportation, environmental protection, government affairs, public security, environmental monitoring, industrial monitoring, individual investigation, and the collection of personal information[40]. With the rapid development of the IoT, more and more smart devices are being connected to the Internet. Statistically[41], 6.4 billion things had been connected to the Internet by the end of 2016 and more than 20 billion things are predicted to connect to the Internet by 2020. Billions of devices that had not previously been connected to the Internet are now producing EB-level data every day[42], which explains why cloud computing and its infrastructure are having difficulty meeting the requirements of the IoT.

First, various IoT devices are very heterogeneous in terms of their computation, storage, batteries, and other resources. Hence, the overall efficiency of resource utilization is currently inadequate. On one hand, some IoT devices that function only as sensors have limited resources that cannot process the collected data. On the other hand, some residual or idle IoT resources are not being fully utilized. Second, the demand for real-time processing of IoT services cannot be met in cloud computing. Data processing tasks that cannot be performed by IoT devices with limited resources must be performed by distant and more highly resourced data centers. However, these centrally deployed remote data centers are often located far from the IoT devices. Data transfers across long-distance networks increase the latency of data processing, which sacrifices the timeliness of some of the information collected by the IoT devices. Third, the centralized data processing framework for the IoT when using cloud computing cannot meet the security and privacy requirements of the IoT. On one hand, the risk of wiretapped, falsified, and monitored information is increased due to the long-distance network transportation. On the other hand, centralized processing increases the risk before, during, and after data processing. In addition, individuals and organizations are often reluctant to send their important and sensitive data to a third party for storage and processing.

As stated above, fog computing was developed to meet the requirements of the IoT. As such, fog computing brings many benefits to IoT applications. Of course, the development of the IoT can also promote the post-cloud computing paradigm. First, post-cloud computing combines decentralized and centralized processing models and supports collaboration between devices. Therefore, IoT devices can not only overcome the shortages of their own resources by leveraging the resources of neighboring devices, but they can also utilize the resources of nearby facilities and remote cloud centers according to their needs. Second, since the facilities are physically located nearby IoT devices, the data collected from IoT devices can be processed at these facilities with less latency, thereby satisfying the real-time processing requirements of some IoT services[43]. For example, in smart cities, one of the major IoT applications, the data collected from various kinds of sensors can be pre-processed, analyzed at the fog nodes, and then aggregated and uploaded to the central data center for final processing[44]. Finally, post-cloud computing can also meet the IoT's requirement for security and privacy protection[45]. On one hand, data processing on a nearby facility can reduce the amount of data transmitted over the network and thus reduce the risk of being wiretapped, falsified, or monitored. On the other hand, users can set up security measures in a targeted manner according to their specific needs for security and privacy protection, and they can select the locations and steps followed to achieve sensitive and private data storage and processing.

5.2 5G mobile network

As mentioned above, MEC was initially proposed to overcome the shortcomings associated with cloud computing in mobile network application scenarios, especially in 5G mobile networks. As such, the 5G mobile network is an important area for the development and application of post-cloud computing paradigms.

In April 2017, the 3rd Generation Partnership Project (3GPP) supported EC as a high-level feature of the 5G system in its technical specification document[46]. This means that EC will become part of the 5G standard and specification in future mobile cellular networks and that the base station (eNB or RNC) will have a built-in EC server or micro-data center. With the 5G network's high bandwidth and low-latency characteristics, MEC or other post-cloud computing paradigms for end-to-end applications can provide real-time processing and services. Considering that local communication and processing can provide high levels of privacy and security, post-cloud computing will greatly accelerate the service proliferation of 5G networks.

For example, in the case of online live video distribution, cameras can be deployed at different angles in the field. This will obviously produce a lot of video data, which is very difficult to transmit to a local or a remote audience if it is processed with a remote cloud via the current 4G network[47]. However, in a 5G network, these data can be passed to the proximal edge server located in the base station, where the collected video data can be synthesized and processed and then distributed among different types of end users who can choose to watch videos at different resolution levels. At the same time, by leveraging the storage capacity of nearby servers, popular videos can be cached on these servers for end users to download. This will not only reduce download delays, but also relieve the transportation pressure on the backbone network. Compared with the content delivery network, which must deploy dedicated servers and use several hops to download, post-cloud computing needs just one hop to download by using the video content cached in a 5G base station[48].

We take code/computation offloading as another example. To overcome the limited computational, storage, and energy resources of mobile or wearable devices, offloading is considered to be a promising way to use the nearly endless power of cloud computing to help these device complete their tasks. However, because user experience is heavily dependent on network latency, these offloading tasks are not suitable for transferring data for handling in a remote cloud center[49]. In contrast, leveraging nearby facilities in post-cloud computing to perform code offloading can not only improve the efficiency of execution, but also reduce energy consumption. Migrating Tesseract-OCR code from Amazon EC2-West to the Cloudlet platform has been shown to not only achieve a faster execution speed, but also a reduction in energy consumption by more than half[50]. The reduction in the amount of energy consumed is a very attractive feature for smart mobile devices.

5.3 Smart grid

A smart grid is a fully automatic power supply network, in which each user and node are monitored in real time and the two-way flow of electric current and information at each point between the power plant and a user's electrical appliances must be ensured[51]. The smart grid ensures the real-time connection of power market transactions as well as seamless links and real-time interactions among members of the power grid via extensively distributed intelligence and communication as well as integration with an automatic control system. The smart grid has three aspects[52]. First, it involves real-time monitoring of key equipment during power generation, transmission, and distribution, and the power supply is transported by the sensing equipment. Second, monitored grid data are collected and integrated via the network system. Finally, optimization of the whole power system is realized by the analysis of the monitoring data.

Post-cloud computing can be easily applied to and benefit the smart grid. Compared with the existing centralized or fully distributed smart grid models, with post-cloud computing paradigms, Supervisory Control and Data Acquisition (SCADA) in the smart grid can be complemented by the use of distributed smart meters and micro-grids. This can not only improve the scalability, cost, security, and response time of the smart grid, but also connect renewable and distributed energy sources (such as wind farms and solar photovoltaic power plants) to the main grid[19].

In post-cloud computing paradigms, the smart grid becomes a hierarchical system of interaction between several layers[7, 53]. The first layer is the grid sensing layer, which is responsible for collecting data, processing the data that must be responded to in real time, and triggering the control command of the executors. In addition, it also filters the data to be processed locally and sends the remaining data to a higher layer. The second layer is the micro grid layer, which is responsible for data visualization and reporting (i.e., the interaction between human and machine) and interaction between systems, as well as data processing (i.e., the interaction between machine and machine)[54]. The third layer is the SCADA and central data processing layer, which is responsible for long-time data storage and business intelligence analysis. In this hierarchical system, the higher the level, the higher the geographical coverage. However, the interaction time between layers may be from seconds to minutes (real-time analysis) or even several days (transaction analysis). This means that the smart grid system using post-cloud computing must support the temporary storage of data at the lowest level and semi-persistent storage of data at the higher level.

5.4 Internet of Vehicles

The IoV facilitates the interaction between one vehicle and another, between a vehicle and the roadside, and between a vehicle and a human. It is also a mobile communication system for achieving communication between vehicles and the Internet[55]. The IoV is used to collect information on vehicles, roads, and traffic through Radio Frequency IDentification technology

(RFID), camera, sensors, and other devices, and then shares, computes, processes, and publishes the collected information via a network information platform to achieve intelligent monitoring, unified scheduling, and the management of humans, vehicles, and roads. IoV technology can effectively solve a number of problems in the current transportation system, such as relieving traffic congestion, reducing traffic accidents, and improving road efficiency[56].

There are many features that make post-cloud computing more suitable for application in the IoV than cloud computing, including multi-tier system architecture, mobility and location awareness, geographical distribution, low latency, and heterogeneous support. First, the IoV not only supports connections between vehicles, but also supports connections between vehicles and the road (e.g., roadside unit and smart traffic lights) and vehicles and information processing systems[57]. The connection requirements are very compatible with the multi-tier architecture of post-cloud computing, as the vehicle corresponds to the end device in post-cloud computing, the roadside device and its adjacent processing devices can be regarded as nearby facilities, and the centralized information processing system corresponds to remote data centers.

Second, the mobility, location awareness, and geographical distribution characteristics are also suitable for IoV services. For example, an intelligent traffic signal lamp can interact with a plurality of sensors in local and adjacent vehicles to perform interactions, detect pedestrians and bicycles, and measure the distances and speeds of nearby vehicles[58]. Based on this information, the intelligent traffic signal lamp can send a signal warning to approaching vehicles and even modify the signal conversion period to avoid the likelihood of traffic accidents. Moreover, a plurality of signal lamps can also dynamically adjust the changing period of the signal lamp according to the traffic flow on different roads, to thereby effectively reduce the number of traffic jams and improve traffic efficiency[59].

Third, the low-latency processing of post-cloud computing can meet the low-latency demand of the IoV and improve its safety performance[60]. In the IoV, vehicle avoidance, vehicle lane change control, safe driving assistance, and other applications have very strict requirements regarding network latency, generally below 50 ms, and even below 10 ms for some applications[61]. The centralized processing model based on traditional cloud computing finds it very difficult to meet the requirements of these applications. However, post-cloud computing can process tasks with different latency requirements in neighboring end devices, nearby facilities, and remote data centers to meet the latency requirements of different applications in the IoV. Moreover, low latency can reduce the number of traffic accidents and improve the safety of the IoV, which is very important in any period prior to an accident. Therefore, the timely processing of data acquired from the IoV and fast return of the processing result can prevent traffic accidents and save lives.

Finally, the heterogeneous support feature of post-cloud computing can overcome the challenges associated with interconnection between complex devices in the IoV. These devices include vehicles, roadside units, intelligent traffic signal lamps, and various sensing devices, which are complex and diverse. Particularly, the software and hardware systems of various vehicles differ. Post-cloud computing can facilitate the interconnection of these heterogeneous IoV devices by the establishment of existing or new communication standards to overcome the difficulties associated with collaboration among heterogeneous devices.

5.5 Unmanned aerial vehicles

UAVs refer to unmanned aircraft operated and controlled by radio remote control equipment using their own program control device[62]. UAVs are widely used by both the military and civilians. In the military, UAVs are used as spy planes and drone aircraft. By civilians, UAVs are widely used for aerial photography, disaster relief, express transportation, surveying and mapping, news reports, and wildlife protection. The application and development of UAVs are in full swing due to their broad application potential. For example, with respect to express transportation, UAVs can achieve accurate and timely delivery to save resources. Currently, Google and Amazon are developing and testing their own UAV express services.

UAVs have yet to be applied at large scales, although they have a very wide application potential. The main reason this has not yet occurred is the many remaining problems associated with UAV technology, safety, and surveillance. Technically, the UAV has high network latency requirements, which the UAV processing model based on cloud computing cannot meet. For example, when an unmanned aircraft assumes the stop position, its speed is very high (up to 10 miles per hour). During descent, the UAV will interact frequently with the ground control tower. When a UAV reports problems, the best time to deal with this problem may be missed if the data are transferred to and processed in a remote cloud center. As a consequence, the UAV is currently faces severe safety issues. UAV application also faces problems related to the sharing of airspace[63]. The same airspace may be shared by many UAVs at the same time and different companies use UAVs to perform different tasks in the air. In addition, there may be flying birds and high buildings in their airspace. Preventing collisions between UAVs and between UAVs and other objects is an urgent safety problem that must be solved. Finally, the UAV also faces a complex surveillance problem[64]. UAVs must be operated in a complicated surveillance environment. They are prohibited from flying in some regions or in some lanes by the aviation administrations in some locations. As such, how to effectively control UAV flight with respect to geographical position is a major problem in UAV surveillance.

Post-cloud computing provides feasible solutions for many of the challenges faced by UAV applications. First, post-cloud computing can meet the low-latency requirements of UAVs[65]. The data generated by UAVs can be processed in nearby facilities or remote data centers according to the latency requirements. Second, post-cloud computing can protect UAVs in multiple levels. It can ensure the safety of UAVs by using information from the UAV itself, neighboring UAVs, nearby facilities (such as a node deployed on a UAV or a high building), and remote data centers. At the UAV level, the UAV can identify nearby obstacles based on the information it has collected to actively avoid the obstacle. Then, adjacent UAVs can share information regarding nearby obstacles and climate conditions, as well as other information that affects UAV flight to achieve mutual benefit and ensure safety. At the level of nearby facilities, these facilities can dispatch the flight path of each UAV uniformly and ensure the safety of the UAVs flying in an area. The remote data centers can make higher-level management and safety protection decisions and ensure UAV safety based on a wider range of statistical information. Finally, post-cloud computing can help to establish a UAV surveillance service based on geographical position. The control of the permanent no-fly zone (i.e., airports and sensitive military areas) with post-cloud computing can be achieved by presetting a specific region for UAVs. A temporary no-fly zone can be deployed in nearby facilities. UAVs can take active avoidance maneuvers when they near no-fly nearby facilities. Moreover, post-cloud computing can also monitor the flight conditions and trajectory of UAVs at nearby facilities and remote data centers. A supervisory department can effectively manage UAVs in a region through the centralized arrangement of regional UAV information.

From the above discussion, we believe that post-cloud computing has excellent future prospects. There are, however, a number of issues to be addressed before post-cloud computing paradigms can be widely applied, including the development of architecture, programming models and languages, heterogeneous network access and management, resource management and scheduling, incentive mechanisms, and pricing models.

6 Conclusion

In this paper, we discussed the bottlenecks associated with cloud computing, identified the basic characteristics of cloud computing, and highlighted its inevitable evolutionary trend. We then briefly introduced newly emerging network computing paradigms, including fog computing, MEC, and dew computing. To help readers understand the characteristics of these post-cloud computing paradigms, we performed a detailed comparative analysis of cloud computing and post-cloud computing and discussed the differences between post-cloud computing paradigms. Moreover, we provided specific examples to analyze and summarize the development opportunities associated with post-cloud computing. On this basis, with the increasingly obvious issues being experienced by cloud computing, post-cloud computing will undoubtedly become a hot research topic in the industrial and academic communities in the near future.

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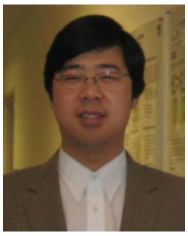

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