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Edge Computing for Real-Time Internet of Things Applications: Future Internet Revolution

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Abstract
The Internet of Things (IoT) is a concept that permits the integration of all objects into an Internet environment. IoT has spawned numerous intelligent applications and services to benefit organizations, society, and consumer experiences. On the other hand, traditional computing methods are incapable of handling the demands of these services. The advent of cloud computing methods that provides software, platform, and infrastructure such as services have realized these applications. However, one of the critical obstacles of real-time cloud-based IoT applications is service response time. Edge computing solutions have been developed to address these issues. In this work, we provide a comprehensive survey of driving enforce edge computing for IoT applications on aspects of the research timeline, applications, vision, challenges, and open research issues. Through this, we highlight the benefits of edge computing over cloud computing in almost domains. This study will contribute to driving empowerment intelligence to the edge of networks to form the next intelligent edge era.

Keywords Edge computing · Cloud computing · Internet of Things · Real-time applications

1 Introduction

The introduction of fifth-generation networks (5G) in the early 2020s made it possible for end users to gain access to a wide variety of Internet services with high bandwidth and low latency. As a direct result of this, a number of different smart applications have emerged, some of which are already providing benefits to society. These include things like smart cities, smart healthcare, smart agriculture, smart transportation, and IoT ecosystems, to name just a few [1, 2]. The Internet of Things (IoT) concept has been brought to fruition

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with the debut of 5G. The Internet of Things (IoT) is a network that enables traditionally separate entities, such as humans and physical things like sensors, devices, software, and technology, to interact with one another and share data and other information in real time. Although there are some challenges, IoT has proved its abilities and capabilities, and it promises a future Internet revolution [3, 4]. Some typical IoT applications are presented in Fig. 1.

Over five hundred billion gadgets will be connected to the internet by the year 2030, as predicted by Cisco. These gadgets will be internally outfitted with the Internet of Things modules to create device-to-device connections (also known as D2D connections), which is the fundamental concept behind the formation of IoT platforms. Moreover, Cisco also expects applications for self-driving, smart agriculture, and intelligent transportation to become widespread worldwide. Over 75% of network traffic will be generated by IoT systems [5]. Regarding economic efficiency, McKinsey Global Institute has forecasted that revenue from IoT-related fields will reach $11 trillion by 2025 [6].

These forecast indexes again demonstrate IoT's massive potential in both aspects of technology and the economy. With the boom of smart applications, real-time QoS-aware IoT applications are increasingly growing. They are present in most applications, such as self-driving, collision warning applications between vehicles in intelligent transportation systems, or monitoring and controlling autonomous devices in smart agriculture. Survey results showed that the operating principle of real-time IoT applications is a combination of three main components, namely big data processing, intelligent decision support, and, IoT systems, as presented in Fig. 2.

IoT devices and applications will generate a massive amount of data. Hence, current traditional storage and processing solutions are impossible [7]. On the other hand, cloud computing provides the necessary storage and processing solutions in terms of infrastructure,

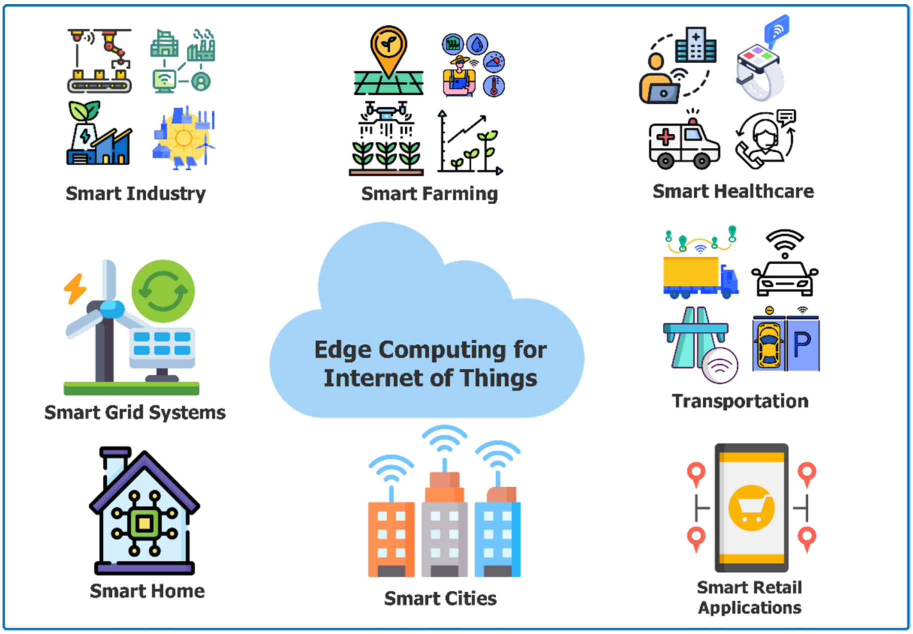

Fig. 1 Typical IoT applications for humanity

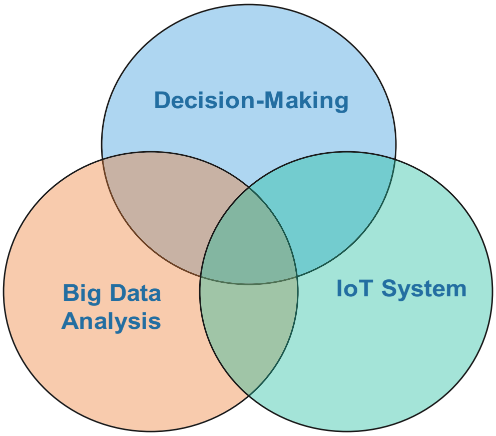

Fig. 2 The three main components of a real-time IoT system

platforms, and software as services. Also, few survey results have revealed that traditional IoT networks use storage, data analysis, and decision-making services based on cloud computing [8]. Therefore, combining cloud and IoT technologies has brought great solutions and technologies to humans [9–11]. However, one of the major challenges for cloud-based IoT applications is the requirement for high service response time. Consequently, real-time IoT applications are infeasible at the moment [12].

To solve this problem, EC has been proposed, which allows data processing at the edge in such a way that autonomous decision-making can be derived. Therefore, real-time IoT applications will perform EC before connecting to the cloud [13], leading to reduced costs and response times as well as privacy and security enhancement. Besides, EC can be integrated with other wireless networks such as MANETs, VANETs, intelligent transportation systems (ITS), and IoT to reduce cost and computation time. When combined with EC, the decision-making in these network applications will be quick and with low response latency. The latter property is the prerequisite for real-time applications, especially those related to traffic safety and human life.

A few examples of typical EC-based applications include (1) emergency healthcare, where ambulances are equipped with an EC-based IoT system that enables the collection of data from the patients, hospital infrastructure, and doctors for autonomous decision-making purposes, including finding the nearest suitable hospital, contact the doctors and relatives without relying on the cloud, etc. [14, 15]; (2) natural traffic management, where terminals such as smartphones and smart endogenous devices are equipped with vehicles integrated EC enabled which can rapidly predict some vital events. Here, decision-making is autonomously generated to avoid accidents and traffic congestion [16, 17]; (3) e-commerce, where EC-based mobile applications are utilized to enhance the user's experience by providing personalized recommendation systems [18, 19].

Although EC has significant advantages compared to cloud computing, it cannot completely replace cloud services [20, 21]. As moving the analytics to the edge network aims to reduce service response times, some services still require support from the cloud system. Furthermore, the EC layer faces some challenges, such as offloading, performance, energy saving, QoS support, and connection management [22, 23]. To address these challenges, robust and reliable EC services should be designed to meet real-time IoT application requirements. This constitutes the motivation for this work. Besides, many survey studies on edge computing solutions have recently been introduced in [3–8]. However, there are no studies that comprehensively evaluate all aspects of EC, including vision, architecture, research time, applications/use cases, as well as highlighting detailed challenges and promising research directions of EC.

In this paper, we provide a complete picture of the recent powerful attraction of EC in almost domains. Indeed, first, we discuss the vision of EC in the future Internet, then, we consider the research timeline of top telecommunication corporates. Moreover, we analyze in detail recent EC-based studies in domains such as virtual reality, medicine, intelligent transportation system, smart cities, agriculture, and industry. Finally, we indicate challenges and open issues to drive EC into real use cases to enhance humanity's living quality. The acronyms used in this work are given in Appendix.

The rest of the paper is organized as follows. Section 2 presents an overview of EC, including the related challenges and architectures for network applications and an analysis of its efficiency. Section 3 shows the research timelines and vision of leading corporations working on EC. Section 4 presents a full picture of EC-based IoT applications in almost domains. Section 5 presents a few EC challenges and related research directions. Section 6 is the conclusion.

2 Edge Computing

In recent years, the information technology and telecommunications revolution have given rise to the advent of IoT systems, and more requirements of humans have led to the huge amount of data generated by these systems [4–6]. Consequently, high latency and system resource consumption problems are inherent. Aiming to address these issues, there is a clear requirement for a more optimized computing technology for real-time IoT applications. Recently, edge computing (EC) has been advocated as one of the promising solutions. EC has been designed to remove barriers of a centralized architecture, pushing the compute capacity to the edge network [24]. Although EC is considered a promising technology, studies on this paradigm are still a stub.

2.1 EC Architecture

This section discusses the EC architecture (Fig. 3) with its physical properties and operation methods. In this architecture, the computing/processing servers are installed at the edge of the network within the scope of the radio access network (RAN), and they are meant to perform computations while providing storage services [25].

The primary goal of the EC architecture is to provide a better quality of experience (QoE) for end-users by reducing the response times and enhancing the throughput [26]. Such architecture allows various real-time applications and highly time-sensitive services to perform autonomous decision-making without reaching the cloud services. Furthermore, due to the flexible characteristics of the EC system, most portable devices, such as smartphones, personal mobile devices, and laptops, can become edge devices. Besides, EC installs applications and services in edge devices, enabling data processing to be performed closer to the end-users. Consequently, the service response time is significantly reduced in the sense that instead of transferring the data to the centralized servers in the cloud, edge devices filter the information, thereby reducing network traffic to backhaul.

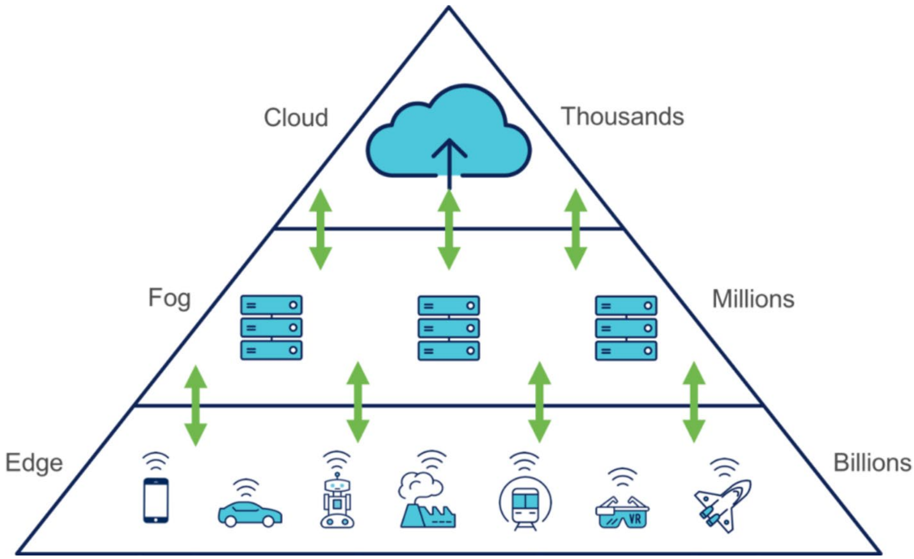

Fig. 3 An overview of all-in-one computing model

In recent times, to improve computational efficiency in different network scenarios, modern computing technologies have been investigated [21, 27]. In the sequel, we analyze, compare, and discuss the advantages and limitations of these technologies.

2.2 Computing Technologies

A significant improvement of cloud-based computing technologies is the so-called fog computing (FC) [28]. Both EC and FC architectures push the data sources closer to the end-users. Still, the critical difference between them is that FC pushes the data processing to the edge of networks. In contrast, EC pushes the data processing directly to a device or edge servers in LAN networks [29]. Like EC, FC is widely recognized as applicable to real-time applications and high latency-sensitive IoT systems [30].

In FC, a fog server is located between the Internet gateway and the Cloud that processes the data to obtain intermediate results and to filter the data before transferring them to the cloud server. Both EC and FC present a similar approach to data computation and storage. FC is a particular case of EC when an edge server is nominated to perform the edge computation tasks.

Another important computing technology that has dominated the tech world for more than a decade is cloud computing (CC). In the CC architecture, data computing and storage are moved to centralized servers on the Cloud. All processing and storage take place in a centralized data center, and the CC technology allows the cloud servers to provide three different services, namely software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS) [31].

The cloud architecture can be divided into two main layers: (1) the cloud layer, which represents the centralized servers with a vast processing and storage capacity, and (2) the access layer, which represents the end-user devices. The access layer devices are connected to the cloud server, which relies on the Internet infrastructure and the client–server protocol suite. Since all computing and storage functions are performed in the Cloud, the end-user devices do not require storage capabilities or intelligent computing mechanisms. Although CC services are more reliable, the biggest concerns of CC systems are high latency and high bandwidth consumption [32]. When compared to EC, CC-based computing solutions have higher service response times. Consequently, this can affect the overall performance of real-time applications. Besides, the data generated from CC-based computing solutions are usually stored in centralized servers in the Cloud, which may lead to congestion in the cloud servers and overloading of the backhaul links.

The Multi-Cloud Computing (MCC) architecture is an extension of the CC architecture in which the services are delivered to multiple clouds. Compared to EC, MCC has the same disadvantages as CC and other complex mobility management issues [33].

The analysis of EC and CC shows a high availability and scalability of EC compared to other computing technologies. In EC, the bottlenecks have been solved because the computation is distributed and decentralized. Although advances in computing technologies such as FC and EC have different operating mechanisms, they all tend to bring the data processing closer to the end-user in order to reduce the service response time. In [34], the authors presented a brief analysis of the EC's contribution in different areas. The results proved that EC is a trusted computing system that provides an efficient service in a decentralized manner. Besides, EC technology is commonly used in various IoT applications [35].

The advantages of EC over other computational techniques based on some highlighted characteristics in Table 1 show that EC provides better performance than CC, FC and MCC.

2.3 Benefits of EC-Based IoT Systems

Many business services have successfully transitioned from CC to EC, and significant benefits of EC (Fig. 4) are as follows [36, 37]:

- The ability of faster data analysis to improve the overall performance of real-time applications.
- The amount of data sent to the cloud is significantly reduced, thereby reducing the computing cost, bandwidth consumption, and energy saving.
- Reduced network traffic on the backhaul links, improved network throughput and reduced cost per data bit.

Table 1 Comparison of computing technologies

Characteristics	Cloud	Multi-cloud	Fog	Edge
Latency	High	Very high	Low	Low
Service response time	High	High	Low	Low
Bandwidth	High	Very high	Low	Very low
Storage	High	Very high	Low	Low
Server overhead	Very high	High	Low	Very low
Energy consumption	High	High	Low	Low
Network congestion	High	High	Low	Low
Energy consumption	High	High	Low	Low

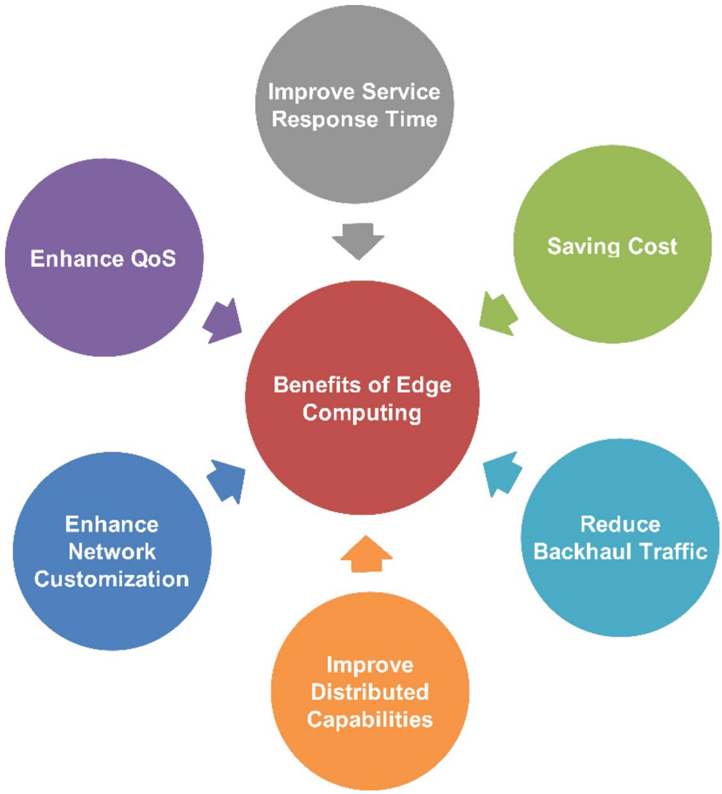

Fig. 4 An illustration of several typical benefits of EC

- Improved distributed computing capabilities.
- Enhanced system's customizability.

EC improves QoS and QoE and enhances reliability by minimizing the data transmission distance between the terminal and the application. In our vision, with the explosive growth of IoT applications and the increasing demand for real-time data analytics, EC centers will be rapidly deployed to serve IoT infrastructures. In current studies, edge devices are deployed at the networks' base stations to monitor data flows from the things layer to the cloud layer aiming to reduce the service response time and data traffic forwards to the cloud [38–41].

3 Research Timeline

Studies have shown that a series of emerging solutions have integrated EC into applications to improve their intelligence, flexibility, and robustness [3, 5–9]. In addition, EC promises a significantly reduced service response time, latency, bandwidth, and energy consumption, which justifies the fact that many real-time applications using CC have upgraded to

EC. We now highlight the importance, applicability, and research timeline of leading telecommunications enterprises in promoting EC applications in various sectors.

3.1 Huawei

Huawei Corporation is a leader in promoting EC and IoT applications in the field of digital transformation. Huawei introduced their so-called Edge-Computing-Internet-of-Things (EC-IoT) solution [42] at the Mobile World Congress 2017 (MWC 2017). This solution consists of a terminal communication module, an AR500 series router (EC IoT gateway), and an agile controller (Fig. 5). Thanks to such a solution, edge nodes can provide intelligent and low-latency computing services to IoT applications. According to Huawei, this solution can be used to realize real-time service analysis and intelligent making-decision and to manage tens of millions of terminals in the cloud, reducing operations and maintenance costs.

More recently, this technique has been implemented in smart lighting utilities, smart electric energy management, and smart transportation. It is anticipated that it will be the driving force behind the growth of intelligent energy as well as the industry of digital transformation.

3.2 Nokia

According to Nokia, EC will emerge as the primary driving force behind the digital transformation sector due to its capability to deliver highly dependable services and extremely low delay. The Multi-access Edge Computing (MEC) group at Nokia presented open

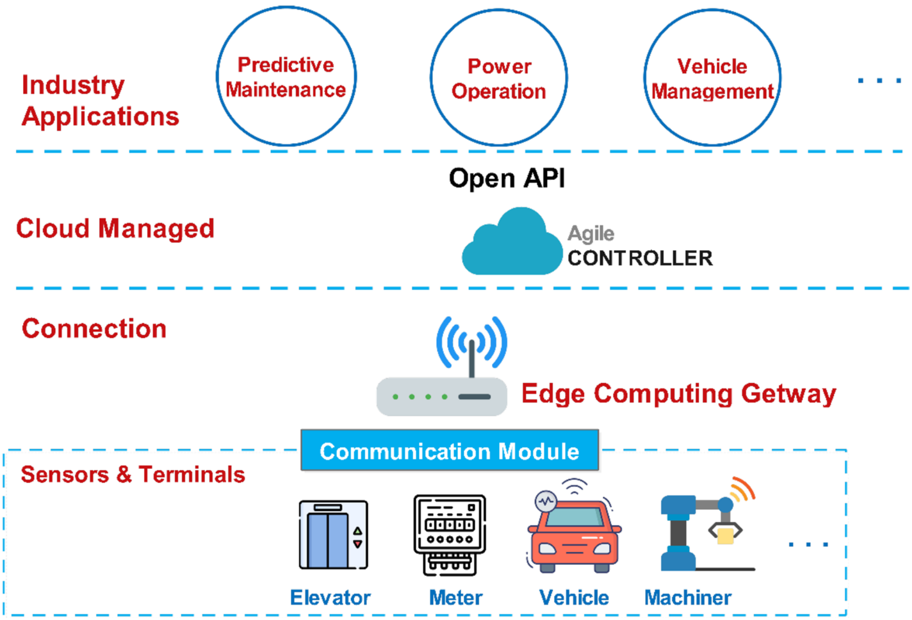

Fig. 5 Huawei's EC-based IoT architecture

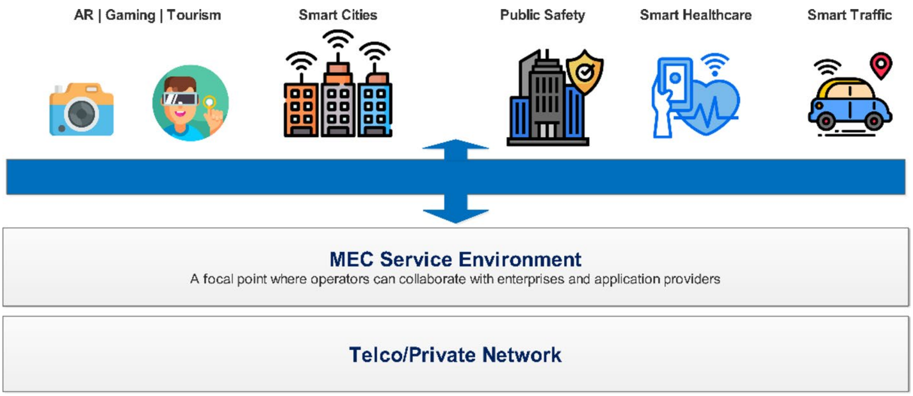

Fig. 6 EC service framework of the MEC group—Nokia

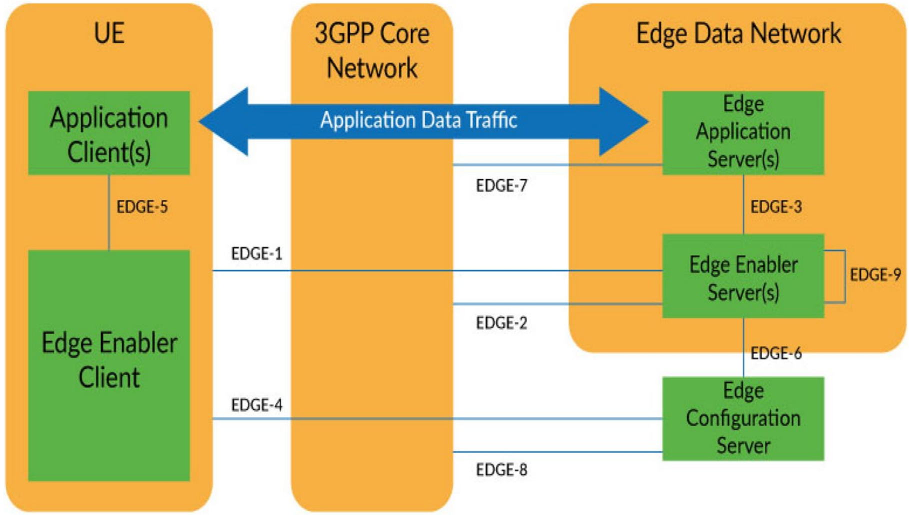

Fig. 7 EC architecture (3GPP TR 23.758) of Samsung

standards for EC in 2014 [43] (Fig. 6). This lays the groundwork for developing protocols that will integrate EC into 5G communications systems. In addition, it has campaigned to implement EC-IoT applications in various fields, including green energy, intelligent transportation, healthcare, and smart cities.

3.3 Samsung

According to Samsung, 5G EC opens the era of the next version of the Internet. In January 2020, the Service and System Aspects Working Group 6 of 3GPP (SA6) proposed a mobile EC architecture called TR 23.758 (Fig. 7) [44, 45]. This architecture introduced an Edge Enabler Client (EEC) and an Edge Enabler Server (EES) to allow the application client to discover the optimal edge application server. Besides, the Edge Configuration Server (ECS) provides the edge configuration information for the EEC so that the EEC can connect to the optimal EES. Relying on this architecture, the complete specification of an EC-based protocol suite is underway. Meanwhile, research on how to design AI-based EC-IoT applications that can optimize resources while reducing the response time is underway [46].

The survey results have demonstrated the potential great of edge computing. EC provides low latency services, energy-saving, bandwidth efficiency, and improved reliability by moving computational resources closer to the end-user device. Although many works remain to be done and EC architecture and standards are being shaped, right now, the visions of all leading telecommunications providers indicate EG is the future of the Internet. It allows realizing the story connecting the virtual world and the real world. The results also showed that EC would be the most attractive research topic for both academia and industry.

4 EC-Based IoT Applications

In recent years, a number of different EC-based Internet of Things applications have been proposed. These applications aim to reduce the service response time and the cost of computation. In the following, we will describe various typical domains, which are discussed in the sequel.

4.1 Augmented Reality (AR)

AR technology enables the realization of the interaction between the virtual and real worlds—Representative EC-based AR applications are described in Table 2 as follows.

In [47], Ren et al. proposed a new framework to support multi-user mobile AR applications based on EC (called Edge AR X5). This framework comprises a heuristic-based communication scheduling method and a motion-aware keyframe selection method. Based on it, an optimized EC mechanism that reduces the service response time is designed and validated by experiments, showing that the considered AR application can achieve multi-user interaction synchronization.

In [48], Al-Shuwaili and Simeone proposed a MEC-based resource allocation algorithm for AR applications, aiming to achieve efficient data processing while reducing the translation response time. In this scheme, a successive convex approximation function is utilized to optimize the energy consumption in the MEC. Simulation results are provided, showing that the proposed scheme can significantly reduce the cost of the system by optimizing communication and computing resources.

In [49], Ahn et al. proposed a mechanism for reducing energy consumption while enhancing the resolution for mobile AR applications based on MEC. In the proposed scheme, some analytical models for reducing the energy consumption of mobile AR services are proposed and validated by experiments.

In [50], the same authors proposed a centralized coordination schema that aims to guarantee QoS for mobile AR applications based on EC. In this scheme, a method for managing the resolution of images based on mobile AR devices and MEC is proposed and validated by experiments, showing an improved service response time, accuracy, and energy consumption compared to a few benchmark schemes.

Table 2 The EC- based AR applications

Ref.	Proposal	Purpose	Method	Accuracy	Delay	Energy	Security	Results
[47]	Edge AR X5	Design a collaborative multi-user framework for mobile web AR to optimize communication efficiency	Use the heuristic-based task scheduling and motion-aware keyframe selection mechanisms	✓	✓	✓	✗	Improve accuracy, latency and energy consumption
[48]	CSA	Optimize the energy consumption of mobile AR applications	Use successive convex approximation to computing resource allocation	✓	✓	✓	✗	Reduce sum-energy consumption around 63%
[49]	MAR-MEC schema	Design a computation offloading framework for mobile AR applications based on the mobile EC for energy-efficiency	Use the tradeoff approach between power and frame resolution for the computation offloading problem	✓	✓	✓	✗	Reduce energy consumption up to 73.64% with an accuracy loss of 1.6%
[50]	MAR-MEC algorithm	Design a performance and energy optimization framework for mobile AR applications	Use the trade-off approach between the accuracy, latency, and energy consumption to computation capacity allocation of EC	✓	✓	✓	✗	Improve the energy consumption, latency while minimum accuracy loss constraint
[12]	MEC-Based AR framework	Design a hierarchical architecture based on edge computing to improve latency and energy for mobile AR	Adding an edge layer to optimize the computation resource allocation, offload, and content-based image retrieval	✗	✓	✓	✗	Improve latency and energy compared to local and cloud computing

In [12], Ren et al. introduced an EC-based architecture for mobile AR applications, in which the edge layer sits between the user layer and the cloud layer. Based on this, some mechanisms are designed to reduce the service response time and energy consumption, namely a computation resource allocation strategy and an image retrieval method based on content. Experiment results showed that the proposed scheme yields reduced latency, energy consumption, and improved performance compared to a few benchmarks.

In [51], Qiao et al. proposed a comprehensive survey of mobile AR applications. In this analysis, the implementation technologies of mobile AR are categorized into hardware-based mobile AR, app-based mobile AR, and web-based mobile AR, then qualitatively compared, showing that:

1. Hardware-based mobile AR and app-based mobile AR applications have many limitations due to their dependencies on devices and compatibility between operating systems, platforms, and software.
2. Web-based mobile AR is favored as future popular technology.
3. MEC is recommended as a solution to reduce the load on EC servers (Fig. 8)

4.2 Smart Home and Smart Cities

One of the main challenges of smart cities is the massive amount of data generated from hundreds of millions of IoT devices in all domains to serve society, such as healthcare, urban transportation, home appliances of each smart home, and other IoT ecosystems to make a smarter city. An EC-based smart city architecture is depicted in Fig. 9—representative EC-based solutions for smart homes and cities are presented in Table 3 as follows.

In [52], Hou et al. argued for the deployment of edge servers as a means to support EC solutions for IoT applications in smart cities, to realize a smart green city by reducing the traffic flows on the backhaul systems while improving the bandwidth efficiency, QoS, and energy consumption.

In [53], Yu et al. proposed a technique to address the issue of limited edge server resources for smart home applications. An efficient method for offloading the data from smart houses to the cloud based on integrating EC and CC is proposed. This method relies on a relation between the computing resources lease cost of the edge or cloud server and the power consumption cost to perform a computing task. The experiment results showed that the proposed scheme could reduce user costs while guaranteeing the service response time.

An EC-based task scheduling technique for smart city applications was proposed by Deng et al. [54]. This algorithm makes advantage of redundant resources from vehicles of IoV in order to tackle the problem of restricted resources in EC servers. The results of the experiments demonstrated that the proposed method is superior to a few benchmarks in terms of the amount of time required to complete the work.

In [55], Liu et al. suggested an EC IoT-based energy management scheme for smart cities. Within this scheme, both EC and deep reinforcement learning are taken into consideration together in order to maximise the effectiveness of the system.

Khan et al. [56], following a trend that is similar, offered a comprehensive survey of EC-based plans for smart cities.

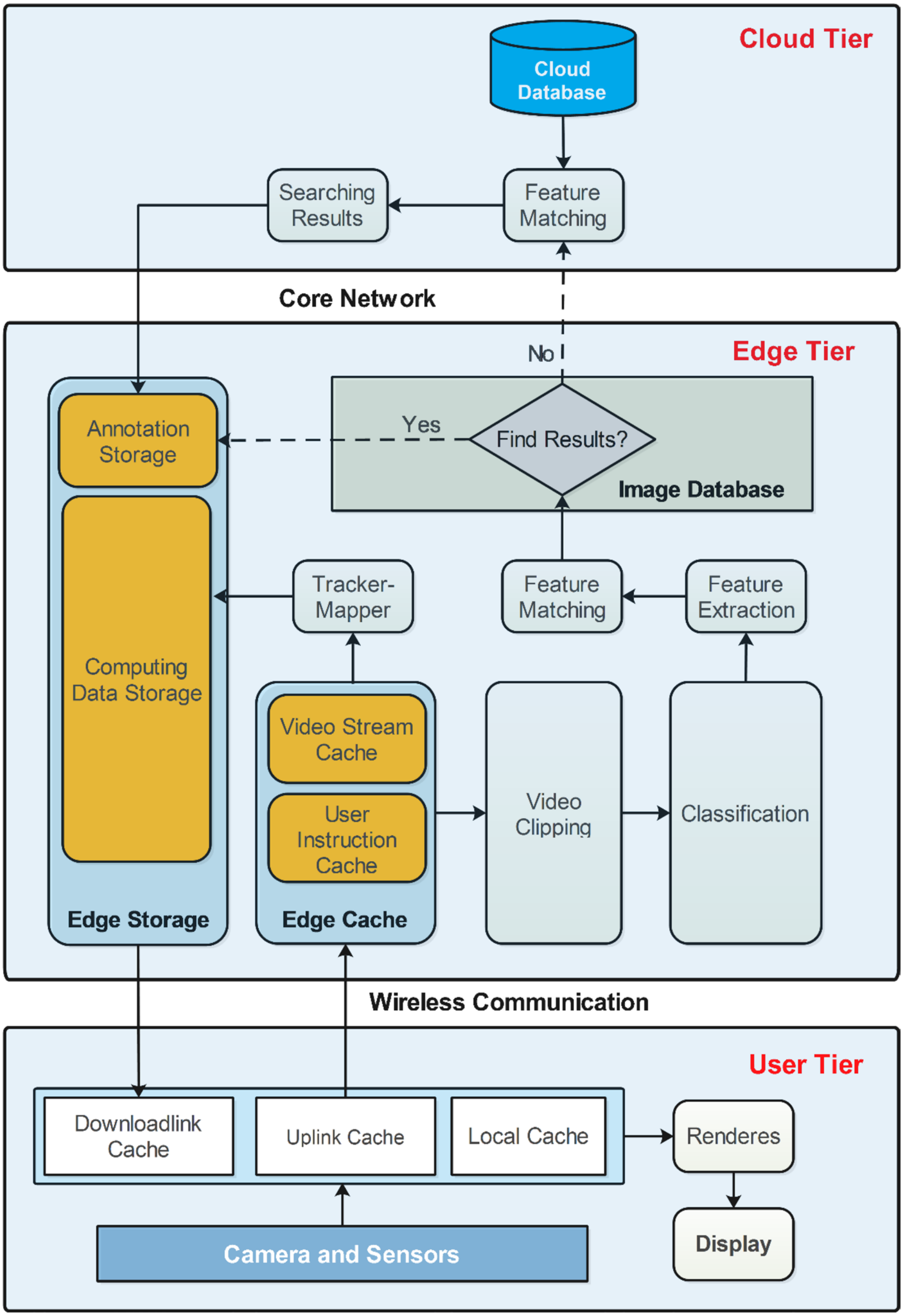

Fig. 8 MEC-based AR operation mechanism

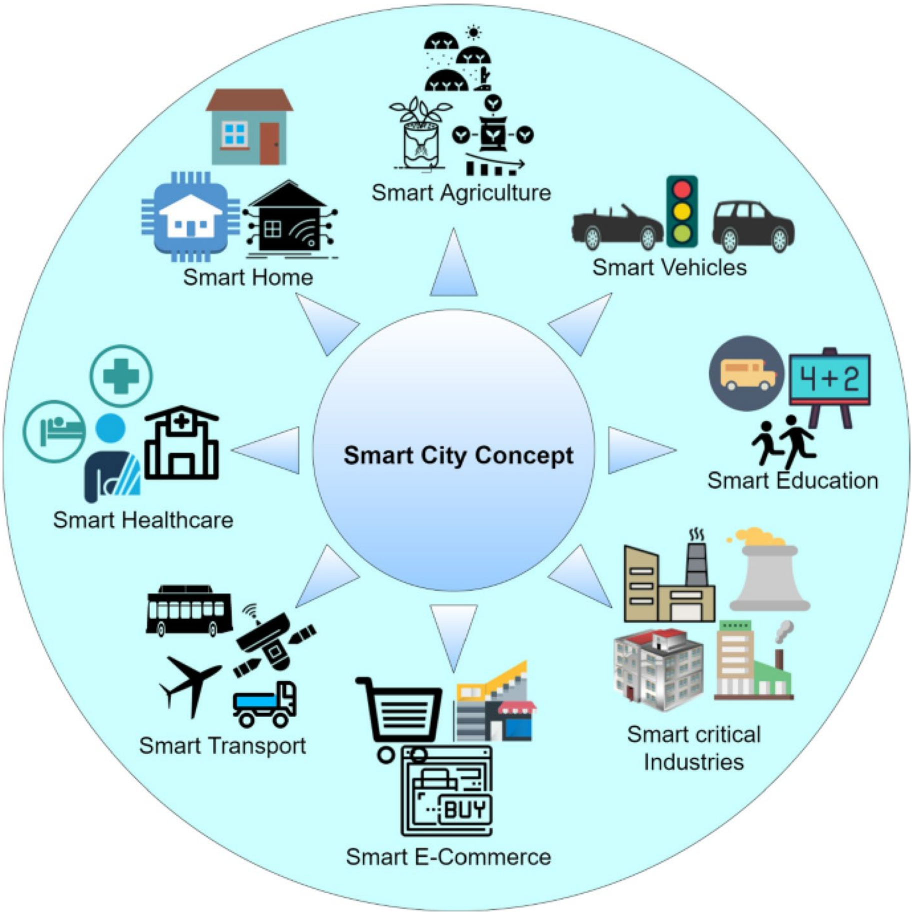

Fig. 9 EC-based smart cities architecture

4.3 Intelligent Transportation System

In the field of transportation, there has been discussion regarding the implementation of cloud-based vehicle management software, sometimes known as cloud-assisted VANETs. EC is robustly motivated (Fig. 10), which is provided in Table 4 in the following manner. This is done so that real-time reaction capability can be realized.

In [57], Cui et al. proposed a cooperative downloading EC-based scheme that aims to enhance the load efficiency and privacy preservation of VANETs. The proposed scheme is based on the encrypted request analysis of vehicles, and the road site units (RSUs) are utilized by the vehicles to achieve common data sharing between the cloud servers and the edge servers.

In [58], Huang and Lai proposed a delay-aware EC-based data offloading method based for VANETs, which enables a vehicle that has an indirect connection to the RSUs to perform data offloading through a limited k-hop. Here, a MEC-based model is utilized to check the status of an offloading path based on the periodically updated information from vehicles that are used to construct the possible backup paths.

Table 3 The EC-based smart home and smart cities

Ref.	Proposal	Purpose	Method	Accuracy	Delay	Energy	Security	Results
[52]	GSVNE	Design a framework to embed the virtual network aims to support EC for smart cities	Embed edge devices onto the common WMN and use heuristic algorithm to optimize collaborative edge computing	✗	✓	✓	✗	Improve virtual networks embedding and backup resource sharing
[53]	Advanced B&B algorithm	Design a computation offloading schema based on EC to optimize energy consumption and cost for smart home	Use the learning approach to improve the B&B algorithm to solve the formulated MILP problem	✓	✓	✓	✗	Improve latency while guaranteeing constraints on the cost and energy efficiency
[54]	ADMM-based algorithms	Design the task scheduling schema for delay-sensitive applications based on MEC	Use the offloading strategy to IoV and develop four evolving ADMM-based algorithms	✗	✓	✓	✗	Improve the latency and offloaded tasks up to 89% and 40%, respectively
[55]	DRL-based scheme	Design an energy management system based on EC-IoT for smart cities	Use an energy scheduling scheme with deep reinforcement learning	✗	✓	✓	✗	Improve energy cost and delay compared to existing schemes

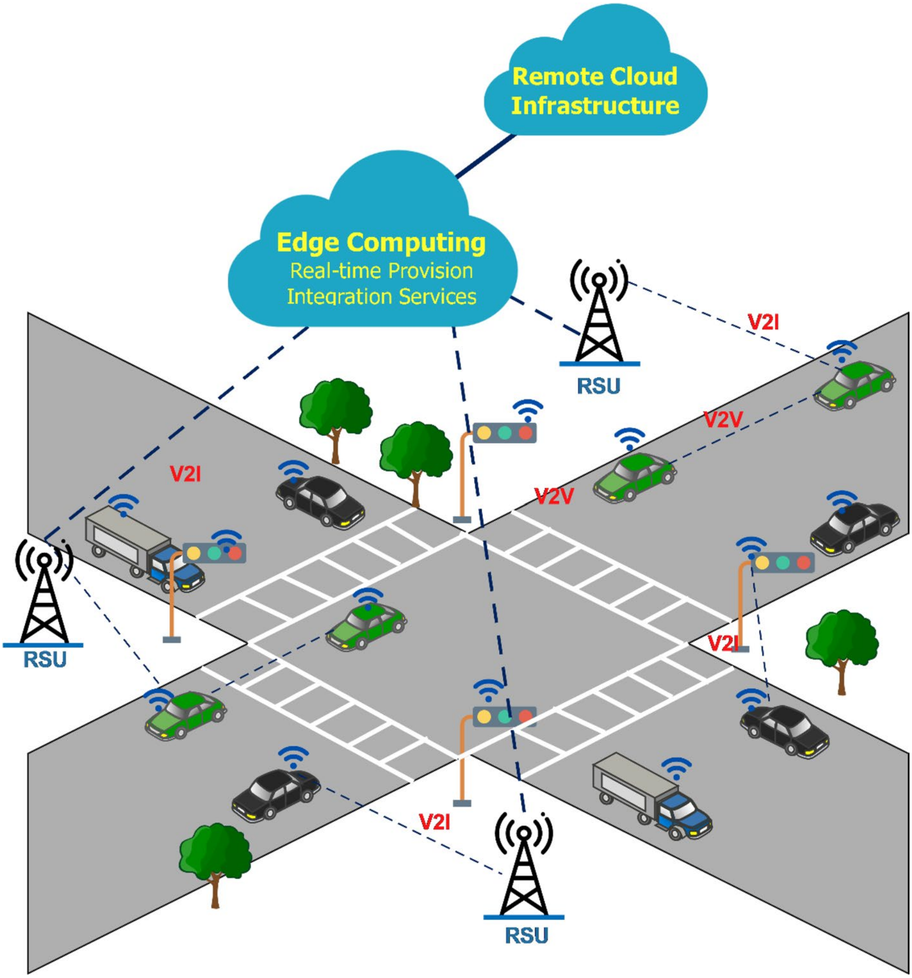

Fig. 10 EC-based ITSs systems

In [59], Deng et al. proposed a multi-hop offloading scheme that aims at reducing the service response time and computing cost for EC-based VANETs applications. This scheme proposes a model to determine real-time multi-hop path reliability.

In [60], Cui et al. proposed an EC-based message authentication scheme for ensuring communication security for VANETs. In this scheme, the message is authenticated at the EC server when each vehicle is in the coverage area of the RSUs.

4.4 Smart Healthcare

When it comes to healthcare, deploying IoT presents significant issues, chief among them being the management of data and the making of decisions in emergency situations. applications for the Internet of Healthcare Things that are based on EC have been presented as a solution to this difficulty (Fig. 11). These applications are known as EC-based IoHT. The

Table 4 The EC-based intelligent transportation systems

Ref.	Proposal	Purpose	Method	Accuracy	Delay	Energy	Security	Results
[57]	SEDD Schema	Design an efficient and secure downloading scheme for EC-IoV	Use lightweight cryptography methods and the fuzzy-logic-based election strategy to select collaborative vehicles	✗	✓	✗	✓	Improve network performance and can limit multiple security attacks
[58]	EC-based V2V2I offloading schema	Design a delay-constrained k-hop-limited offloading framework for VANET	Optimize the VANET data offloading by selecting paths with constraints of quality, lifetime and delay	✗	✓	✗	✗	Improve the path's lifetime and offloading rate is higher 3.4 times than existing solutions
[59]	MHVA schema	Design a multi-hop VANET data offloading schema to improve delay and cost	Use the delay-aware multi-hop reliability model and the binary search algorithm to optimize offloading tasks	✗	✓	✓	✗	Improve offloading task's performance, delay and cost
[60]	Message-Authentication Scheme	Design an efficient message authentication Scheme based on EC for VANETs	Use fuzzy logic and binary search to authenticate messages and share the authentication tasks of all vehicles in RSUs	✗	✓	✗	✓	Improve redundant authentication, security and network performance

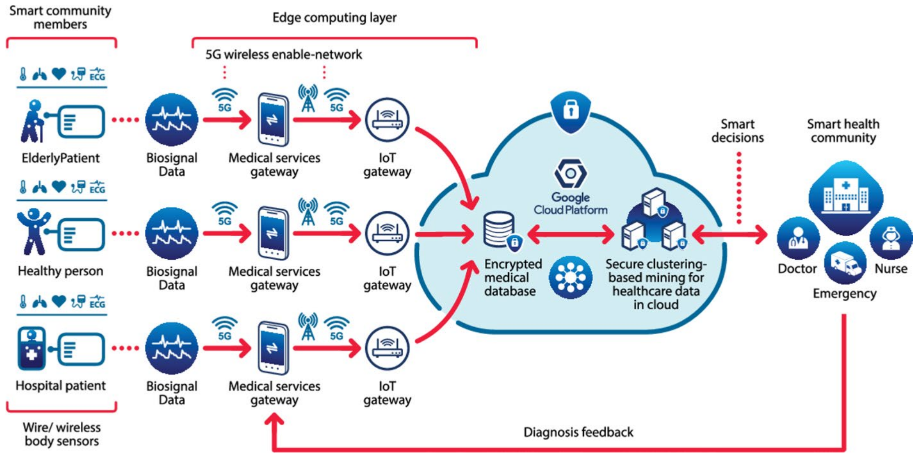

Fig. 11 EC-based IoHT architecture

following Table (i.e. Table 5) provides an explanation of some representative EC-based IoHT schemes.

In [61], Li et al. proposed an EC-based security framework for patient healthcare, which relies on software-defined networks (SDN). In this scheme, each healthcare IoT device is authenticated by the edge server before it can connect to the system, and the SDN controller supports the EC server load balancing.

In [62], Abdellatif et al. proposed a framework for medical data processing that is based on the integration of EC and blockchain. An optimal monitoring patient scheme is proposed to identify the patient's unusual symptoms based on blockchain in such a way that the service response time and computing costs are reduced.

In [63], fully homomorphic encryption is proposed in the scheme introduced to secure patient data.

In [64], Pace et al. proposed an EC-based architecture for innovative healthcare IoT applications, which consists of a tiny mobile client module and an edge gateway supporting multi-radio and multi-technology communication to collect and process data from different entities locally.

In [65], Amin and Hossain proposed a comprehensive survey of EC-based healthcare IoT applications, along with AI-based data classification schemes that can be utilized to track the status of patients' treatment in a healthcare environment.

4.5 Smart Manufacturing

The fourth industrial revolution (known as Industry 4.0) has resulted in the development of EC-based Internet of Things applications (Fig. 12). These applications have the potential to improve labor productivity and production cost, as well as reduce backhaul network overload. The following is a presentation of some representative uses of apps based on EC that are used in IoT.

Usman et al. [66] proposed an EC-based framework composed of edge servers that use a lightweight aggregation technique to reduce the data size and enhance the data privacy and an efficient offloading process to carry the data from the edge to the cloud while enabling

Table 5 The EC-based smart healthcare

Ref.	Proposal	Purpose	Method	Accuracy	Delay	Energy	Security	Results
[61]	SDN-based EC-IoHT framework	Design a secure framework for SDN-based edge computing in IoT-enabled healthcare system	Use a lightweight scheme to authenticate and patient data offloading to SDN-based EC	✗	✓	✗	✓	Improve performance metrics such as latency, delivery ratio, throughput, and overhead
[62]	MEdge-Chain framework	Design a framework to process the big data problems in medical based on EC and blockchain	Use an patients monitoring scheme at the edge to fast response for urgent scenarios and blockchain-based model to optimize	✗	✓	✗	✓	Improve the overall system performance
[63]	EoT framework	Design a patient data secure framework for IoHT applications	Use the fully homomorphic encryption algorithm to encrypted patient data and clustering techniques to optimize system	✓	✓	✗	✓	Improve response time while achieving accuracy and security
[64]	BodyEdge	Design a software framework for IoHT based on EC to reduce the data traffic toward the Internet	Establish a real testbed implementation to consider real performance metrics under different conditions	✗	✓	✗	✗	Improve processing time compared to cloud comping

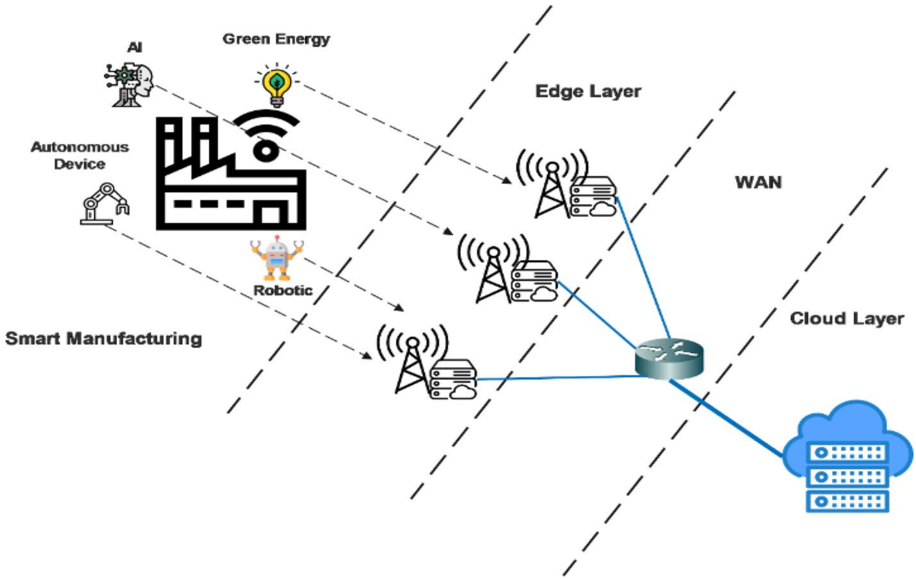

Fig. 12 EC-based IIoT applications

the edge servers to detect the presence of moving objects in the data based on the use of a convolutional neural network.

Jiang et al. [67] proposed an efficient scheme to deploy EC servers while improving smart manufacturing applications' latency and computational cost. Their proposed method uses a K-Means clustering algorithm to determine the location of the edge servers.

Following a similar trend, Qi and Tao [68] proposed an all-in-one computing architecture for smart manufacturing.

Li et al. [69] proposed a hybrid computing framework, along with an efficient resource scheduling algorithm, to help reduce the service response time of real-time intelligent manufacturing applications. Similarly, Lee et al. [70] proposed an EC-based and blockchain-based smart manufacturing scheme that can be used to achieve a low computation time of edge computing when the computing tasks are distributed.

Moreover, Qiu et al. [71] introduced a complete picture of EC-based IIoT architecture, and some typical IIoT application scenarios are presented and validated. Besides, some discussion on the state-of-art routing algorithms, scheduling algorithms, and data analysis techniques for EC-based IIoT based on the architecture as mentioned above is presented.

4.6 Discussions

One of the main reasons for moving to the edge is minimizing service response time. The survey results indicated the huge potential of edge computing for a series of essential fields to serve humanity. In this section, we have considered recent studies of edge computing and divided these works into five main categories based on their goals.

Survey results showed that recent advances in augmented reality (AR) applications require truly real-time service response times [12, 47–51]. Conventional computational techniques such as CC cannot meet the increasing demands of AR processing. Another trend is IoT-based smart home/city applications. One of the challenges for these applications is low latency. Therefore, intelligent IoT applications based on EC for smart homes/cities are inevitable.

In the transportation domain [57–60], real-time applications for warning collision of autonomous vehicle control are increasingly popular. Solving challenging problems related to real-time intelligent transportation systems based on EG is possible.

EC architectures play an essential role in e-health applications [61–65]. It can save many lives. As EC ensures faster response and higher throughput, decision-making becomes faster and easier in e-health applications.

The IoT applications for smart industry are inevitable to realize a green factory [66–71]. With the development of the automation and robotics industry, IoT applications based on edge computing will be able to improve labor productivity, reduce labor, increase production efficiency, and save energy.

Much work still needs to be done to apply edge computing to all domains. Right away, we can imagine IoT applications based on edge computing as an inevitable development trend to meet the requirements of humanity better.

5 Challenges and Open Research Issues

In light of the above discussions, it is abundantly evident that there is a desire for an EC-based architecture that is strong, reliable, and flexible to maximize the performance of the network systems from the point of view of operational efficiency while simultaneously taking into account an efficient method of cost management. The following is a list of potential difficulties and areas of research that could be pursued in the field of EC in the future:

- *Selection of edge device*: The selection of edge devices for performing EC is crucial in various network situations [72]. For instance, in IoV networks, the EC device can be a vehicle or a dedicated edge server. The computation will be distributed to the selected edge devices. As a result, the implementation costs of these devices will increase. On the other hand, if the network has a dedicated edge server, it may face some challenges in handling the growing demands of the terminals. Therefore, the application needs to incorporate an efficient resource management scheme to manage both the edge servers and the connected devices for an efficient EC system.
- *Computation offloading*: The computation offloading between the edge devices is also a challenging problem [73]. In large-scale IoT networks, computations on several edge nodes need to be offloaded in a distributed manner. Without the use of a distributed scheme to achieve a such task, the workload will increase and even overload in some nodes. The making policy combined with an effective compute coordination and management schema is therefore required for a cost-efficient and saving energy workload coordination system.
- *Tasks allocation between the Cloud and the Edge*: Due to certain limitations on the abilities of computing and storage of EC, some services and computations are required to invoke the cloud services to increase the reliability of the systems. A task scheduling scheme needs to be integrated into EC to appropriately allocate the tasks between the edge and the Cloud in order to optimize the system's performance [74, 75].
- *Guarantee QoS*: Efficient network layer routing protocols and standards must be designed for EC systems to ensure minimal service response times [76].

- *Connection management*: Highly mobile IoT networks such as MANETs and VANETs will frequently face loss of connectivity [77]. As a result, data processing and decision-making can be affected by significant latency. Therefore, reliable collaboration schemes should be incorporated into the EC devices to solve the issue of loss connectivity effectively.
- *Privacy and Security*: Moving the computations into the edge network may lead to the vulnerability of the information to various types of attacks. In this sense, encryption algorithms are required for EC systems in order to handle security issues and prevent attacks [78, 79]. Some varying methods for securing the edge network against security attacks into sensors, IoT gateways, network operating systems, deployment environment, and sharing resources of edge servers are in detail introduced in [80–83].

In spite of a number of obstacles that still need to be overcome, we believe that, in the future, edge computing will be effectively incorporated into intelligent IoT systems in the majority of fields in order to improve the quality of living. In the future, with the development of lightweight AI techniques and federated learning techniques, the trend of embedding AI into the edge of the network will be actively driven towards constructing intelligent edges. This will take place as a direct result of the creation of intelligent edges (Table 6).

6 Conclusion

The introduction of 5G technology paves the way for the Internet of Things (IoT) concept and makes it possible to provide services with exceptionally low latency. The Internet of Things (IoT) is a collection of technologies that enables individuals, objects, platforms, solutions, and software to communicate and collaborate via the internet. In spite of the many obstacles it faces, the Internet of Things has already proven enormous abilities and capabilities, and it has the potential to make revolutionary contributions to the Internet in the future. Various computing technologies have been born to provide optimal computing services for IoT networks. CC is a core computing technology that has been around for decades, enabling the provision of computing resources and services for IoT over the Internet. The robustness, efficiency, and reliability make CC will continue to be one of the irreplaceable core technologies in next-generation networks. One limitation of CC is storing and processing data on Cloud, so it has a high service response time and is infeasible for real-time interactive services. To address this issue, FC and EC have recently evolved by pushing the Cloud's capabilities to the edge of the network. EC and FC technologies can provide flexible resources that enable distributed data processing and remove the limitations of traditional centralized architectures. The survey results have demonstrated that EC and FC-based IoT applications improved reliability and service response time compared to CC-based applications. However, toward the provision of effective real-time service, EC technology needs to continue to be researched and improved to be suitable for different IoT scenarios based on the increasing requirements of humans. We have high hopes that this work will serve as a guide for future research in edge computing for IoT applications that require real-time processing.

Table 6 The EC-based smart manufacturing

Ref	Proposal	Purpose	Method	Accuracy	Delay	Energy	Security	Results
[66]	RaSEC framework	Design a reliable and secure framework based on multi-level EC for IIoT applications	Use the aggregation, clustering techniques and CNN to reduce the size of the generated data and security	✗	✓	✗	✓	Improve performance metrics compared to existing frameworks
[67]	IKCD algorithm	Design an efficient edge nodes deployment algorithm for IIoT	Use the k-means clustering algorithm to the optimal number of edge computing node	✗	✓	✓	✗	Improve delay and computing cost
[68]	Multiple Level architecture	Design the hierarchy computing architecture based on the edge, fog and cloud for IIoT	Integrating edge, fog and cloud into the digital twin shop-floor framework	✗	✓	✓	✗	Improve the overall system performance
[69]	SAE_CEC framework	Design a resource scheduling schema to guarantee the real-time EC-IIoT	Use AI, greedy algorithm and threshold strategy to optimize tasks scheduling schema	✗	✓	✓	✗	Improve energy consumption, computing cost and satisfaction degree
[70]	EC-Chain-Smart framework	Design a smart manufacturing framework based on EC and blockchain for IIoT	Integrate EC and blockchain into an advanced manufacturing system and use the swarm intelligence to optimize the computational task assignment	✗	✓	✓	✓	Improve delay, energy consumption, computing cost compared to existing solutions

Appendix

Acronyms used in this paper

Acronym	Meaning	Acronym	Meaning
AR	Augmented reality	EG	Edge computing
AI	Artificial intelligence	M2M	Mechanism to mechanism
AODV	Ad-hoc on-demand distance vector	MANET	Mobile ad hoc networks
API	Application programming interface	MCC	Multi-cloud computing
D2D	Device to device	MEC	Mobile edge computing
DDoS	Distributed denial of service	PHM	Prognostics and health management
DoS	Denial of service	QoS	Quality of service
IIoT	Industrial Internet of Things	RSU	Road side unit
CC	Cloud computing	SaaS	Software as a service
GIS	Geographic information systems	SDN	Software-defined networking
GPRS	General packet radio service	FC	Fog computing
GPS	Global positioning system	UAV	Unmanned aerial vehicle
IaaS	Infrastructure as a service	V2I	Vehicle to infrastructure
IoT	Internet of Things	V2V	Vehicle to vehicle
IoVs	Internet of vehicles	VANET	Vehicular ad hoc networks
EC	Edge computing		

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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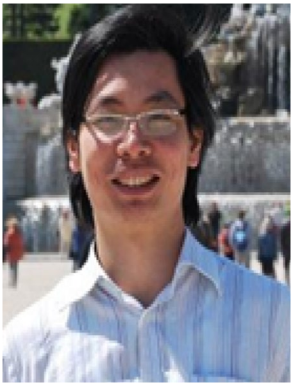

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