The Role of Edge Computing in Internet of Things

Najmul Hassan, Saira Gillani, Ejaz Ahmed, Ibrar Yaqoob, and Muhammad Imran

The authors investigate, highlight, and report on recent advances in edge computing technologies with respect to measuring their impact on IoT. They establish a taxonomy of edge computing by classifying and categorizing existing literature, and by doing so, they reveal the salient and supportive features of different edge computing paradigms for IoT.

Abstract

Remarkable advancements in embedded systems-on-a-chip have significantly increased the number of commercial devices that possess sufficient resources to run full-fledged operating systems. This change has extended the potential of the IoT. Many early IoT devices could only collect and send data for analysis. However, the increasing computing capacity of today's devices allow them to perform complex computations on-site, resulting in edge computing. Edge computing extends cloud computing capabilities by bringing services close to the edge of a network and thus supports a new variety of services and applications. In this work, we investigate, highlight, and report on recent advances in edge computing technologies with respect to measuring their impact on IoT. We establish a taxonomy of edge computing by classifying and categorizing existing literature, and by doing so, we reveal the salient and supportive features of different edge computing paradigms for IoT. Moreover, we present the key requirements for the successful deployment of edge computing in IoT and discuss a few indispensable scenarios of edge computing in IoT. Several open research challenges are also outlined.

Introduction

Billions of smart devices can now connect to the Internet in the form of the Internet of Things (IoT) due to advancements in networking technologies [1]. According to a Cisco report, these devices will generate 507.9 ZB of data by 2019. Data generated by IoT-devices are essential for organizations that are interested in improving their productivity and revenues. However, management and analysis of such large amounts of data are cumbersome and challenging for organizations that rely on conventional computing paradigms. Edge computing is gaining popularity in this context because IoT is becoming common in processing data on the edge of networks [2].

Given that data are rapidly produced at the edge of networks, dealing with these data at the edge of the network would be effective. Several approaches, such as cloudlet [3], fog computing [4], and mobile edge computing (MEC) [5], provide complementary solutions to cloud computing to reduce data processing on the network edge. In short, edge computing is a general term that represents fog computing, MEC, cloudlets, and micro clouds. Storage, computing, and power are regarded as being on the edge of networks to increase availability, reduce latency, and eventually overcome cloud computing issues [6]. Edge computing facilitates the processing of delay-sensitive and bandwidth-hungry applications near the data source [7]. Figure 1 illustrates a layered model for cloud edge-based IoT service delivery.

Although several studies have been conducted on different edge computing paradigms (i.e., fog, edge, and cloudlets) [8][9][3], no study has examined all of the previously mentioned edge computing paradigms in terms of IoT. Research in this direction should be conducted because of the significance of the emerging paradigm of edge computing and its role in the success of IoT. This study highlights the role of edge computing in the IoT context.

The contributions of this work are manifold:
- We investigate, highlight, and report recent premier advances in edge computing from the IoT perspective.
- We categorize and classify edge computing literature by devising a taxonomy.
- We outline key requirements for the successful deployment of edge computing in IoT.
- We present a few indispensable scenarios of edge computing in IoT.
- We identify and elaborate several open research challenges.

These contributions are discussed separately in the following sections with the concluding remarks provided in the final section.

Taxonomy of IoT-Based Edge Computing

Figure 2 depicts a taxonomy of IoT-based edge computing that considers particular features, such as wireless network technologies, computing nodes, computing paradigms, service level objectives, major enablers, data types, applications, and attributes.

Network Technologies

IoT devices send collected data to a locally available edge server for processing. These devices communicate with edge computing platforms through either wireless networking technologies, such as WiFi and cellular networking (e.g., 3G, 4G, and 5G), or wired technologies, such as Ethernet. These network technologies vary in terms of data rate, transmission range, and number of

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supported devices. Wireless networks provide flexibility and mobility to users who execute their applications on the edge server. However, wireless network technologies are not as reliable as wired technologies.

Computing Nodes

IoT devices have limited processing capabilities, which make them unsuitable for computation-intensive tasks. However, resource-constrained IoT devices can augment their capabilities by leveraging the resources of edge servers. The edge computing paradigm relies on different computational devices to provide services to IoT users. These computational devices are the core element of IoT-based edge computing. Computing nodes include servers, base stations (BS), routers, and vehicles that can provide resources and various services to IoT devices. The use of these devices is specific to the computing paradigm.

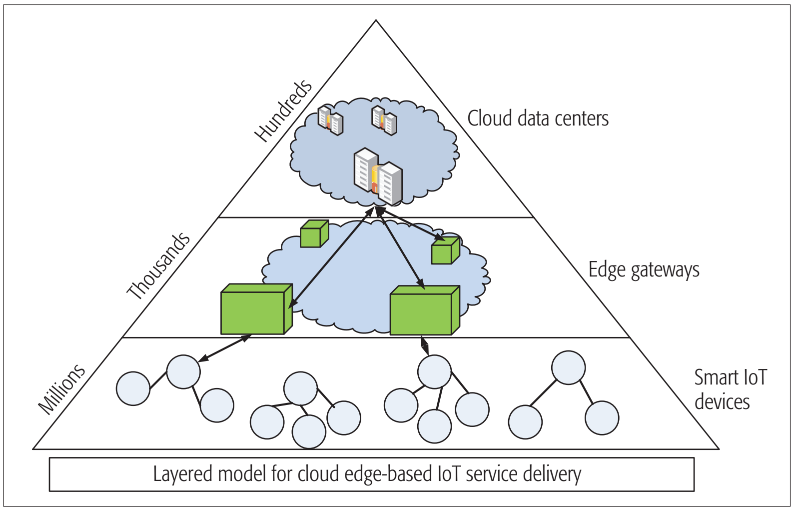

Figure 1. Layered model for cloud edge-based IoT services delivery.

Computing Paradigms

Various computing paradigms are used in IoT to provide different services depending on diverse application requirements. These paradigms can be categorized into cloud computing, edge computing (i.e., MEC, fog, and cloudlet), mobile ad hoc cloud (MAC), and hybrid platforms. Cloud computing is a centralized computing infrastructure that aims to provide interruption-free access to powerful cloud servers. These servers can rapidly process large amounts of data upon receipt from remote IoT devices and send back the results. However, real-time delay-sensitive applications cannot afford long delays induced by a wide area network. Continuous transmission of voluminous raw data through unreliable wireless links may also be ineffective. By contrast, edge computing is a decentralized computing platform that brings cloud computing capabilities near IoT devices, that is, the network edge. An important type of edge computing platform is MEC, which brings cloud computing capabilities to the edge of a cellular network [10]. Computational and storage services in MEC are provided at the BS. Unlike MEC, fog computing employs local fog nodes (i.e., local network devices such as a router or switch) available within a limited geographic region to provide computational services. Fog computing is considered a premier technology following the success of IoT. Cloudlet is another form of edge computing, in which delay-sensitive and computation-intensive tasks from IoT devices are performed on a server deployed in the local area network. Unlike cloud and edge computing platforms that rely on infrastructure deployment, MAC capitalizes the shared resources of available mobile devices within local proximity to process computation-intensive tasks. Cloud and edge computing are used together in hybrid computing. Such infrastructure is usually adopted when we require the large computing resources of cloud computing but cannot tolerate the latency of the cloud. Variants of edge computing can be employed in such applications to overcome the latency problems of cloud computing.

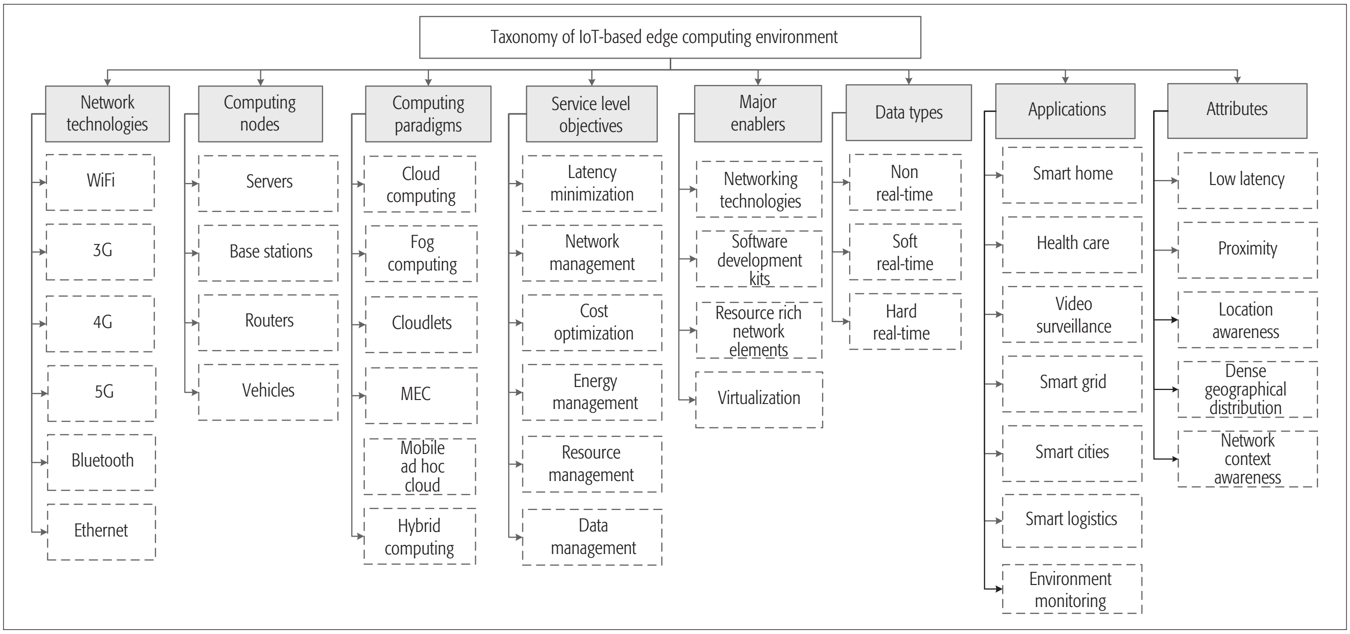

Figure 2. Taxonomy of IoT-based edge environment.

One of the primary reasons for edge computing is that its precursor (i.e., cloud computing) was unable to fulfill certain requirements of applications dealing with various data types. These data types can be broadly categorized based on delay sensitivity. Hard real-time data cannot tolerate any delay at all, whereas soft real-time data can afford several bounded delays. Delay-tolerant applications can be classified as non-real-time.

Service Level Objectives

The different service-level objectives for edge computing in the context of IoT are as follows:

Latency Minimization: High latency has become a crucial problem for IoT-based smart applications. An alternative platform, such as edge computing, that can guarantee timely delivery of services is required to fulfill the quality of service (QoS) requirements of delay-sensitive IoT applications (e.g., smart transportation and online gaming).

Network Management: A number of phenomena, such as inadequate virtualization support, lack of seamless connectivity, and inefficient congestion control, degrade the overall network performance. Therefore, efficient usage of network resources in edge computing is vital for IoT.

Cost Optimization: The use of an adequate platform for enabling edge computing necessitates extensive infrastructure deployment that involves substantial upfront investment and operational expenses. Most of these expenses are related to network node placement, which requires deliberate planning and optimization to minimize the overall cost. Deployment of an optimal number of nodes at appropriate positions can significantly reduce capital, and optimal arrangement of edge nodes can minimize operational costs.

Energy Management: Energy management is also an important objective of IoT-based edge computing. Subscribers need to have strict control over power management. Energy-efficient IoT devices and applications are desirable in edge computing. According to a study, one trillion IoT nodes need sensing platforms that support various applications using power harvesting to ensure scalability, reduce costs, and avoid frequent battery replacement.

Resource Management: Optimal management of computational resources is crucial in obtaining service-level objectives. Appropriate resource management includes coordination of resources, estimation of available resources, and proper allocation of workload.

Data Management: The large number of IoT devices at present are expected to generate large amounts of data that need to be managed in a timely manner. Efficient and effective data management mechanisms are desirable in edge computing. Transmission and aggregation of IoT-generated data are important concerns in data management.

Major Enablers

The driving forces behind the success of edge computing are different types of technologies. Emerging network technologies, such as 4G and cognitive radios, are vital in fulfilling the requirements of delay-sensitive applications. These communication technologies are used in edge computing for device-to-device and device-to-edge server communication. Software development kits with appropriate application programming interfaces assist in developing and integrating new compatible applications and customizing existing applications and services. Cloud computing utilizes powerful servers for computation-intensive jobs; the same idea has been envisioned to bring cloud capabilities to the edge devices of networks to minimize latency. Such servers can help offload computations from small resource-limited mobile devices. Virtualization is another emerging enabler that allows for the creation of logically isolated resources using similar physical resources. Virtualization is used by different virtual machines for a number of cloud computing services at the edge of networks.

Data Types

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Applications

A number of applications currently use edge computing.

Smart Homes: Smart homes equipped with a number of IoT devices belong to an emerging application domain of edge computing. The IoT applications envisioned for the monitoring and metering of smart homes will allow subscribers to obtain automated and precise readings of different meters and access invoices accordingly without delay [11]. These IoT applications are designed for remote monitoring and metering of various utilities, such as water, electricity, and gas. The data collected from IoT devices can be transmitted to an edge server for processing instead of sending them to the cloud, which can lead to real-time data analytics.

Healthcare: Edge computing has been successfully implemented in recent years and is now commonly used in different medical appliances. Edge computing enables end users to monitor and react to health-related data generated by various servers. Different architectures that use cloud, fog, and edge computing have been proposed to reap the benefits of collaborative computing paradigms. Healthcare applications are usually considered delay-sensitive applications in IoT. Initially, cloud computing was employed for healthcare applications but was not highly successful because of latency issues. The introduction of edge computing resolved these issues and made cloud computing realistic for healthcare IoT applications.

Video Surveillance: Edge computing is currently used for smart video surveillance in different sectors of life, including domestic security and anti-terrorism. Different video contents are obtained and shared from different video cameras and video sensors. These videos are stored and efficiently managed for further processing. Different security applications can automatically extract the required data from the archive of stored video contents. Video surveillance is usually performed with the collaboration of edge and cloud computing.

Smart Grid: Edge computing and IoT are utilized in smart energy management. Such applications automatically observe consumption and distribution patterns. Contributing nodes are used by edge computing for real-time sensing and processing. Cloud computing is also utilized as a collaborative tool to make such applications robust and dynamic for large amounts of data in the deployment of wide area energy networks.

Meanwhile, edge computing is used for agility and load distribution.

Smart Cities: Edge computing in IoT can assist in designing smart cities. Edge computing can be effectively used in lighting control systems of streets and roads, air and water quality monitoring, exploring emergency routes in cases of disasters or accidents, and automatic watering of different gardens in cities.

Smart Logistics: Edge computing in the IoT environment helps conventional logistics and offers new fascinating possibilities that make the flow management of things automated and easy. This system enables a smooth flow of transactions between the product manufacturer and end consumer in terms of cost and time. Apart from these applications, interested readers may refer to the work of J. Pan and J. McElhannon presented in [12] that discussed several edge cloud opportunities for IoT applications.

Environment Monitoring: The collaborative use of edge and cloud computing in IoT can enhance the quality of existing monitoring systems. An automated system will collaborate with sensors and actuators. Applications have been developed for monitoring critical entities that exert a major effect on the environment. These entities include monitoring of gas concentration in air, water levels in lakes and underground, lighting conditions, soil humidity, and changes in land position. Environment monitoring is crucial in many fields, such as agriculture, forestry, and food safety.

Attributes

Edge computing is characterized by certain attributes, such as low latency, proximity, location awareness, dense geographical distribution, and network context information. Mobile operators, content providers, and application developers can utilize these favorable attributes in their corresponding business domain by using them to enhance the quality of experience for mobile broadband subscribers.

Key Requirements of Edge Computing in IoT

Successful deployment of edge computing in the IoT environment has certain requirements. These requirements are desirable features for the smooth functionality of any edge computing application or service. A system is considered user-friendly and feasible when it fulfills the requirements enumerated below. Notably, several of the requirements are conflicting. Therefore, application designers must maintain good balance among all of them by considering the environment.

Latency: Delay is one of the basic reasons for preferring edge computing over cloud computing in delay-sensitive applications. Many modern-day applications are delay-sensitive and perform computation on real-time data. Bringing many services and applications from the cloud to the edge of the network drastically reduces the latency of IoT applications. Low latency enables real-time communication, which leads to improved decision making in IoT-based edge computing.

Reliability: Edge computing is envisioned to be used in almost every field of life. Edge computing plays several roles in critical fields where it is used, such as healthcare and banking, which require a reliable system. Reliability is a critical requirement of any edge computing system to make the system a practical choice for real-life IoT applications of smart computing.

Mobility Support: In IoT, different types of devices are utilized for different architectures. Mobility techniques are frequently used in different cloud and edge architectures and are gaining popularity in applications employed in hybrid infrastructures. In infrastructures with mobile devices, mobility control is always an issue. Meanwhile, mobility support is mandatory for certain edge applications. The provision of mobility is important for direct communication between different modules and for message exchange among different mobile devices.

Real-Time Interactions: Real-time applications are gaining popularity in all fields of communication. In IoT, certain edge applications require real-time interaction. Other options, such as batch processing, are available but may not be suitable for many modern applications in IoT that use edge computing, such as healthcare systems and many other critical and time-sensitive applications.

Security: Security is one of the core requirements of all modern systems. The use of edge computing in IoT is subject to developing secure systems and applications. The security requirement is almost undefined in cloud computing; therefore, cloud services are vulnerable to certain types of attacks. Cloud computing services are easy targets of security threats and data breaches because of their specific structure. However, in edge computing, security should be well defined and clearly implemented. Therefore, improved data security can be provided because client data are aggregated at certain access points placed close to the end user.

Interoperability: Interoperability is a key requirement in information technology and telecommunication. Applications and services developed for IoT-based edge computing must be interoperable to ensure compatibility with other applications and hardware components. Several of the key requirements above are mentioned in the perspective of IoT. This set of requirements is not a full and complete list. Other requirements may be applied in different applications.

Role of Edge Computing in the Internet of Things

Edge computing is expected act as a strategic brain behind IoT. Identifying the role of edge computing in IoT is the main research issue at present. Edge computing is utilized to reduce the amount of data sent to the cloud and decrease service access latency. Figure 3 illustrates the complimentary role of edge and cloud computing in the IoT environment. In this section, several major roles of edge computing are discussed with IoT scenario examples.

Data Acquisition: Edge devices, including sensors or machines, can capture streaming data for rapid analysis and perform immediate actions or processing of the data. According to Beckman, we are moving the algorithm to the data, not the data to the algorithm. Consequently, we can increase productivity and prevent product

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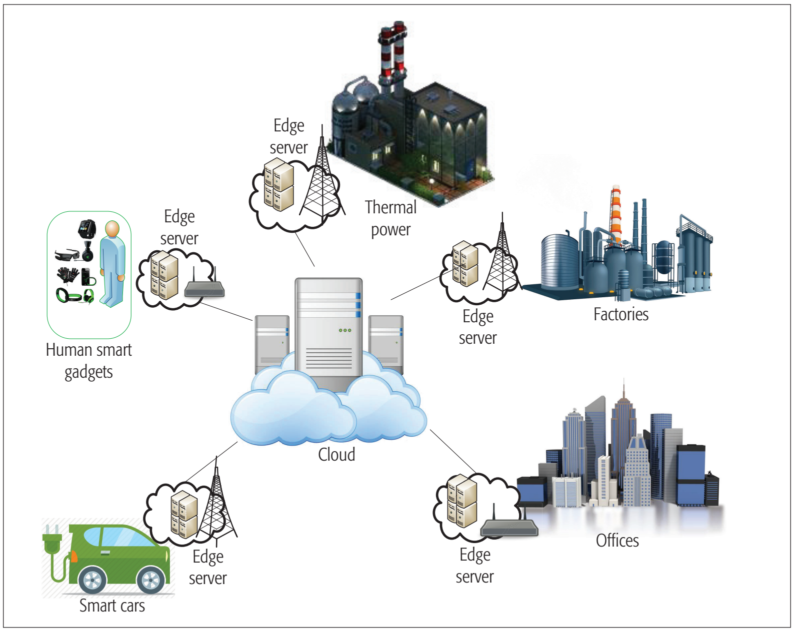

Figure 3. Illustration of edge cloud computing complimentary role in IoT environment.

defects efficiently and rapidly. In a smart transportation scenario, traffic light cameras can not only capture data but also analyze the collected data and make immediate decisions on their own to improve the flow of vehicles.

Inferential Controls: Inferential controls are key components of any edge device. They refer to the capacity of a device to interpret things in its environment accurately. These controls also communicate with an infrastructure that is controlled by other entities. However, bringing inferential capability to edge devices is difficult because it depends on contextual information. In a smart transportation scenario, this inference ability can provide drivers with highly intelligent navigation instructions by using GPS and front and back cameras.

Data Analysis: Edge computing enables real-time data analysis. Analyzing data in the place of data generation can reduce the latency of information generation from the collected data. Therefore, edge devices can collect and analyze data from surrounding devices, thus allowing decision makers to deliver actionable insights faster than before. Edge devices can also help reduce network bandwidth and cost because data will be locally analyzed. This can be helpful for many organizations in many industries, including manufacturing, healthcare, telecommunication, and finance, such that the need for the IoT concept increases. Therefore, instead of traffic light cameras sending data to a central infrastructure for data analysis, they can analyze streaming data themselves, communicate with other devices, and make immediate decisions to accomplish the required tasks.

Decision Making: After locally analyzing the data, the next step for edge devices is to make critical strategic decisions. In a smart transportation system, each car generates a large amount of data every second and requires real-time processing and correct decisions. For real-time processing, the data cannot be sent to the cloud for processing and decision making because the response time would be too long in this case. In such a case, the data should be analyzed locally on any edge device. In this manner, the car can make a correct decision on the spot to avoid adverse situations.

Enhanced Data Security: When data are sent abroad for data processing, data insecurity is increased. Data collection and analysis are performed locally in edge computing. Extensive routing is not involved, such that identifying any suspicious activity is easy. Implementing necessary actions before any security breach occurs also becomes easy.

Open Research Challenges

The following discussion highlights the open research challenges in the deployment of edge cloud in the IoT environment.

Heterogeneity: Heterogeneity in the IoT-based edge computing environment exists in computing and communication technologies. Computing platforms can have different operating systems and hardware architectures, whereas communication technologies can be heterogeneous with regard to data rate, transmission range, and bandwidth. One of the challenges in edge computing is to develop a solution in software space that is portable across different environments. This challenge is crucial because various applications are deployed in edge devices. Several researchers have proposed software solutions to resolve this issue, but all of these solutions are hardware specific. Thus, they cannot resolve the problem in heterogeneous environments. To solve this issue, programmers should develop a programming model for edge nodes that is supported by task- and data-level parallelism to facilitate the execution of workloads simultaneously at multiple hardware levels. The second consideration is to use a language that supports hardware heterogeneity.

Standard Protocols and Interfaces: Edge computing is an emerging technology in the IoT field. In this heterogeneous environment, different devices and sensors connect and communicate with one another and with the edge server via communication protocols. These devices have their own interfaces and thus demand specific communication protocols. Considering that different vendors manufacture different devices in the IoT environment, standard protocols and interfaces should be developed to enable communication among these heterogeneous devices. The development of standard protocols and interfaces in the IoT environment is challenging because of the rapid development of new devices.

Availability: Availability in the IoT-based edge computing environment includes hardware-level and software-level provision of resources and services anywhere and anytime for subscribed IoT devices. Usually, availability comprises three factors, namely, mean time between failure, failure probability, and mean time to recovery. Ensuring the availability of resources and services for the growing number of IoT devices is a challenging research perspective. However, availability can be optimized by maximizing the mean time between failures and minimizing the failure probability and mean time to recovery.

Data Abstraction: With IoT, a number of data-generating devices are connected in the network, and all of these data generators report tremendously large raw data to the edge device. For the edge device, analyzing such big data is computationally difficult. Security risks are also involved. Therefore, the data should be preprocessed at the gateway level, such as noise/low-quality removal, event detection, and privacy protection. The processed data will be sent to the upper layer for future service provision. However, many challenges may occur in this process. For privacy and security purposes, applications running on edge devices should be blind to these raw data. Therefore, the details of the data should be removed during data preprocessing. However, the usability of the data can be affected by hiding the details of sensed data. Defining the extent to which the raw data should be filtered out is also a challenge because several applications cannot obtain accurate results from such data.

Security and Privacy: Edge computing acts as a boon to cybersecurity because data do not travel over a network. However, a highly dynamic environment at the edge of a network makes the network unprotected. Given that different devices are connected in IoT, a large array of potential security threats can be generated. Many applications are running at the network edge, so the data provided to these applications should be in a hidden form. Otherwise, any intruder can use the open data for illegal purposes. For example, if a home is connected to IoT, then private data, such as individual health data, can be stolen. In this case, how to support the service without harming privacy is a challenge. Applications running on edge devices should be blind to the raw data. Personal data can be removed before reaching the edge device. Several solutions have been provided by researchers to standardize and store health data [13]. X. Sun *et al.* [14] proposed a hierarchical fog computing framework called EdgeIoT. This framework uses a proxy virtual machine for securing the privacy of user content and reducing data traffic in the core network. However, security features with enhanced robustness should be implemented on edge nodes.

Conclusion

In this article, we investigated, highlighted, and reported recent premier advances in edge computing technologies (e.g., fog computing, MEC, and cloudlets) with respect to measuring their effect on IoT. Then, we categorized edge computing literature by devising a taxonomy, which was used to uncover the premium features of edge computing that can be beneficial to the IoT paradigm. We outlined a few key requirements for the deployment of edge computing in IoT and discussed indispensable scenarios of edge computing in IoT. Furthermore, several open research challenges to the successful deployment of edge computing in IoT are identified and discussed. We conclude that although the deployment of edge computing in IoT provides numerous benefits, the convergence of these two computing paradigms brings about new issues that should be resolved in the future.

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