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Fog Computing: Architecture and Application

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Abstract

Nowadays, owing to the advancement of electronics and telecommunications and the increasing usage of the Internet, various powerful devices with networking capabilities are attracting industries to accept this technology for the development of their daily business to increase their productivity. Not only the industrial sector but also other sectors, such as public services and assisted living amenities have a huge demand for Information and Communication Technology growth. Therefore, there is a demand for a new model that enables objects to connect to global network. This model is known as the IoT. The use of the IoT has grown according to the demands of the current era. IoT combinations with clouds have brought different benefits to devices that operate on various platforms. Applications based on the IoT generate enormous amounts of data from different sensors. These data were used to make different decisions.

It is true that cloud computing has some issues in data transmission owing to the limitations of networks and infrastructure, which immensely decrease the performance of cloud computing. Therefore, the fog computing model was introduced to act in the middle between cloud computing and IoT. Fog is an extended version of cloud computing that can provide computing facilities at the edge of the network, and it allows this technology to deal with several data locally. As devices connected to the Internet and the use of the Internet of Things (IoT) continue to grow, the need for efficient and scalable computing solutions has become paramount. Fog computing has emerged as a model that extends the features of cloud computing to the network edge, bringing storage, computation, and networking closer to end users and devices.

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This article presents an in-depth analysis of the architecture, applications, and challenges of fog computing. It also discusses the fundamental concepts of fog computing, including its architectural components. Fog computing has been compared with IoT and cloud computing. Furthermore, it explores the different uses of fog computing in different domains, such as healthcare, smart cities, transportation, manufacturing, and agriculture. This paper also examines the different challenging features and future study guidelines in the field of fog computing.

***Keywords*:** IoT, cloud computing, edge computing, fog computing, smart city, sensor, edge nodes

1.1 Introduction

This fog computing can be considered as the computation of the next generation which is an extended version of cloud computing towards the edge of the network. Therefore it is also known as edge computing [16]. Issues faced by cloud computing can be addressed using fog computing.

Currently, the volume of data generation is exploding owing to the vast quantity of data generated daily by sensors, IoT devices, wide volume of internet usage, and so on. Fog computing can report the impractical features of a cloud that cannot fulfill the demands of users in real time. IoT applications, the Industrial Internet of Things, and the Internet of Everything, etc. are different reasons for the motivation or interest in the application of fog computing. Currently, data are one of the most important and essential factors for fulfilling and maintaining existence in today's era, and the usage of fog computing is spreading rapidly across organizations. Fog computing has gained significant attention as a promising paradigm for extending cloud-computing capabilities to network edges. While fog computing offers numerous benefits, such as reduced latency, improved scalability, and enhanced data privacy, it also presents several challenges that need to be addressed. Resource allocation is becoming an issue with respect to IoT application in fog computing [1, 2]. Several features of the different methods for allocating resources are used in fog computing. The objective of this article is to study the latest research on the allocation of resources in the fog area and to conduct a comparative study with cloud and IoT with different applications of fog computing. The justification of this study is to understand the architecture and application of fog computing and to provide a clear idea of the future applications of fog computing. From this article, researchers will benefit from a better understanding and utilization of this technology. Soon, different IoT devices will occupy the world because of the significant increase in the usage of different objects connected by different sensors connected by the Internet [3].

In this study, the remainder is divided into different sections. Section 1.2 presents an overview of Fog Computing, Section 1.3 describes fog computing for intelligent cloud IoT systems, Section 1.4 discusses the architecture of fog computing, Section 1.5 presents the basic module of fog computing, Section 1.6 presents the differences between cloud computing and fog computing, Section 1.7 discusses the differences between fog computing and IoT systems, Section 1.8 presents fog computing applications, Section 1.9 discusses whether fog computing can be taken over by cloud computing, Section 1.10 presents the challenges in fog computing, Section 1.11 discusses the future of fog computing, and finally, the conclusion is drawn in Section 1.12.

1.2 Fog Computing: An Overview

Cloud and fog computing are interrelated. In 2014, CISCO created the word fog computing, so obviously it is a new term for common human beings. As we know, fog exists closer to Earth than clouds, and the same is applicable in technical terms. Cloud capabilities are easier to use using fog computing.

Therefore, fog is an extension technology of cloud computing, which consists of several *edge nodes* connected with physical devices.

These nodes are much closer to devices if related to centralized data centers, which is why they can provide prompt connections. The computation power of edge nodes permits them to execute the processing of an enormous amount of data generated without transferring it to servers at a distance. Fog computing, also known as fog networks or edge computing, is an emerging paradigm that extends cloud-computing capabilities to the edge of a network. It brings computing resources, including storage, processing power, and networking capabilities closer to the data source or end-user devices. Fog computing offers several significant benefits, which contribute to its increasing importance in various domains.

Fog computing [8] can be considered as a decentralized computing arrangement. Here, decentralized indicates that computing resources are not fixed. Computing resources in fog computing will be moved and fixed closer to the IoT devices that generates records. Thus, this idea reduces the latency and network bandwidth usage, which can result in faster computation. Different large organizations have recently utilized fog computing to compute faster.

One of the important factors is the fog node. These are the virtual instances existing in the fog layer, which are used to provide extra benefits to the process of cloud computing. A fog node is a group of computing resources related to a specific sector. A small storage component acts similarly to a fog node. The fog layer is linked with a big cloud that may be a private or public cloud from which the fog nodes fetch records and push the record to it. Fog nodes can be used to provide transient storage ability. If the data are not transient, then it is relocated to the cloud to store the data.

Fog nodes rapidly agree whether to compute a record or send the record to the cloud for computation.

Each fog node has a comprehensive fog node and can be deployed over the entire network. Examples: routers, switches, etc.

The fog consists of *cloudlets*, which are small-scale datacenters situated at the edge of the network. Their main objective is to support resource-intensive Internet of Things applications that require low latency.

Fog computing services are very close to end devices. Because it is closer to end devices, the proposed computing model has important benefits over other conventional computing models. The important features of this study are as follows:

- Geographical distribution
  Fog nodes are widely distributed geographically [4]. These were positioned at different locations. For example, they are located on different positions of roads and highways, on the museum floor, and so on.
- Decentralization
  Fog computing has a decentralized architecture. No central server is available for managing different computing resources and facilities. Therefore, fog nodes are self-organizing and work together to provide a facility for real-time IoT applications to end users.
- Location awareness
  The ability to determine the geographical location of a device is called location awareness. The fog node is linked to the nearby fog node, and it knows the location of the fog client. Location awareness can be used in emergency conditions or targeted advertising.
- Real-time interaction
  The fog application supports real-time interaction instead of batch processing. Real-time stream handling and gaming are used in fog computing. Because fog is very close to the

edge, it offers healthy network information on the local network, traffic information, and status information.

- Save storage space
  Fog computing reduces latency and storage space [21, 22] consumption by avoiding inopportune data from moving across the entire network.
- Low latency
  The time taken for data to move from the source device to the server device is called the latency. By placing computing resources near the edge, the network latency of fog computing can be significantly reduced. This is crucial for applications that require real-time or near-real-time responsiveness, such as Internet of Things (IoT) devices, autonomous vehicles, industrial automation, and healthcare systems. In fog computing, latency is lower because the data do not have to move far away from the device. In the IoT and Cloud model, data generated by sensors are moved to the data center of the cloud, which is situated far from the IoT devices. Therefore, end-to-end delay occurs, such as deferral of data sent from IoT devices to data centers situated remotely, the delay of investigating the data, and the response coming back is delayed by the cloud to the end user. Therefore, cloud computing has a high latency. The nodes of fog computing are much closer to IoT devices [5], which provide different computing facilities, and decisions are made based on local data without the use of the cloud. Therefore latency in response is comparatively much lower [4] than that of cloud computing. With fog computing, data processing and decision making can occur locally, enhancing the overall user experience and enabling faster response times.
- Heterogeneity support
  The fog computing model has various types of nodes, such as set-top boxes, edge routers, high-end servers, and access factors, and even end nodes. Examples include cellular phones, automobiles, and sensors. They have received high-speed servers, edge routers, etc., operated via an operating device with special storage capabilities and computational electricity. It also provides virtual network platform. As different computing nodes and nodes of a virtual network can be used as fog nodes, fog nodes are heterogeneous in nature.

- Mobility support
  Using different protocols, mobility support is an important characteristic for different fog computing applications to communicate directly with movable devices. We know the ID separation protocol developed by CISCO, which can use a directory system that separates the identity of the host from identity of the site.
- Close to the end user
  To remove delays [24] in data communication, fog permits data to be closer to users than in data centers kept in remote locations.
- Bandwidth optimization
  Fog computing optimizes the network bandwidth [20] by processing data at the edge rather than transmitting it to centralized cloud servers. This is particularly valuable in scenarios in which IoT devices or sensors generate massive amounts of data. By locally performing data filtering, preprocessing, and aggregation, fog computing reduces the amount of data transmitted to the cloud. This alleviates network congestion and minimizes bandwidth costs.
- Enhanced privacy and security
  Sensitive data can be processed and stored locally in fog computing, whereas data can be sent to a remote cloud server in cloud computing. This distributed approach to computing enhances privacy and security [9, 14, 27] because data can be kept closer to its source and subject to localized security measures. It reduces the risk of data breaches and unauthorized access and ensures compliance with privacy regulations.
- Improved reliability
  Fog computing increases the reliability and resilience of networked systems. Distributing computing resources across a network mitigates a single point of failure. If a connection to the cloud is lost, fog nodes can continue to function independently and maintain critical operations. This is particularly critical for applications in which uninterrupted connectivity is crucial, such as autonomous, industrial control, and emergency response systems.
- Scalability and agility
  Fog computing enables scalability and agility in the deployment and management of distributed applications. As the

number of edge computing nodes and IoT devices increases, fog computing allows for easy resource scaling by adding more edge devices. It also enables the dynamic provisioning of computing resources based on demand, allowing applications to adapt and respond efficiently to changing workload requirements.

- Cost optimization
  By offloading computational tasks to edge devices, fog computing reduces the need for high-end servers and an expensive cloud infrastructure. It can leverage existing computing resources at the edge, such as routers, gateways, and IoT devices, thereby optimizing resource utilization and reducing operational costs. Fog computing enables cost-effective solutions for deploying and managing distributed applications, particularly in scenarios in which large-scale cloud infrastructure is not feasible or cost prohibitive.

Fog computing plays an important role in enabling effective and reliable computations at the network edge. This has important advantages with respect to reduced latency, optimized bandwidth, enhanced privacy and security, improved reliability, scalability, agility, and cost optimization. As the demand for real-time and edge-centric applications grows, fog computing is becoming increasingly relevant in various domains, including IoT, industrial automation, smart cities, healthcare, and transportation. The characteristics of fog computing are summarized in Figure 1.1.

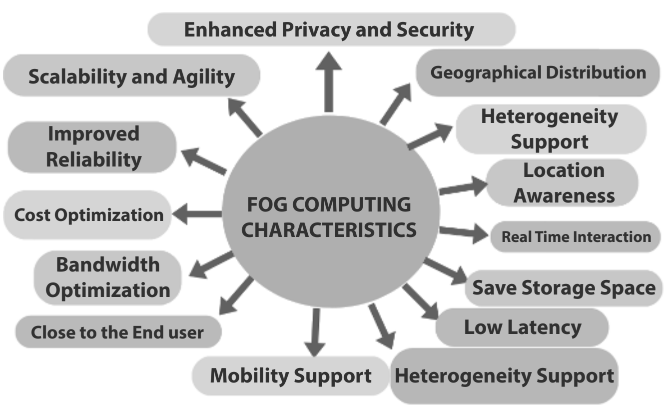

Figure 1.1 Fog computing characteristics.

Fog computing can be considered situated between remote servers and hardware. Therefore, it is easier to decide and control the sending of data to a server or executed locally. A fog serves as a smart gateway that offloads cloud computing, allowing for more effective data processing, storage, and analysis [22].

Decentralization of computing infrastructure is the main factor in fog computation. Here, a flexible computing infrastructure consisting of data, storage, and applications is situated somewhere between the cloud and data source, which is a data generator. Similar to edge computing [16], fog computing reduces the distance between the data source and the location where it is executed. Edge computing and fog computing concepts are nearly the same, as both technologies bring computation and processing closer to the data generation location. Sometimes, it is done to increase efficiency, as well as for compliance and security reasons.

Currently, low-cost sensors are helping to increase the usage of IoT devices. IoT can be implemented successfully when the following requirements are met:

- Reliability of data.
- High data security
- Reduction in latency of data
- Based on the data type, the execution of data at the appropriate location.
- To monitor data through large geographical area

Fog computing meets all the above requirements for IoT networks.

1.3 Fog Computing for Intelligent Cloud-IoT System

Fog computing is an architectural concept that extends cloud computing capabilities to the edge of the network, closer to the data sources in an Internet of Things (IoT) ecosystem [9]. It aims to address the limitations of traditional cloud-centric architectures by leveraging the computational resources available at network edges, such as gateways, routers, and IoT devices. This enables faster processing, reduced latency, improved bandwidth utilization, and enhanced privacy and security in cloud-based IoT systems. When combined with intelligent capabilities, fog computing can further enhance the performance and efficiency of cloud-IoT systems. Some concepts related to fog computing for intelligent cloud-IoT systems are as follows:

- Edge Intelligence: Fog computing enables intelligent processing and decision-making at the edge of the network. By deploying machine learning algorithms and artificial intelligence models on edge devices, data can be analyzed and acted upon in real time without the need to send it to the cloud. This reduces the latency and enables quicker response times for time-sensitive applications.
- Distributed Data Analytics: Fog computing allows data analytics tasks to be distributed across clouds and edge devices. By partitioning data processing and analysis between the cloud and edge, it is possible to strike a balance between computational capabilities and network-bandwidth usage. This approach optimizes overall system performance and reduces the need for extensive data transfer to the cloud.
- Dynamic Resource Allocation: Fog computing enables intelligent resource allocation and management in cloud-IoT systems. By leveraging edge devices' computational capabilities, tasks can be dynamically assigned to the most suitable resources based on factors like proximity, network conditions, and resource availability. This adaptive resource allocation ensures efficient utilization of computing resources and improved system scalability.
- Context-Awareness: Fog computing enhances the context-awareness of cloud-IoT systems by leveraging data from sensors and devices at the edge. Contextual information such as location, environmental conditions, and user preferences can be processed locally to provide personalized services, real-time monitoring, and better decision-making. This localized processing minimizes the need for constant communication with the cloud, thereby reducing latency and conserving the network bandwidth.
- Security and Privacy: Fog computing improves security [17, 27] and privacy in cloud-IoT systems by keeping sensitive data closer to its source. Instead of transmitting all the data to the cloud for processing, fog nodes can perform data filtering, aggregation, and anonymization at the edge. This approach reduces the attack surface and risk of data breaches, making the system more resilient to cyber threats.
- Hybrid Cloud–Fog Collaboration: Fog computing can be seamlessly integrated with cloud computing to create a hybrid cloud–fog architecture. This collaboration allows for

the offloading of resource-intensive tasks to the cloud, while maintaining time-sensitive and critical operations at the edge. The hybrid model provides the benefits of both cloud and fog computing, optimizing the trade-off between scalability, agility, and latency in cloud IoT systems.

These concepts demonstrate how fog computing can enhance cloud-IoT systems by providing intelligence, real-time processing, and efficient resource management to the network edge. By leveraging the strengths of both cloud and fog computing, organizations can build scalable, responsive, and secure IoT ecosystems that can fulfill the demands of a large variety of applications.

1.4 Fog Computing Architecture

Fog computing architecture is generally composed of three different working layers. There are three working layers in the fog computing architecture [6, 8, 25]: the edge layer, fog layer, and cloud layer. The three-layer architecture of fog computing is described below and presented in Figure 1.2.

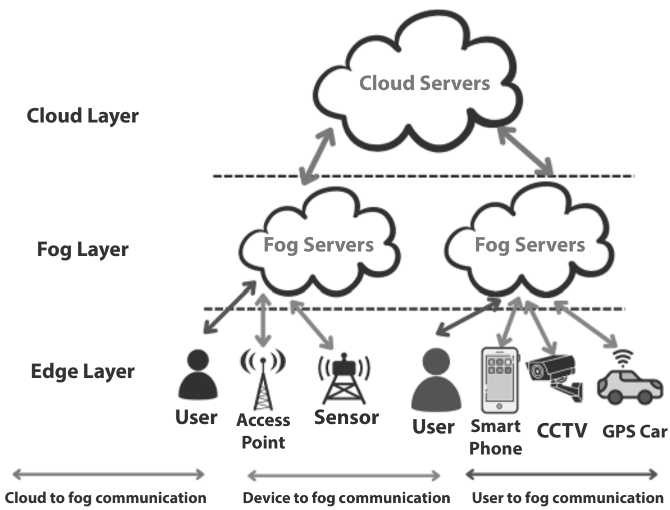

Figure 1.2 Fog computing architecture.

a. Cloud Layer:
   - Cloud layer represents the centralized cloud infrastructure at the top of the architecture. It provides storage, computing power, and advanced analytics capabilities for fog computing deployment.
   - The cloud layer is responsible for handling resource-intensive tasks, storing large datasets, and supporting long-term data analyses.
b. Fog Layer:
   - The fog layer is located closer to the network edge and comprises a distributed network of fog nodes.
   - Fog nodes are interconnected devices that include edge servers, routers, gateways, and IoT devices.
   - These nodes are responsible for processing, analyzing, and storing data locally, thereby reducing latency and network congestion.
   - Fog nodes can be deployed at various levels of the network hierarchy, such as near end-devices, within access points, or at aggregation points.
c. Edge Layer:
   - The edge layer consists of edge devices representing sensors, actuators, and IoT devices that generate data and interact directly with the physical world.
   - These devices are responsible for collecting and transmitting data to fog nodes for local processing and analysis.
d. Communication Infrastructure:
   - Communication infrastructure connects fog nodes and edge devices, facilitating data exchange and communication.
   - It can include wired and wireless networks such as Ethernet, Wi-Fi, cellular networks, and other IoT-specific protocols.
e. Data Processing and Analytics:
   - The fog nodes within the fog layer perform data processing, analytics, and decision-making tasks.
   - This layer can utilize various techniques, including machine learning algorithms, stream processing, and real-time analytics, to extract insights from data.

f. Resource Management and Orchestration:
   - Resource management and orchestration mechanisms optimize the allocation and utilization of computing, storage, and networking resources within the fog layer.
   - This involves tasks such as load balancing, task scheduling, and dynamic resource provisioning to ensure efficient resource utilization.

g. Security and Privacy:
   - The security and privacy layers focus on ensuring the confidentiality, integrity, and availability of data within the fog computing environment.
   - This includes encryption mechanisms, access control, authentication, and intrusion detection systems to protect data and preserve user privacy.

h. Cloud–Fog Integration:
   - Cloud–fog integration enables seamless communication and collaboration between cloud and fog layers.
   - It allows fog nodes to offload certain tasks to the cloud, access additional resources when needed, and enable the long-term storage and analysis of data.

It is important to note that fog computing architectures can vary depending on specific use cases and deployment scenarios. The described architecture provides a general overview of the components and their relationships within a fog-computing environment.

Different types of fog computing exist, such as client-based, server-based, and hybrid fog computing.

- **Client-Based Fog:** It is based on the computing power of edge devices to execute and analyze data. Client-based fog computation is best for applications that require real-time processing, such as industrial IoT and autonomous vehicles.
- **Server-Based Fog:** It is based on the computing power of servers located in the fog layer to execute and analyze data. Server-based fog computation is best for applications that require extra computing power compared with edge devices.
- **Hybrid Fog:** This fog computation is a mixture of client-based and server-based fog computations. Hybrid fog computing is perfect for applications that require a combination of high computing power and real-time processing.

1.5 Basic Modules of Fog Computing

There are several ways of creating a fog computing system. The well-known parts across these architectures are explained below and are summarized in Figure 1.3.

a. Physical and Virtual Nodes/End Devices
   In the real world, end devices function as points of interaction. They may be end devices, such as smart watches, module phone sensors, edge routers, application servers, and edge routers. These devices are record producers and can span a large band of technology. This means that they may have variable processing and storage capacities, and many hardware and software applications.
b. Fog Nodes
   Fog nodes are independent devices that collect the information produced. Fog nodes fall into three categories: gateways, fog servers, and fog devices. These devices can store the necessary data, whereas fog servers can compute their data to take the course of action. Fog devices are generally connected to servers. The fog gateways redirect information between several fog devices and servers. This layer is responsible for the speed handling and flow of information.
c. Monitoring Services
   Monitoring services usually include application programming interfaces or APIs that keep track of how the system

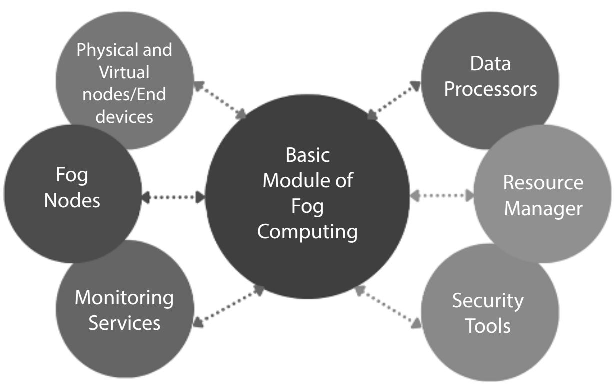

Figure 1.3 Basic modules of fog computing.

will perform and the availability of resources. This guarantees that all fog nodes and end devices are active and communication is not delayed [24]. It is observed that if we wait for a node to be free, then it may be comparatively more costly than to hit the cloud server. The monitor manages such situations. Monitors can be used to assess the present system and predict future resource necessities based on their overall usage.

d. Data Processors

Data processors play an important role in fog computing. The function is to operate on fog nodes. They trim, filter and occasionally rebuild damaged data that flow from end devices. Data processors can decide whether the data should be kept locally on a fog server or sent for long-term storage in the cloud. Data from different sources were homogenized for easy communication and transportation by these processors.

This can be achieved by revealing a programmable and uniform interface with other modules in the system. If one or more sensors do not work, some data processors are so intelligent that they can fill the information based on old historical data. This can prevent any type of application failure.

e. Resource Manager

Fog computing contains different independent nodes that can operate synchronously. The resource manager assigns and frees the resources to several nodes and schedules data transmission between the nodes and the cloud. It also considers the data backup to ensure zero data loss.

As fog modules take up some of the SLA [20] promises of the cloud, great availability is necessary. The resource manager works with the monitor to decide where and when the demand is higher. This confirms that there is no redundancy in the fog servers or data.

f. Security Tools

Fog components can directly interconnect with raw data sources. Encryption is necessary because all communication tends to occur over wireless networks. In some cases, end users directly ask fog nodes for data. Therefore, user and access management are part of safety efforts in fog computing.

1.6 Cloud Computing vs. Fog Computing

Fog computing and cloud computing are two distinct paradigms [10, 14] that serve different purposes in the realm of distributed computing. The key differences between fog computing and cloud computing are as follows:

a. Proximity to End Users and Devices:
   - Fog Computing: Fog computing brings computing resources closer to the network edge, end users, and IoT devices. It extends cloud-computing capabilities to the edge of the network, reduces latency, and improves real-time responsiveness.
   - Cloud Computing: Cloud computing, on the other hand, centralizes computing resources in data centers located at a distance from end users. Users access these resources on the internet.

b. Data Processing and Storage:
   - Fog Computing: In fog computing, data processing and storage occur at the network edge, close to where data are generated. This enables faster processing, reduced bandwidth usage, and localized decision making.
   - Cloud Computing: In cloud computing, data processing and storage occur in centralized datacenters. Users send data to the cloud for processing and the results are sent back to the user.

c. Scalability and Resource Allocation:
   - Fog Computing: Fog computing allows for horizontal scalability because fog nodes can be deployed in a distributed manner to handle increasing workloads. Resources can be dynamically allocated and managed at an edge.
   - Cloud Computing: Cloud computing enables vertical scalability, as additional resources are added to centralized data centers to handle increased demand. Resource allocation [4] and management are performed centrally.

d. Network Bandwidth and Latency:
   - Fog Computing: Fog computing reduces network bandwidth [20] requirements by processing and analyzing data locally at the edge and sending only relevant information to the cloud. This minimizes the latency and congestion.

- Cloud Computing: Cloud computing relies on network connectivity for data transfer between the end user and the cloud, potentially leading to higher latency owing to data transmission over longer distances.

e. Use Case Focus:
- Fog Computing: Fog computing is particularly suitable for latency-sensitive and real-time applications such as IoT, edge analytics, and time-critical systems. It is well suited for scenarios in which immediate decision-making and local data processing are crucial.
- Cloud Computing: Cloud computing is commonly used in applications that require extensive computing

Table 1.1 Difference between cloud computing and fog computing.

Feature requirements	Cloud computing	Fog computing
Architecture	Centralized	Distributed
Proximity to End Users and Devices	Centralizes computing resources in Data Centers located at a distance from end user	Closer to the network edge, closer to end users and IoT devices
Data Processing and Storage	Far from the Data Source, Computing Capability and Storage Powerful	Close to the Data Source, Computing Capability and Storage less Powerful
Scalability and Resource Allocation	High, easy to scale	Scalable with in Network
Network Bandwidth and Latency	High	Medium
Use Case Focus	Suitable for complex modeling and big data analytics	Suitable for latency-sensitive and real-time applications, such as IoT, edge analytics, and time-critical systems
Data Privacy and Security	Less Secure	High Secure

resources, storage, and long-term data analysis. It is suitable for applications with less stringent latency requirements, where data processing can be offloaded to a centralized infrastructure.

f. Data Privacy and Security:
    - Fog Computing: Fog computing enhances data privacy and security by keeping sensitive data localized at the edge. Data can be processed and analyzed within a local network to reduce exposure to potential threats during data transmission.
    - Cloud Computing: Cloud computing involves transmitting data over the Internet to centralized data centers, raising concerns about data privacy and security during transmission and storage.

It is important to note that fog computing and cloud computing are not mutually exclusive or complementary. In certain scenarios, a hybrid approach that combines fog computing at the edge and cloud computing in centralized datacenters may be the most effective solution, leveraging the strengths of both paradigms. The differences between the above two are summarized in Table 1.1.

1.7 Fog Computing vs. IoT

Fog computing and the Internet of Things (IoT) [12, 13, 19] are related concepts, but have distinct differences. There are some key differences between fog computing and IoT:

- Scope and Scale: IoT refers to a network of interconnected devices, sensors, and objects that collect and exchange data. It encompasses a wide range of devices from everyday objects to industrial machinery and infrastructure. On the other hand, fog computing is an architectural paradigm that extends cloud computing capabilities to the edge of the network. It focuses on computation, storage, and processing capabilities at the network edge to enable real-time data processing and analysis.
- Location of Data Processing: In IoT, data are generated by various devices and sensors, which are typically transmitted to a centralized cloud infrastructure for processing and

analysis. However, fog computing emphasizes localized processing at the edge of the network closer to the data sources. It aims to reduce latency, minimize data transfer, and enable real-time decision making by processing data closer to where it is generated.

- Latency and Real-Time Capabilities: IoT systems often rely on cloud computing for data processing, which can introduce latency owing to the time it takes to transmit data to the cloud and receive a response. Fog computing addresses this issue by enabling real-time processing and decision-making at the network edge. By processing data locally, fog computing reduces latency and allows for faster responses, making it wee suited for time-sensitive applications.
- Scalability: IoT systems can involve a large number of devices and generate a vast amount of data. Cloud computing provides scalability for handling such large-scale deployments. Fog computing complements cloud computing by distributing computational resources and enabling localized processing at the edge. This enhances scalability by offloading processing tasks from the cloud to the edge, thereby reducing the overall system load.
- Security and Privacy: Security and privacy [27] are critical concerns in IoT systems. Cloud-based IoT solutions often involve transmitting sensitive data to the cloud, thereby increasing the privacy and security risks. Fog computing mitigates these risks by keeping the data processing and storage closer to the edge, thereby reducing the need to transmit sensitive data to the cloud. This localized approach improves security and privacy because data can be processed and filtered locally before being sent to the cloud, thereby minimizing the attack surface.
- Network Bandwidth Usage: IoT systems generate vast amounts of data and transmit all data to the cloud for processing, which can strain network bandwidth [20]. Fog computing reduces the amount of data sent to the cloud by performing an initial processing and filtering at the edge. It only sends relevant and actionable data to the cloud, optimizing network bandwidth usage and reducing the costs associated with data transfer.

Table 1.2 Difference between fog computing and IoT.

Feature requirements	Fog computing	IoT
Scope and Scale	Distributed	Centralized
Location of Data Processing	Localized processing at the edge of the network, closer to the data sources	Data is generated by various devices and sensors, which is typically transmitted to a centralized cloud infrastructure for processing and analysis
Latency and Real-Time Capabilities	Low Latency	High Latency
Scalability	High scalable	Less Scalable
Security and Privacy	High	Medium
Network Bandwidth Usage	Needs less Bandwidth	Needs more Bandwidth

The fog computing and IoT differences are summarized in Table 1.2.

Overall, while IoT focuses on the network of interconnected devices and data generation, fog computing complements IoT by extending cloud-computing capabilities to the edge of the network. Fog computing enhances IoT systems by providing localized processing, reducing latency, improving scalability, and addressing security and privacy concerns, thereby making it an integral part of a robust and efficient IoT architecture. The combination of fog computing with IoT will bring various benefits to many IoT applications.

1.8 Applications of Fog Computing

There are various applications of fog computing [7, 25] in different areas. These are described as follows, and the summarized presentation is shown in Figure 1.4:

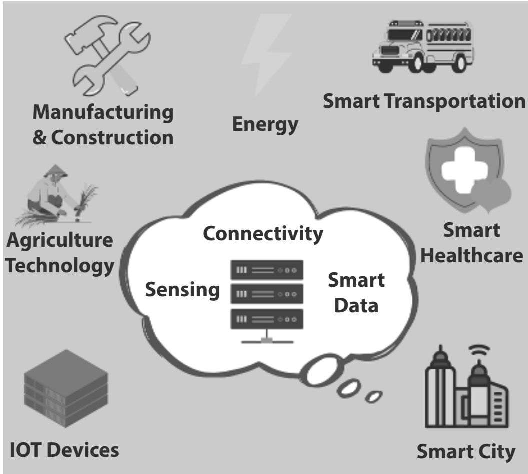

Figure 1.4 Applications of fog computing.

a. Smart Utility Service
Saving energy is the primary challenge of modern life. Using smart utility facilities, we can achieve this. IoT-related applications create huge amounts of data transmission; this problem can be addressed using fog computing, which can analyze data from different applications for updating continuously.

b. Smart Cities
Traffic regulation in smart city is another popular example of use of fog computing [15, 23]. Sensor-based road barriers and traffic signals are installed to collect vehicle movement data on busy roads. As real-time data analysis can be performed by fog computing, it helps traffic signals to function properly and accurately.

c. Health Care
Evolution in healthcare has been introduced by the involvement of IoT with wearable sensors, which has brought about a remarkable change in healthcare systems [30]. A simple watch that tells us time and date, but a smart watch can do the same thing with some extra features by providing different health conditions for users. Currently, wearable sensors are used in smart hospitals to obtain continuous information on different parameters related to health. Fog computing has low latency, which is why it is helpful to these

wearable IoT devices, as it guarantees the delivery of data without delay at the time of emergency.

d. Video Surveillance
In different crowds, such as shopping malls, cinema halls, and railway stations, the installation of surveillance cameras is very important to track different movements of public behaviors. Surveillance cameras can gather large amounts of video data. To stop the delay of data transmission from these devices, fog computing is important for helping to identify the anomalies in those places and to alert specific authorities to act against such an event.

e. Fog Computing in Agriculture and Farming
Agricultural production is now being advanced with the benefit of Fog Computing. An example is a Smart Water Management Platform. The agricultural production industry has benefitted and transformed with the help of fog computing. The Smart Water Management Platform (SWAMP) project is a beautiful example, where IoT, autonomous devices, and data analytics [18], etc. have been used. Fog computing allows the platform to collect sensor analysis data from the fields and, subsequently, to improve the allocation of water.

Another application was developed using iFogSim, which is an application of fog computing for smart or precision agriculture. This is an IoT-based farm management systems called Agrifog.

1.9 Will the Fog Be Taken Over by the Cloud?

There are many problems with fog computing, and its adoption by industry is very low. Different industries are contesting to acquire fog technology quickly and perform rapid research to grow and capture the market; however, some companies are taking policies such as waiting and watching the market scenario on fog computing. Denny Strigl who is a former CEO of Verizon Wireless and a lecturer at electrical engineering department in the Princeton, said that it would took nearly twenty years for proper implementation of wireless system which is maneuvered. Fog computation and proper implementation are difficult tasks. Safety and security are the main issues in proper implementation. The final difficulty is confusion, as a human phenomenon. Adding another level of complication in some cases creates a certain fear that individuals and industries will not be ready to control and maintain it. However, industries may be cautious about accepting this challenge. Fog computing is one of the solutions that can create problems in the form of technology to entertain things to marketing and retail. Fog computing will not fully replace cloud computing because, until now, clouds have been preferred for processing high-end batch jobs, which are important for the business world. Thus, it can be said that cloud and fog would be existing technologies and both have usages in different applications, and these are complementary to each other where required.

1.10 Challenges in Fog Computing

This section discusses the key challenges [11, 17, 21] faced by fog computing and explores potential research directions for overcoming these challenges.

a. Scalability and Heterogeneity: Among the different challenges, the scalability and management of many heterogeneous devices and resources are one of them in fog computing [26]. As the number of IoT devices continues to grow, fog nodes must efficiently handle the increasing volume of data and computational demands. Future research should focus on developing scalable architectures, resource-allocation algorithms, and load-balancing mechanisms to handle diverse workloads and ensure the optimal resource utilization.
b. Resource Management and Optimization: Efficient resource management is crucial in fog computing environments to ensure optimal utilization of computing, storage, and networking resources. However, resource management in a highly distributed and dynamic environment is complex. Future research should explore intelligent resource management techniques, including task scheduling, resource allocation, and dynamic provisioning, to optimize resource usage, reduce energy consumption, and improve the overall system performance.
c. Security and Privacy Concerns: As fog computing involves processing and storing sensitive data at the network edge, ensuring security and privacy becomes a critical challenge. Fog nodes are vulnerable to various security threats

including unauthorized access, data breaches, and malicious attacks. Future research should focus on developing robust security mechanisms, including authentication, encryption, access control, and intrusion detection systems to protect data and preserve user privacy in fog computing environments.

d. Data Processing and Analytics: Fog computing generates vast quantities of data for execution and analysis in real time. However, processing and analyzing data at the network edge poses challenges owing to the limited computational capabilities and bandwidth constraints. Future research should explore lightweight and efficient data processing techniques, including edge analytics, machine learning, and stream processing algorithms, to enable real-time insights and decision making in the fog layer.
e. Energy Efficiency and Sustainability: Fog computing deployments often consist of resource-constrained devices with limited power resources. Efficient energy management is essential for prolonging the battery life of edge devices and minimizing their environmental impacts. Future research should focus on developing energy-efficient algorithms, power management strategies, and energy-aware protocols to optimize the energy consumption and improve the sustainability of fog computing systems.
f. Interoperability and Standardization: The heterogeneity of devices, protocols, and platforms in fog computing ecosystems presents interoperability challenges. The lack of standardized interfaces and protocols hinders seamless integration and communication between fog nodes and cloud resources. Future research should address interoperability issues by developing standardized protocols, middleware, and APIs to enable seamless communication and collaboration between heterogeneous fog computing devices and cloud platforms.
g. Edge Intelligence and Autonomy: To achieve real-time decision-making and autonomy at the network edge, fog nodes must possess intelligence and self-learning capabilities. Future research should focus on developing intelligent algorithms, machine learning techniques, and edge intelligence frameworks to enable autonomous decision making,

context awareness, and adaptive behavior in fog computing systems.

h. Quality of Service (QoS) and Service Level Agreements (SLAs): Fog computing involves the provisioning of various services to end-users and meeting the QoS requirements specified in SLAs is crucial. However, ensuring the QoS in a dynamic and distributed fog environment is challenging. Future research should explore QoS-aware resource management, service placement, and SLA negotiation mechanisms to guarantee reliable service delivery and meet user expectations in fog computing deployments

1.11 Future of Fog Computing

Fog computing can solve difficulties related to internet traffic, space, and congestion. Fog computing provides smart techniques to achieve real-time and distributed features for developing IoT setups [12, 13]. Emerging these types of facilities with the use of fog computation can lead to different business models as well as new openings for network providers and operators. Current research predicts that the fog-computing-related market will be increased to USD 934 million by 2026. We know that in 2017, the global market size for fog computing was expected to be USD 12.87 million and most probably, it will get a fast progress rapidly with a CAGR of 62.6% or more between 2017 and 2026. Therefore, fog computing applications have great scope in the global world.

The future of fog computing appears promising, as it evolves and gains traction in various industries. Some key aspects that highlight potential future developments and trends in fog computing are as follows:

- Edge Intelligence: Fog computing will increasingly incorporate advanced analytics and artificial intelligence capabilities at the edge. This will enable real-time data processing, analysis, and decision making at the network edge, empowering autonomous systems, smart devices, and IoT applications. Edge intelligence will facilitate faster insights, predictive maintenance, and proactive decision making, leading to improved efficiency and performance across industries.
- 5G and Fog Computing Integration: 5G networks synergize with fog computing, unlocking new opportunities and capabilities. 5G's high-speed, low-latency, and high-bandwidth

characteristics align well with the fog computing requirements. The combination of 5G and fog computing will enable more real-time applications, such as augmented reality, virtual reality, connected vehicles, smart cities, and industrial automation, with enhanced performance and user experience.

- Decentralized Data Governance: Fog computing promotes a decentralized approach to data processing and storage. In the future, there will likely be increased emphasis on decentralized data governance frameworks to ensure data privacy, security, and compliance. Distributed ledger technologies, such as blockchain may enable secure and transparent data management and establishing trust [28] among fog nodes and stakeholders. Trust is very important for assisting in decision creation and allows independent connections to be made between resource-constrained IoT devices and fog nodes, which are called fog clients. The requirements of trust in fog computing are very important.
- Industry-Specific Fog Solutions: Different industries will continue to adopt fog computing to address specific challenges. For example, fog computing can facilitate remote patient monitoring, real-time medical data analysis, and personalized treatment. In manufacturing, fog computing can optimize production processes, enable predictive maintenance, and improve supply chain visibility. As fog computing matures, industry-specific solutions [29] will emerge to cater to the unique requirements of different sectors.
- Edge-to-Cloud Orchestration: Fog computing and cloud computing will increasingly work together in a coordinated manner, enabling seamless orchestration of resources and workload distribution. Applications and services dynamically balance processing between the edge and cloud based on factors such as latency, resource availability, and energy efficiency. This hybrid approach maximizes the benefits of both fog computing and cloud computing, offering a scalable and efficient infrastructure for diverse workloads.
- Energy Efficiency and Sustainability: Energy efficiency is a significant consideration in fog computing. As the number of edge devices and sensors increases, more energy-efficient computing solutions are required. Fog computing can leverage low-power processors, energy-harvesting techniques,

and intelligent resource management to optimize energy consumption and promote sustainability in networked ecosystems.
- Standardization and Interoperability: Standardization and interoperability are essential to realize the full potential of fog computing. Industry consortiums and standardization bodies play a crucial role in establishing common frameworks, protocols, and interfaces to ensure seamless integration and compatibility between different fog-computing platforms and devices. Interoperability enables a vibrant ecosystem of applications, services, and devices that seamlessly work together, fostering innovation and collaboration.

In conclusion, fog computing holds great promise. As technological advancements continue and industries embrace edge-centric solutions, fog computing will evolve to achieve real-time processing, intelligent decision-making, and distributed data management. It will be a key enabler of various transformative technologies, such as IoT, AI, 5G, and decentralized computing, driving innovation and efficiency across industries.

1.12 Conclusion

Fog computing has tremendous potential for addressing the challenges posed by the increasing number of IoT devices and the requirement for real-time data processing. However, several challenges must be overcome to fully realize the benefits of fog computing. By focusing on scalability, resource management, security, data processing, energy efficiency, interoperability, intelligence, and QoS, researchers can pave the way for future advancements in fog computing, enabling its widespread adoption and facilitating innovative applications in various domains. Fog computation is a distributed architecture in which software, computing parts, and storage are kept someplace between the cloud and the data source. Fog computing provides different cloud-computing services to the end users. Explanation of different modules, architectures, and characteristics of fog computing is performed with different diagrams. Fog computing and cloud computing differences, as well as fog computing and IoT differences, are discussed to provide a complete view of their applications and usage. In this article, different security and privacy issues are discussed. Fog computing is an extension of cloud computing for the end users. Fog computing with IoT holds significant promise for the near future. With advancements in technology and industries embracing edge-centric solutions, fog computing will evolve to satisfy real-time processing, intelligent decision-making, and distributed data management. It will be a key enabler of various transformative technologies, such as IoT, AI, 5G, and decentralized computing, driving innovation and efficiency across industries. Research on fog computing is ongoing in a rapid manner, and although this technology is in the beginning stage, but in near future fog computing will play an important role in the development of IT solutions.

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