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A Comparative Study of Fog and Edge Computing Architecture: Exploring Potential, Challenges, and Future Directions

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***Abstract* - Fog and edge computing have developed into transformative systems that solve the needs for fog and edge computing because data-driven applications experienced rapid expansion and users required fast network connections with high data transfer rates. The new computing methods create a direct link between people who use devices and cloud services which base their operations on centralized systems to deliver 5G and IoT and augmented reality and vehicle-to-vehicle communication technologies. The new computing paradigms offer better performance than traditional cloud systems because they combine low latency with mobility features and location tracking capabilities which enable instant access to mission-critical services. The paper maps existing research to the real-world needs of fog and edge infrastructure and platforms to create a complete evaluation of technology optimization and system integration. The paper compares fog and edge computing systems through a research assessment which examines their current opportunities and challenges and identifies future research pathways. The study investigates network optimization and resource allocation and network connectivity and communication and security and privacy and data management and system complexity as key challenges which exist within fog computing environments. The paper identifies essential research shortcomings in fog and edge computing research and recommends future research paths to develop these technologies by focusing on their system integration and interoperability and their capability to power forthcoming intelligent distributed systems. The conclusion emphasizes that while fog and edge computing are not replacements for cloud computing the two technologies serve as vital elements which enhance cloud services through their ability to process data locally and their capacity to enhance service delivery.**

Keywords: Fog computing, edge computing, Internet of Things, low latency, scalability, security, resource management, data management.

I. INTRODUCTION

The connected device market has expanded rapidly during recent years to create a need for new computing systems which can handle real-time processing requirements. The combination of Fog and Edge computing functions as two interconnected systems which deliver computing power to locations that are situated close to data generation sites. Fog computing (FC) functions as a distributed computing system which improves traditional cloud computing methods according to [1]. The system places processing and storage and networking resources at locations which are near to the network boundary between local area networks and wide area networks. Fog computing achieves three benefits through its system by decreasing latency and reducing bandwidth usage which leads to better data processing results according to [1]. The implementation of fog computing technology operates as an extension of Internet of Things (IoT) systems which connect multiple devices to create extensive data streams according to [2]. Fog computing provides an alternative to remote cloud processing by enabling data to be processed at the network edge. The use of localized systems creates multiple benefits which include decreased network congestion and better response times and improved security and privacy according to [3]. Edge computing (EC) focuses on bringing computing resources closer to the data source, typically at the network's edge, near IoT devices [4]. Edge network devices include routers and gateways and dedicated edge servers which maintain local data processing functions at network boundaries [5]. The system enables immediate decision-making which decreases the requirement for ongoing links to remote servers and cloud services. Edge computing offers multiple benefits which include reduced latency and improved system reliability and better scalability and optimized network resource usage [4]. Edge computing enables faster data processing through its ability to perform data operations at the location where data originates which makes it suitable for applications that need immediate reactions like autonomous vehicles and industrial automation systems and smart city

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technologies [6]. The operation of distributed systems depends on both edge computing and fog computing. Fog computing extends cloud functions to the edge of networks whereas edge computing delivers network resources to the most remote parts of the system. The two technologies create a system which efficiently processes increasing IoT device data while supporting the development of new applications across different industries [7]. Fog computing and edge computing create a new way to process and analyze data because they place computing power close to where data exists. The close distance between computing resources and data sources improves multiple applications through better performance and shorter waiting times and improved system capacity and higher operational efficiency which drives IoT growth and supports the development of a smart interconnected world [2].

1.1 Background

The computing resource access methods underwent a fundamental change after cloud computing services achieved mainstream popularity during the early 21st century. The system provided users with instant access to flexible computing resources which included both storage and processing power and software applications that operated through internet connections [2]. The Internet of Things (IoT) gained momentum during this period as it established internet connections between billions of devices and sensors and actuators throughout the world[1]. IoT devices generate vast amounts of data which require efficient mechanisms for processing and analyzing this data according to this research. The emerging applications of autonomous vehicles and industrial automation and smart grids and remote healthcare monitoring demand system components that can make decisions in real time. The system required a complete operational change because its design resulted in unacceptable delays when data traveled between edge devices and their corresponding cloud processing locations. Cisco introduced the term fog computing in 2012 as a solution that would address the IoT challenges and the cloud computing constraints. OpenFog Consortium [3] defined Fog computing as the distribution of computing resources across different network locations that bring processing power closer to data sources which includes edge computing. The system provides a solution that enables data processing to occur either in the cloud or at the edge device locations throughout the network. Edge computing extends fog computing by delivering processing power to locations which are nearer to edge devices. Edge devices which include routers and gateways and dedicated edge servers execute local data processing at locations that exist outside the main network area. Edge computing delivers instant processing capabilities which enable real-time decision-making for applications that require immediate results.

1.2 Motivation

The increasing need for services that require minimal delay and maximum data transmission capacity has shown that traditional cloud-based systems cannot handle real-time data processing tasks. Fog and edge computing have developed into revolutionary technologies because they solve these problems through their ability to execute processing operations near data storage locations. The research investigates how these factors can improve system performance through increased scalability and security measures while optimizing resource utilization to become essential components of future data-centric systems and Internet of Things (IoT) networks.

1.3 Objective

The primary objective of this study is to provide an in-depth analysis of fog and edge computing, highlight their key features, architectures, and differences. This paper target to understand how fog and edge paradigms extend cloud capabilities to the network edge and enable efficient data processing, reducing latency and enhancing real-time decision-making. In doing so, we try to highlight the opportunities and benefits offered by fog and edge computing. Additionally, this paper also aims to explore the challenges associated with these paradigms. Finally, the objective is to present a comprehensive overview of ongoing research efforts and potential future directions in fog and edge computing. This study is committed to advancing the knowledge about fog and edge computing, which could transform the way to handle and analyze data and ultimately propel the IoT expansion, paving the way for a more intelligent and connected society. The following are the study's contributions:

Highlight the appearance of emerging technology in literature with standard definitions of fog and edge computing given by Cisco, OpenFog consortium, and others [1] [8].

Based on various standard definitions, suggest a definition for fog and edge computing, and also provide a comparison of fog and edge computing.

Proposed a new fog-edge computing architecture and its components of the architecture. Also provides a comparative analysis of various fog and edge computing architectures.

The remainder of this article is organized as follows. In the next Section 2 provides an overview and architecture of fog and edge computing; this section also provides a comparative analysis of fog and edge architecture. Section 3 provides opportunities in the field of fog and edge computing paradigms. Section 4 provides the issues and challenges in the field of this computing paradigm. Section 5 provides the

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details of research efforts and their solution in detail. Sections 6 and 7 provide future direction and conclusion, respectively.

II. FOG AND EDGE COMPUTING OVERVIEW AND ARCHITECTURE

Fog computing and edge computing are two distributed computing paradigms that aim to bring computing resources closer to the data source, enabling faster data processing and reducing latency [9]. While they share similar goals, they differ in terms of their architectural approach and deployment scenarios. The appearance of emerging paradigms is shown in Figure 1.

Figure 1: The appearance of Edge, IoT, Cloud, and Fog computing in the literature [6] [10]

- In 2004-2005, Edge computing was introduced in the literature.
- Although the IoT was conceptualized in 1999 at the Massachusetts Institute of Technology (MIT) Auto-Id Center, the earliest published publications on the topic did not appear until 2006.
- Cloud computing was first deployed by Google and Amazon in 2006. Google CEO Eric Schmidt mentioned it at the Search Engine Strategies (SES) conference, which focuses on search engine methods. Cloud computing was described as a "commercial product" by Amazon.
- There is a well-established precedent for fog computing. Flavio Bonomi, a CISCO employee, initially brought it up and defined it in 2012.

2.1 Fog Computing

Due to the exponential and continuous growth of IoT-enabled devices, such as mobiles, computers, CCTVs, and smart devices, a significant volume of service requests is transmitted from these IoT devices to Cloud resources to access various services. However, this unimpeded flow of data in the network gives rise to challenges such as network congestion, security threats, and subpar quality of services. To address these issues, fog computing serves as an intermediary layer between cloud computing and IoT devices. Fog Computing facilitates efficient access to cloud computing services for IoT devices, leading to enhanced performance in terms of speed, bandwidth, security, and quality. Here are some common standard definitions are as follows:

Definition 1: According to Cisco [9], Fog computing refers to decentralizing a computing infrastructure by extending the cloud through the placement of nodes strategically between the cloud and edge devices.

Definition 2: Flavio Bonomi et al. [1] defined Fog Computing as a heavily virtualized infrastructure, usually but not necessarily located on the edge of the network that supplies computing, storage, and networking facilities between IoT devices and conventional cloud data centers.

Definition 3: According to the OpenFog Consortium [3], Fog computing is a horizontal, system-level architecture that distributes computing, storage, control, and networking functions closer to the users along a cloud-to-thing continuum.

Definition 4: According to Naha et al. [11], Fog computing is a distributed computing platform where most of the processing will be done by virtualized and non-virtualized end or edge devices. It is also associated with the cloud for non-latency-aware processing and long-term storage of useful data by residing between users and the cloud.

According to Sharma and Sajid [8], the proximity of Fog nodes to IoT devices ensures that data processing occurs closer to the source, minimizing the interactions of IoT devices with Cloud resources. Fog computing extends the capabilities of cloud computing to the network's edge, bringing services closer to the data source or end devices [8]. Considering the above definitions, we define Fog computing as follows: *"Fog computing is a decentralized infrastructure that extends cloud capabilities by placing nodes between the cloud and edge devices. It distributes computing, storage, control, and networking functions closer to users, supporting both virtualized and non-virtualized end devices. This proximity allows for real-time data processing, reduces latency, and decreases dependency on cloud resources, enhancing the efficiency of IoT and edge applications".* This approach is very helpful for the distribution of data processing, storage, and application services across a continuum of fog nodes. In this approach devices are typically situated at the network edge, such as routers, switches, gateways, and access points. There are following key components and characteristics of fog computing discussed as follows:

- **Fog Nodes:** These are the those computing devices that make up the fog infrastructure and are responsible for processing and analyzing data at the edge. Fog nodes can be a powerful servers, industrial gateways, IoT devices, or even connected vehicles [3].
- **Fog Computing Architecture:** The architecture of a fog computing system consists of multiple fog nodes that form a hierarchical structure [1]. Nodes in this architecture are interconnected and work together to process and store data. Fog nodes are closer to the data

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source and perform initial data filtering, aggregation, and analysis, while higher-level fog nodes handle more complex tasks [3].

- **Proximity to Data Sources:** Fog computing emphasizes proximity to data sources. It enables real-time or near-real-time data processing. By reducing the need of data transfer to distant cloud data centers, fog computing minimizes latency and bandwidth requirements [9].
- **Scalability and Heterogeneity:** Fog computing supports a scalable and heterogeneous infrastructure. It allows a diverse range of devices and applications to participate in the fog network. This flexibility is crucial for accommodating the growing number of IoT devices and edge computing deployments [6].
- **Collaboration with Cloud:** Fog computing expands computing power to remote locations while it establishes connections with cloud computing systems [8]. The fog nodes have the ability to transfer their heavy processing tasks to the cloud for more thorough examination and permanent data preservation. The shared method between fog and cloud systems enables their most effective resource use.

2.2 Edge Computing

Edge computing, also known as edge analytics or decentralized computing, pushes computing resources even closer to the data source, often right at the edge of the network [5]. It involves processing data on or near the devices generating the data, eliminating the need to transmit vast amounts of data to remote servers or cloud data centers [12]. Edge computing is a type of distributed computing that extends processing and data storage closer to the network's periphery, where it is closer to the devices that generate data. Conventional models of cloud computing involve passing information to off-site data centers for processing and analysis. In edge computing, however, processing and storage capabilities are moved nearer to the devices or sensors generating the data. According to Accenture, “The term 'edge computing' refers to a variety of networks and devices that are at or close to the user. It represents a new paradigm in computing. Edge is about processing data closer to where it is being generated, enabling processing at faster speeds and volumes, leading to more action-led results in real-time [4].

Researchers have different definitions of edge computing. Some of them are as follows:

Definition 1: According to Cisco, “Edge computing is a model that shifts computing resources from central data centers or public clouds closer to devices, that is, embedded at the edge of service provider networks” [9].

Definition 2: Satyanarayanan, a professor at Carnegie Mellon University in the United States, describes edge computing as: “Edge computing refers to a variety of architectural methods that aim to bring processing and storage resources closer to end users and devices, acting as an umbrella term for such endeavors” [4].

Definition 3: Shi et al. [12] defined edge computing as: “Edge computing refers to computer resources located at the network's edge, which provide localized data processing to reduce latency. Edge computing refers to technical improvements that make computation more efficient at the network's edge”.

Definition 4: According to Khan et al. [13], “Edge computing directs computational data, applications, and services away from Cloud servers to the edge of a network”.

Considering the above definitions, our proposed definition of edge computing is as follows: *“Edge computing is a model that shifts computing resources, including processing and storage, from centralized data centers or public clouds closer to end users and devices at the network's edge.”*

Edge computing is helpful to reduces latency and enhances efficiency by providing localized data processing”. There are the key components and characteristics of edge computing:

- **Edge Devices:** The network edge devices which include sensors and gateways and routers and switches and smartphones and IoT devices provide computing power which edge computing uses [12]. The devices used in this system have lower computing power than fog nodes.
- **Decentralized Processing:** The edge devices in edge computing perform data processing either on their own or through the adjacent edge servers or gateways. The system enables users to conduct analysis in real time while achieving instant results and decreasing network usage [14].
- **Latency Reduction:** Edge computing enables edge processing of data which results in lower latency and better application efficiency for uses that require quick response times such as autonomous vehicles and industrial automation and augmented reality [12] [14].
- **Localized Decision-making:** Edge computing allows localized decision-making through critical decisions which can be made at edge devices and edge servers without needing cloud support. The system enables offline operation through its ability to function without continuous cloud access [5].

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- **Centralized Cloud Interaction:** While edge computing emphasizes local processing. But it can still interact with cloud resources when necessary. Aggregated or processed data can be transmitted to the cloud for further analysis, long-term storage, or global decision-making [4] [12] [14].
- **Heterogeneity:** Heterogeneity in edge computing refers to the presence of diverse platforms, architectures, infrastructures, computing capabilities, and communication technologies used by different edge computing components which include end devices and edge servers and networks. The different software and hardware and technological standards used in devices lead to end device heterogeneity. On the edge server side, heterogeneity arises from differences in application programming interfaces (APIs), custom-built policies, and platforms. These disparities can lead to interoperability challenges, posing a significant obstacle to the successful implementation of edge computing. Network heterogeneity, on the other hand, encompasses the wide range of communication technologies that impact the delivery of edge services [13].

2.3 Fog vs Edge Computing

In the above section, we elaborate on fog and edge computing separately. This section compares fog and edge computing. The authors [13] have proposed fog computing and edge computing as similar concepts. They explained that fog computing is a type of edge computing. Cisco also defined fog computing as a type of edge computing [9]. Some other researchers have also introduced fog and edge computing as similar concepts. However, our paper considers that fog computing and edge computing are related but distinct concepts in the area of distributed computing. Because both computing has some key differences and work on different layers of the network. Table 1 shows the comparison between fog and edge computing.

Table 1: Difference between Fog Vs Edge Computing

Aspect	Fog Computing	Edge Computing
Definition	Extends cloud capabilities to the edge of the network, typically involving intermediate nodes between edge devices and the cloud.	Brings computing resources closer to the data source, minimizing latency by processing data at or near the edge devices themselves.
Location	Intermediate nodes are placed between edge devices and centralized cloud data centers.	Computing resources are deployed directly on or very close to edge devices.
Latency	Offers lower latency compared to cloud computing but may not be as low as edge computing.	Provides the lowest possible latency since data is processed locally.
Use Cases	Well-suited for applications that require real-time or near-real-time processing, data filtering, and some level of analytics at the network edge.	Ideal for applications where minimal latency is critical, such as autonomous vehicles, industrial automation, and IoT devices.
Scalability	Scalable, but scalability is limited by the capacity of fog nodes and intermediate devices.	Scalable, as edge devices can be added or removed easily, and processing tasks can be distributed across them.
Resource Availability	Offers more resources than individual edge devices, allowing for more complex processing and analytics.	Leverages the resources of individual edge devices, which may have limited processing power and memory.
Data Volume Handling	Suited for handling moderate to large data volumes as it can aggregate data from multiple edge devices before processing.	Best suited for handling smaller data volumes, especially data generated by individual edge devices.
Network	Somewhat dependent on network	Generally, more self-reliant as it can process data

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Dependence	connectivity, but can function with intermittent connectivity.	locally, reducing dependence on network connectivity.
Complexity	Moderately complex due to the need for intermediate fog nodes and associated network management.	Simpler in design and easier to manage, as it involves fewer network layers.
Cost	Potentially higher upfront cost due to the deployment of fog nodes and infrastructure.	Lower upfront cost as it leverages existing edge devices, but costs can vary based on device selection and deployment.
Security	Security measures must be applied to both edge devices and fog nodes. Data encryption and access control are crucial.	Security focus is primarily on individual edge devices, requiring robust device-level security measures.
Bandwidth	The bandwidth requirement is high. Data originating from edge nodes is transferred to the cloud.	The bandwidth requirement is very low. Because data comes from the edge nodes themselves.
Operating Cost	Operational cost is comparatively lower.	Operational costs are higher.
Privacy	The probability of data attacks is higher.	High privacy. Attacks on data are very low.
Power Consumption	The power consumption of node filters important information from the massive amount of data collected from the device and saves it in the filter high.	The power consumption of nodes is low.
Example	Smart cities, smart grids, and applications that require localized data processing with some cloud interaction.	Autonomous vehicles, industrial automation, IoT devices, and any application where real-time decision-making is vital.

Table 1 provides a concise comparison of key aspects between Fog Computing and Edge Computing, highlighting their differences and use cases. While fog and edge computing share the goal of improving data processing efficiency by bringing resources closer to the source, they operate at different levels of the network and are optimized for different types of applications. They work together to create a strong and adaptable distributed computing environment. The decision between the two depends on the particular needs of the application and the trade-offs you are willing to make regarding latency, scalability, complexity, and cost.

2.4 Architecture and Components

The architecture of Fog and Edge computing as shown in Figure 2.

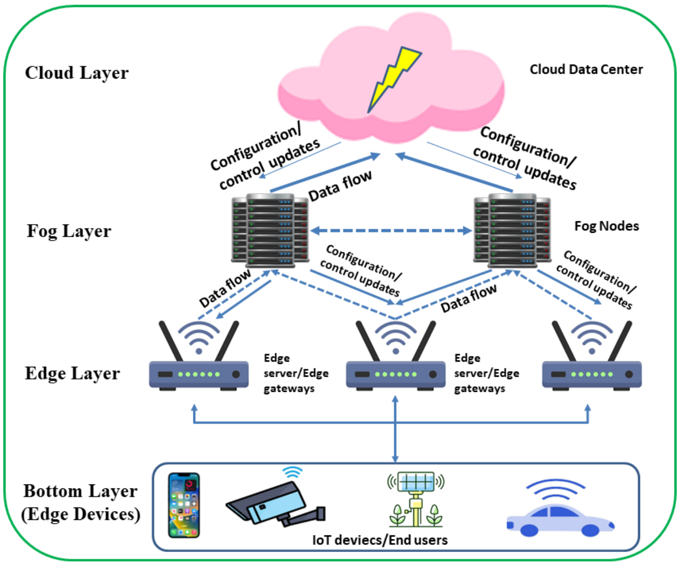

Figure2: Architecture of Fog and Edge Computing

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When we talk about data storage, administration, and processing, fog, and edge computing provide a decentralized and flexible architecture that is positioned between the cloud and the data source [14]. These concepts bring cloud computing capabilities to the edge of the network, where data sources and end-users are located. The purpose of this architecture is to overcome the limitations associated with traditional cloud computing, including issues like high latency, bandwidth constraints, and the need for real-time processing. This paper proposed a four-layer architecture composed of (1) Bottom Layer - smart devices/Edge devices and sensor layer for data collection, (2) Edge Layer- consisting of edge devices (routers or even smartphones) and sending to layer III to be more processed, (3) fog layer- consist of servers, which uses computation resources for analysis of the input data and preparing them for entering the cloud layer, and (4) cloud layer capable of large intensive-analysis. For more clarity, we used the '1+5' architectural views model to comprehensively analyze this architecture as depicted in Figure 2. Rozanski *et al.* [15] explained, "An architectural view represents the specific aspects or elements of the architecture that address the concerns it aims to resolve, aligning with the interests of the stakeholders for whom those concerns are significant". The author [16] presents a 1+5 model of architectural views for designing an IT system. In this paper, this model divides the system's representation into six perspectives, which are represented in Figure 3, where one **central view** provides an integrated understanding of the architecture, supported by five supplementary views addressing functional, dynamic, physical, and contextual aspects. The architecture of fog and edge computing typically comprises the following view model:

2.4.1 Central View: Unified Architectural Diagram

The central view integrates all perspectives into a unified representation of the fog and edge computing environment. Figure 2 shows the four-layer architecture, which consist of the following components:

2.4.1.1 Bottom Layer (Edge Devices)

This layer is made up of various physical devices known as edge devices, which are responsible for gathering data. Edge devices serve as the endpoints in a network that both produce and occasionally use data. Common examples of these devices include sensors, actuators, and other Internet of Things (IoT) devices that engage directly with the physical world [7]. Generally, these devices have restricted processing and storage abilities.

2.4.1.2 Edge Layer

This layer consists of devices at the edge of the network and able to perform basic data processing and filtering. Edge servers, edge gateways, microcontrollers, or even smartphones are the type of devices at this edge layer. They connect to edge/end devices and send data upstream to the fog layer. Edge servers/edge gateways are computing entities situated in proximity to edge devices [12]. These devices possess greater computational power and storage capacities compared to the edge devices themselves. Edge servers/edge gateways are responsible for local data processing, executing analytics, running applications, and delivering services directly at the edge of the network [14].

2.4.1.3 Fog Layer

The fog layer represents the distributed network of fog nodes, which are more powerful than the devices of the edge layer. Fog nodes can be physical devices, such as gateways or mini-servers, or they can be virtual instances running on existing infrastructure. It enables communication and coordination among the nodes for collaborative processing [17]. Fog nodes collect data from multiple edge layer, and perform more complex processing and analytics, and make decisions about what data to send to the cloud. Devices at fog layer store data for future use. The fog layer may employ various networking technologies, such as Wi-Fi, Ethernet, or cellular connectivity, depending on the deployment scenario [11].

2.4.1.4 Fog Network

The fog network is the connective fabric between edge devices and fog layer nodes, enabling two-way transfer of data and control messages over a mix of wired and wireless links (for example, Ethernet, Wi-Fi, cellular, or fog-specific protocols) [17]. In Figure 2, dotted arrows show data moving upward from the edge to the fog, solid arrows indicate control or configuration signals sent downward from higher layers, and the thick dotted arrows represent horizontal links between fog nodes. These lateral connections let fog nodes share information, coordinate and offload processing, and rebalance workloads across the network and helping to smooth peak demand, improve resource utilization, and increase overall system efficiency.

2.4.1.5 Edge Network

The edge network work as a connection between edge devices and edge layer devices by enabling seamless communication and data transfer between them. It comprises a mix of wired and wireless connections, including Ethernet,

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Wi-Fi, cellular networks, and specialized communication protocols specifically designed to support low-latency and high-bandwidth operations at the edge [12] [14].

2.4.1.6 Cloud Layer

The cloud layer comprises large-scale data centers that offer extensive storage for information that does not require real-time processing or local edge access, such as historical records, backups, and archives [17]. Cloud data centers also deliver substantial computational resources for heavy workloads; complex analytics, large-scale simulations, and machine-learning training are typically executed in the cloud to take advantage of its superior processing capacity [18].Beyond storage and computation, the cloud acts as a centralized management and monitoring platform for the entire fog–edge ecosystem, handling configuration management, software updates, and system-wide security oversight for connected devices and fog nodes. Interactions between the cloud layer and the fog and edge layers are described as follows:

- **Data Flow:** The fog layer typically forwards processed or aggregated data to the cloud, acting as a filter that pre-processes information and transmits only the relevant results for long-term storage or deeper analysis [8]. In Figure 2, the thick arrows depict this flow from fog to cloud.
- **Configuration and Updates:** The cloud serves as the centralized source for deploying configuration changes, security patches, and software upgrades to fog nodes and edge devices. In Figure 2, thin arrows represent these control and update signals moving from the cloud to lower layers.
- **Offloading Tasks:** Computationally intensive jobs that exceed the capacity of edge or fog resources may be offloaded to the cloud, freeing fog nodes to focus on latency-sensitive, local decision making and real-time processing [5].

2.4.2 Logical View: Functional Structure

The logical view highlights the functional organization of the four-layer fog and edge architecture. At the base, resource-constrained devices, sensors, and actuators collect raw data. The edge layer performs lightweight preprocessing, such as filtering and local analytics to provide low-latency responses for time-sensitive applications. The fog layer aggregates inputs from many edge nodes and enables distributed, cooperative processing across interconnected fog nodes. The cloud layer handles heavy computation and long-term storage, manages the system centrally, and pushes configuration updates to lower layers. Together, these layers form a scalable and efficient framework for decentralized data processing and management.

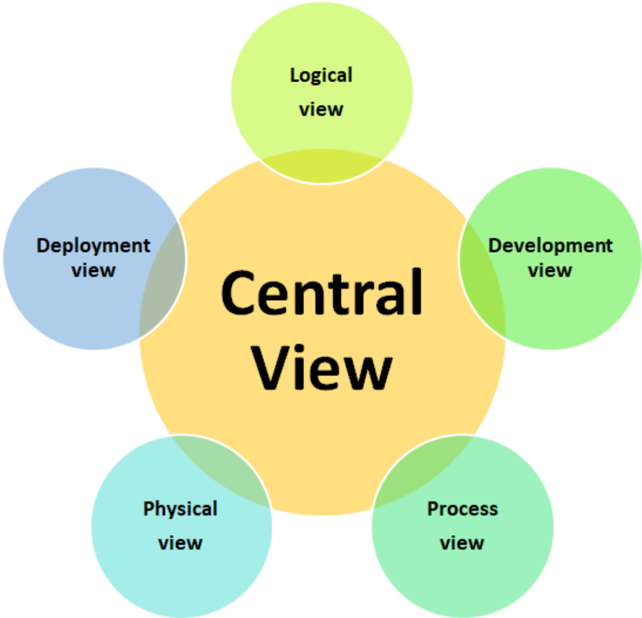

Figure 3: 1+5 Architectural Views Model

2.4.3 Development View: Software Architecture

The development perspective examines the software stack, tools, and frameworks that power fog and edge deployments. Modular, well-defined APIs enable seamless interoperability between edge devices, fog nodes, and cloud services, while middleware supplies core capabilities such as task scheduling, load balancing, and resource management. Virtualization allows fog nodes to flexibly allocate resources and integrate with cloud platforms. [19] Edge-focused platforms like AWS IoT Green grass and Microsoft Azure IoT Edge simplify packaging and deploying applications at the edge, making systems easier to scale and maintain.

2.4.4 Process View: Runtime Behavior

The process view of the fog–edge system describes its operational functions by explaining how data and tasks move through different system layers. Edge devices and sensors produce unprocessed data which receives its first preprocessing treatment through edge processing that performs filtering and aggregation and event detection before sending data to fog processing. The fog layer transmits only essential information to the cloud for advanced analysis which requires long-term storage whereas the system uses cloud computing to handle it's most demanding tasks [5]. The system retains its latency-sensitive functions and real-time capabilities at the edge and fog locations for immediate response times. The system uses control traffic which includes configuration updates and security patches and

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synchronization commands to distribute information from the cloud to fog and edge layers in order to maintain system consistency and operational integrity.

2.4.5 Physical View: Hardware Deployment

The physical views are concerns about the concrete hardware elements and their interconnections across the architecture. Resource-constrained edge devices like IoT nodes, wearable's, sensors, actuators capture data and typically communicate over short-range protocols such as Bluetooth. Edge gateways (such as routers, smartphones) serve as intermediaries that perform gateway-level processing and bridge devices to the fog tier via wired and wireless links (Wi-Fi, Ethernet, cellular) [17] [11]. Fog nodes which exist as mini-servers and virtual instances provide edge devices with their exceptional computational power and storage capabilities while enabling distributed task execution through horizontal peer-to-peer communication.

2.4.6 Deployment View: Real-World Applications

The Deployment view show, how fog and edge computing are used in real-world environment across multiple disciplines. In smart cities, the edge layer devices are used to monitors traffic in real-time using sensors and cameras. The fog layer combines and analyzes the traffic data for route optimization, and the cloud layer does long-term analysis for urban planning. In the field of healthcare, wearable devices at the edge layer is used to monitor patient data and detect anomalies; the fog layer analyzes key situations in real-time and provides alerts; and the cloud layer collects past data and trains prediction models. In IIoT (industrial IoT), edge-enabled machines/nodes track the production parameters, where the fog layer performs advanced analytics to improve operational efficiency, and the cloud layer enables predictive maintenance and centralized monitoring. By analysing and structuring this discussion in the 1+5 Architectural Views Model, this section provides a multi-dimensional analysis of the fog and edge computing architecture, enhancing clarity and facilitating a comprehensive understanding of its components, functions, and practical relevance. In this architecture, the cloud layer plays a crucial role in fog and edge computing by providing scalable storage, high-performance processing, and centralized management capabilities. By strategically utilizing the cloud alongside fog and edge devices, to create a robust and efficient architecture for various applications that require a balance between real-time processing, local control, and powerful analytics. Several research papers are discussed in Table 2 about the architecture of fog and edge computing from 2017–2023. The research work of the selected paper is as follows:

Liu *et al.*, 2017 [20] presented a paper with comparisons to other technologies, the definition and architecture of fog computing, the framework of resource allocation for latency reduction combined with reliability, fault tolerance, privacy, and underlying optimization problems, and then investigated an application scenario and conduct resource optimization by formulating the optimization problem and solving it via a genetic algorithm. Wang *et al.*, 2017 [21] are driven to address the resource management dilemma by developing the first framework to manage edge nodes, the Edge NOde Resource Management (ENORM) framework. They presented mechanisms for supplying and automatically scaling edge node resources. A revolutionary capillary computing architecture was developed by Taherizadeh *et al.*, 2018 [22]. It depends on a series of new services, such as an Edge/Fog/Cloud Monitoring System and a Capillary Container Orchestrator, and benefits from common Fog and Cloud computing methodologies. There is a hierarchical reference architecture for smart manufacturing introduced by Qi and Tao, in 2019 [23]. It is anticipated that the architecture will be used in the digital twin shop floor, which presents a promising avenue for novel production applications.

In 2021, Skarlat and Schulte [24] created and implemented the fog computing framework FogFrame, which is capable of managing and monitoring edge and cloud resources in fog landscapes as well as executing Internet of Things (IoT) applications. FogFrame enables communication and interaction as well as application management in a fog landscape, namely decentralized service placement, deployment, and execution. In order to promote a mutual understanding of architectural difficulties in fog computing, Mann, 2021 [25] produced a study that presents a conceptual framework for thinking about architecture in fog computing. Three separate dimensions are used in this conceptual framework to explain architecture. Several architectural views may be established based on the three dimensions of architecture to emphasize various features of the building and accommodate the varying perspectives of the participating disciplines. Núñez-Gómez *et al.*, 2021 [26] introduced HIDRA, a novel architecture for resource orchestration in fog computing environments using an Ethereum blockchain implementation. A prototype implementation on a testbed comprised of single-board computers was carried out. This study aims to define and evaluate HIDRA, a distributed, heterogeneous, and interoperable architecture for orchestrating applications operating in a fog computing environment using smart contracts and blockchain technologies.

Liu & Chen, 2021 [27], In order to get beyond obstacles like connecting environment limits and bandwidth restrictions, computing resources must be distributed between A IoT gateways or tiny cloud servers. In this study, a new hardware

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layer was added to the fog edge computing IoT (FECIoT) architecture. In particular, an IoT protocol, microservices, containers, hardware artificial intelligence engine technology, and a 3.5-tier edge computing AIoT (ECAIoT) architecture were created. In order to conduct latency-sensitive analysis with low latency, Muneeb et al., 2021 [28] suggested a prototype of a multi-layered architecture for data analysis across cloud and fog computing layers. The primary objective of this study is to improve the real-time data analysis system based on IoT devices using this multi-layer fog computing platform. In [9], the authors discussed various computing paradigms, features, and reference architecture of fog computing, analyzed its integration with IoT, examined fog system algorithms, and addressed challenges of Fog Computing as a middle layer between IoT devices and cloud data centers.

A new integrated edge-fog-cloud architectural paradigm is put out by Alharbi & Aldossary, 2021 [29], and it promises to improve the energy efficiency of smart agriculture systems and the associated carbon emissions. In order to process and analyze agricultural data that has to be operated in real-time (such as weather temperature, soil moisture, soil acidity, and irrigation), this architecture enables data gathering from several sensors in multiple levels (fog, cloud, and edge) with help of mathematical modeling, specifically Mixed-Integer Linear Programming (MILP).

Abdali, *et al.*, 2021 [30] conducted a thorough analysis of fog computing, covering the most recent research to address and resolve the problems currently facing FC. They also conceptually reviewed and defined fog computing technology, taking into account its architecture, benefits, and open issues, as well as the optimization techniques used to achieve the best possible services. Asgha *et al.*, 2021[31] suggested a fog-based health monitoring system design to reduce latency and network use, as well as a novel Load Balancing Scheme (LBS) to balance the load among fog nodes while deploying the health monitoring system on a broad scale. The authors utilized the iFogSim tools to simulate and compare the results to the cloud-only implementation, Fog Node Placement Algorithm (FNPA), and LoAd Balancing (LAB) scheme in terms of latency and network use.

In their comparison of computing technologies, Quy *et al.*, 2022 [32] offer a shared architectural framework for fog computing-based Internet of Health Things (Fog-IoHT) applications. Additionally, this study outlines the difficulties and potential uses of fog computing in IoT healthcare applications. Ortiz *et al.*, 2022 [33] proposed a technological solution that uses three paradigms and specific technologies (agent-oriented software, SOA 2.0, and CEP) for the three layers of Collaborative Internet of Things(C-IoT) sensing, gateway, and services, with real-time data processing at the edge, fog, and cloud, respectively. Vehicular Ad-hoc networks (VANET) are a time-sensitive technology that uses less time to process a request from a vehicle. VANET and fog computing are infamous for their delays and latency. To address these issues, Farooqi *et al.*, 2022 [34] created a priority-based fog computing paradigm for smart urban vehicle mobility that decreases fog computing delay and latency. To enhance the fog computing infrastructure to fulfill latency and Quality of Service (QoS) standards, 5G localized Multi-Access Edge Computing (MEC) servers were employed, resulting in a significant reduction in delay and latency. Aleisa *et al.*, 2022 [35] proposed a fine-grained data access control model based on the IoT-Fog-Cloud architecture's attribute-based encryption to restrict access to sensor data while meeting permission requirements. This research also presents a blockchain-based certificate model for the IoT-Fog-Cloud architecture that enables IoT devices to authenticate with fog devices while meeting authentication criteria.

In 2023, Singh and Chatterjee [36] presented a Secure Framework based on the Edge of Things (SEoT). Developed for Smart Healthcare Systems. This framework is primarily intended for real-time health monitoring, ensuring the security and confidentiality of healthcare data in a controlled environment. This research discussed clustering techniques for analyzing bio-signal data for anomaly detection, as well as attribute-based encryption (ABE) for bio-signal data security and access. An IoT architecture based framework on a physical asset with three IoT platforms, MATLAB on a PC, and ThingSpeakis used as a cloud is presented in a study by Dogea *et al.*, 2023 [37]. In this study, a basic wireless sensor network used to create the five layers that made up the Internet of Things architecture. In order to increase the dependability of airplane components, this study demonstrates how temperature, humidity, air quality, and air pressure were measured, preprocessed, and visualized in real-time. Janbi *et al.*, 2023 [38] provide a taxonomy for research on the subject of distributed artificial intelligence (DAI), as well as a full assessment of all elements of DAI, including workflow, paradigms, infrastructure, management, and applications, and propose the imtidad framework for delivering distributed AI as a service (DAIaaS) and facilitating future network change. The authors additionally improve this framework and present the Imtidad Software Reference Architecture (RA) for developing and deploying DAI services.

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Table 2: A Comparative Study on the Architecture of Edge and Fog Computing

Authors	Methodology	Objective	Tools	Environments	Advantages	Limitations
Wang *et al.*, 2017	An Edge Node Resource Management framework that integrates edge nodes in the computing ecosystem to realize fog computing.	ENORM addresses the resource management problems of provisioning edge nodes for cloud applications, deploying workloads on provisioned edge nodes, and dynamic resource allocation on edge nodes.	JMeter	Edge Network	Reduced application latency by 20-80% and data transfer /communication frequency between edge node and cloud by up to 95%.	No one uses algorithms or techniques for dynamic resource management. Real-world deployment, Security, network conditions, and system integration are ignored.
Liu *et al.*, 2017	Conduct resource optimization by formulating the optimization problem and solving it via a GA.	A framework for resource allocation and latency reduction is proposed.	-	Fog Network	Reduced the latency calculation process	Challenges in Data Processing, the complexity of Fog, and latency-sensitive issues
Taherizadeh *et al.*, 2018	Design and development of a capillary computing architecture that leverages Edge, Fog, and Cloud computing approaches.	Support computationally and data-intensive applications running at the edge of the network, such as on cars, robots, Raspberry Pis, and smartphones.	GitHub	Fog-Edge Computing	Improved Elasticity Management, Reduced Network Traffic, and Scalability	Complexity, Resource Overhead, Security, and Integration Challenges
Qi & Tao, 2019	A hierarchical reference architecture for smart manufacturing is proposed, which leverages state-of-the-art technologies such as cloud, fog, and edge computing.	To enhance smart manufacturing systems by addressing network limitations and enabling real-time applications through this architecture.	-	Edge-Fog-Cloud	Improved Data Processing Efficiency, Real-time Responsiveness, Optimized Robustness, Scalability, and Bandwidth Usage	Complex Implementation, Costs, Security Concerns, Interoperability
Skarlat & Schulte, 2021	FogFrame aims to manage and monitor edge and cloud resources in fog landscapes, as well as execute IoT applications.	To optimize service placement within the fog landscape by formalizing a system model, defining objective functions and constraints, and implementing greedy and genetic algorithms.	Fogframe framework and Raspberry Pi	Fog Network	Fogframe offers several advantages for fog computing, including stability, compatibility, and effective service distribution.	Challenges to address, such as dynamic adaptability, and optimizing fog landscape topologies
Mann, 2021	The framework is designed to provide a structured approach to reasoning about	To address the problem of divergent interpretations of the term “architecture” in	-	Fog Network	Conceptual Framework, Usability, and Extensibility	Generalizability, Applicability to Other Fields

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	architecture in FC.	the context of FC.				
Núñez-Gómez *et al.*, 2021	The study involves the development and testing of a novel architecture called HIDRA for resource orchestration in FC environments.	To describe and validate HIDRA with the use of Ethereumblockchain implementation for smart contracts, distributed and reliable information storage.	Blockchain platform Geth and Docker, and Raspberry Pi	Fog-Edge Computing	Efficient Resource Management, Distributed and Autonomous, Transparency and Immutability, Fault Tolerance	Complexity, Resource Constraints, Scalability, Security, Privacy.
Chen & Liu., 2021	Development and expansion of the FECIoT architecture to address the challenges posed by the explosive growth of AIoT devices and the need for distributed computing resources	Offer low latency, fast response times, and scalability for various scenarios and demands, enabling resource management and flexible scaling without central cloud services.	Raspberry Pi 4.0 Nvidia Jetson TX2	Edge Computing	Improved performance, effective load balancing, enhanced edge computing,	Complexity, Resource Overhead, Integration Challenges,
Muneeb *et al.*, 2021	To develop of a multi-layered architecture from new technologies and the IoT era, focusing on compute-intensive applications and data analytics.	To minimize latency in data analysis tasks, particularly in latency-sensitive applications.	iFogSim	Fog Computing	Low Latency, Efficient Resource Management, Real-Time Data Analysis, Flexibility, and Energy Efficiency	Complexity, Integration Challenges, Resource Overhead
Sabireen & Neelanarayanan, 2021	The study reviews various computing paradigms and features of FC and present an in-depth reference architecture of FC with its various levels.	To explore how FC can address the challenges faced by integrated cloud computing when dealing with IoT applications.	-	Fog Computing	Reduced Latency, Improved Security, Efficient Resource Management, and Scalability	Complexity, Resource Intensive, Interoperability, Data Consistency
Alharbi & Aldossary 2021	An integrated edge-fog-cloud architectural paradigm is proposed for smart agriculture systems using MILP.	To optimize the efficiency in terms of energy consumption, carbon emissions, and network traffic over the traditional cloud-based architectures in smart agriculture systems.	CPLEX	Edge-Fog-Cloud Computing	Energy Efficiency, Reduced Carbon Emissions, Real-time Processing, and Network Traffic Reduction	Complex Implementation, Resource Availability, Data Privacy and Security, Machine Learning Integration
Abdali *et al.*, 2021	To conduct a comprehensive survey of FC technology. The researchers reviewed existing literature and analyzed FC based on its core concept, architecture, applications, and	To highlight the optimization methods used in FC, specifically focusing on energy, latency, cost, and reliability.	-	Fog Computing	Proximity to Edge Devices, Lower Latency, Energy Efficiency, Cost Efficiency, and Reliability	Complexity, Security Concerns, Scalability, Interoperability, Resource Allocation

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	optimization methods.					
Asghar *et al.*, 2021	Propose a fog-based health monitoring system architecture and a LBS to distribute the load among fog nodes when the system is deployed at a large scale.	Suggest a fog-based architecture for health monitoring systems to reduce latency and network use in large-scale deployments.	iFogSim	Fog Computing	Reduced Latency, Load Balancing, Efficiency, and Realistic Simulations	Complexity, Resource Limitations, Real-World Validation, and Scalability
Quy *et al.*, 2022	Present an architectural framework for Fog-IoHT.	To explore the role of FC in healthcare IoT applications.	-	Fog Computing	Low latency, energy efficiency, improved performance, and reliability for IoT healthcare applications	High service response time and increased computing costs.
Ortiz *et al.*, 2022	A software architecture is proposed for the C-IoT that integrates three tiers: edge, fog, and cloud.	Present a novel software architecture that overcomes the identified deficiencies. This architecture should be suitable for managing resources at the edge, fog, and cloud tiers.	JADE & CEP engine	Edge-Fog-Cloud	Enhanced network performance, scalability, efficient data processing, and real-time decision making:	Complexity, Data Privacy, Interoperability Challenges, Resource Demands
Farooqi *et al.*, 2022	To develop and evaluate a fog computing model for smart urban vehicle transportation. The researchers compared cloud and fog computing in the context of VANETs using a 5G network.	To address the challenges of delay and latency in fog computing for VANETs.	-	Fog Computing	Reduced Delay and Latency, Enhanced Communication Efficiency, Smart City Benefits,	Scalability, Complexity, Energy Consumption, and Communication Costs
Aleisa *et al.*, 2022	To address security challenges in the IoT-Fog-Cloud architecture by proposing two security models: a blockchain-based certificate model for authentication and a fine-grained data access control model based on ABE for authorization.	Propose security models (blockchain-based certificate model and fine-grained data access control model) to address security challenges in the IoT-Fog-Cloud architecture.	DHT11 sensor + Raspberry Pi and AWS Cloud	Real-world environment	Improved Security, Access Control, Real-Life Experiments, and evaluate the performance and efficiency of these security models in real-life experiments.	Performance Impact, Complexity, Resource Requirements, and Limited Validation
Singh & Chatterjee 2023	Clustering approaches for analyzing bio-signal data for abnormality detection and ABE for bio-signal data security and secure access.	A SEoT for Smart Healthcare Systems.	Weka Explorer (Weka Machine Learning tool).	Edge Network	Quick response in case of the production of abnormal data and store/access the sensitive data	Hardware cost increases

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					securely.	
Dogea *et al.*, 2023	Deploying an IoT architecture in aircraft wings to collect and analyze data from sensors embedded in the wings.	Enhance aircraft component reliability, support in-flight IoT services, and enable predictive maintenance through real-time data collection and visualization.	MATLAB &ThingSpeak	Fog and Edge Network	Real-time Data Transmission, IoT Architecture Design, verification of WSN Functionality	Limited Environmental Conditions, Threshold-Based Pre-processing, Lack of Detailed IoT Platform Information, Limited Mention of Data Security
Janbi *et al.*, 2023	The Imtidad framework for the provisioning of DAIaaS over the cloud, fog, and edge layers.	To advance the understanding and development of DAI as a field and to enable the provisioning of DAI as a service, DAIaaS.	-	Fog-Edge Computing	Imtidad framework, reference architecture, future networking vision	Complexity, Heterogeneity, Computational Burden, Standardization.

III. OPPORTUNITIES FOR FOG AND EDGE COMPUTING

Fog and Edge Computing offer numerous opportunities for various industries and applications. These opportunities arise from their ability to process, store, and analyze data closer to the data source or end-user, providing real-time insights and reducing the dependence on centralized cloud resources. Here are some key opportunities:

3.1 Reduced Latency and Improved Response Time

Latency refers to the time delay between the moment data is generated and the moment it is processed [3]. With Fog and Edge Computing, data can be processed locally, closer to the point of generation. This reduces the time taken to transmit data to distant data centers for processing and receiving the results. This reduced latency delivers advantages to applications which need applications that need instant or almost instant response times to their operations. The user experience improves when response times increase [4] [39]. Users experience frustration when cloud applications experience delays because their data must travel over extended distances. The use of edge computing enables services to provide faster responses which results in better application performance and increased customer satisfaction [40] [36]. The main benefits of fog and edge computing systems include their ability to scale up operations while maintaining efficient performance.

3.2 Scalability and Efficiency

According to research, systems achieve scalability through their distributed architecture and load balancing and resource pooling and ability to support various device types [5]. The fog and edge computing systems achieve their full operational potential through their capacity to make energy-efficient decisions while reducing latency and optimizing bandwidth and enabling immediate decision-making abilities. The process of adding new edge devices and fog nodes creates primary obstacles to maintaining scalable operations [11]. The network should allow new device and node additions to occur without creating any operational hurdles or network performance issues.

3.3 Enhanced Security and Privacy

With fog and edge computing, sensitive data can be processed locally, closer to its source, reducing the risk of data breaches during transmission to central servers. This localized processing enhances data privacy and security compliance [39]. With the adoption of fog and edge computing concepts, more cloud-based applications are shifted to the edge of the network. Upon deployment and connection to IoT devices, we could easily change our house to a more digitalized medium with automatic adaptation to behaviours. 5G enabled computing networks require more security and privacy for vehicular networks [41,42,43]. Despite its considerable advantages, some privacy and security issues should be addressed. For instance, the attitudes of a family can be easily read through simple access to the data collected by the

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corresponding sensor deployed in the house. Thus, data privacy and security have posed serious challenges to the development of edge and fog computing [14].

3.4 Real-Time Decision-making

Fog and edge computing enable real-time data processing and decision-making by processing data locally at edge devices, which include IoT sensors, gateways, or edge servers [4], which is crucial for applications where immediate responses are required [2][3]. The approach achieves substantial latency reductions which enable rapid system responses that are required for disaster response operations and healthcare monitoring systems and financial trading activities. The network decision process operates through all network components which include edge devices and fog nodes and cloud servers while making essential choices near the data location [6][8]. The combination of edge-based machine learning models and multiple data sources and inter-edge communication and system backup systems and strong protective measures enables operators to make instant decisions with higher efficiency and system dependability [11]. The system uses ongoing performance tracking and active performance control to guarantee peak operational efficiency which benefits self-driving vehicles and factory automation systems and immediate Internet of Things data processing.

3.5 Resource Utilization and Cost Efficiency

Fog and edge computing optimize resource utilization and enhance cost efficiency through their ability to process computational tasks and data closer to the edge which results in lower data transfer expenses and better resource management [14] [5]. The methodology implements energy-saving techniques but needs fresh resource management systems to achieve efficient resource use. The main methods of operation consist of resource profiling and monitoring and virtualization and containerization and load balancing and dynamic resource allocation and edge intelligence and analytics and caching and edge-optimized algorithms [44]. Resource management improves through energy efficiency optimization which includes data compression and deduplication and predictive maintenance and cost modeling and budgeting and the implementation of a hybrid cloud-fog-edge system. Resource scaling policies together with open-source solution implementation and favorable vendor contract negotiations create a business environment that operates at reduced expenses.

IV. ISSUES AND CHALLENGES

As an emerging technology, fog and edge computing aim to address the challenges faced by the large volume of data and increasing demand in real time processing due to IoT, 5G services and other interconnected technologies. While these emerging technology offering numerous advantages, but there are also several issues and challenges associated with their implementation, which is shown in Figure 4.

Figure 4: Issues and Challenges of Fog and Edge Computing

4.1 Network Connectivity and Communication

Fog and edge computing face network connectivity and communication problems which create obstacles to building reliable connections for data transfer between edge network devices and computing resources and sensors. Achieving minimal data transmission delay between edge devices and central systems or between multiple edge devices proves to be a complex task [8]. Organizations face challenges in transferring vast amounts of information because their limited bandwidth capacity causes operational slowdowns which lead to decreased system efficiency [9]. The design and operation of complex network topologies require multiple device layers which extend from edge devices to central servers to achieve optimal data transmission performance [45]. Organizations need to create communication protocols which address different device requirements while maintaining system compatibility through standardization processes.

4.2 Resource Constraints and Heterogeneity

Resource constraints and heterogeneity is also a major issue in the fog and edge computing environment. Various edge devices, such as sensors and IoT devices, these devices have limited processing power, memory, and storage capacity [1]. Similarly, fog nodes also may have resource limitations.

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This can lead to difficulties in executing complex applications and may require careful resource management to avoid overloading the nodes. The edge and fog computing environment consists of diverse types of devices, platforms, and protocols. Ensuring seamless interoperability among these heterogeneous components can be complex and time-consuming [13]. Here's a closer look at these challenges:

- **Resource Constraints**

Edge and fog computing face multiple resource limitations which render them unsuitable for resource-demanding applications because they have restricted processing capabilities [46] and because their memory capacities prevent them from running data-heavy programs and advanced algorithms and their local storage capacity prevents them from managing extensive data sets and power limitations from battery-operated devices restrict their operational time and their low-bandwidth network connections result in slower data transfer rates and diminished real-time processing abilities and their cooling systems cannot effectively manage heat dissipation during extreme environmental conditions which results in decreased computational efficiency [44].

- **Heterogeneity**

Fog and edge computing environments face several challenges due to their heterogeneous nature which includes multiple device types that operate with different architectural systems which include various operating systems and software stacks [8] and multiple network types which combine wired and wireless and cellular connections and the need to create interoperability solutions for different data formats and communication protocols [12] and the geographical distribution of edge devices which creates different latency levels and resource availability and network operation standards and the different operational lifetimes of edge devices which require effective management to achieve system stability [14].

4.3 Data Management and Distribution

The distributed environment requires data synchronization and consistency to function properly. The process of managing data among edge devices and fog nodes and cloud data centers becomes difficult when data duplication and loss must be be prevented. Handling the large data volumes which edge devices produce remains a major challenge for organizations [46]. The Data management and distribution process experiences multiple challenges which include Data transmission that needs to operate effectively while maintaining reliable data transmission throughout the network to achieve minimum latency and bandwidth usage in areas with restricted connectivity. The implementation of scalable storage solutions faces difficulties because they must process growing edge device data while maintaining data integrity and availability [13]. The two main challenges involve controlling data distribution through multiple network nodes and layers to achieve smooth data movement and processing and securing data during transmission and storage against unauthorized access while meeting data privacy compliance requirements [47].

4.4 Security and Privacy Concerns

Security threats become more dangerous for edge and fog environments because their system distribution creates multiple points of entry. The ecosystem security system faces difficulty because people connect too many devices and nodes which creates more attack points [47]. The processing and storage of data across multiple distributed nodes creates privacy issues which require organizations to implement strict data protection protocols [2]. The network edge needs to protect user privacy through usage control while securing data because both functions serve as vital network protection elements. A home environment IoT system needs to collect data because it reveals extensive personal details about users [48]. The presence of electricity and water consumption data allows people to determine whether someone is inside or outside an empty house. Providing services in these situations while protecting users' privacy creates a major obstacle. The solution requires data pre-processing through the process of anonymizing personal details which includes face image masking from video recordings. The network's edge still contains multiple obstacles which block data security and user privacy protection [12]. The first community challenge requires people to learn about both privacy and security protection methods. To illustrate, consider the security of WiFi networks. The 439 million US households with wireless internet access face a major security risk because 49 percent of them operate unsecured WiFi networks which 80 percent of users access through factory default router passwords. Public WiFi hotspots show an alarming security problem because 89 percent of them operate without any security protection [49].

4.5 System Complexity and Management

To manage large and complex networks becomes more difficult as the number of devices and applications are increases. It is a challenging task to properly configure, monitor, and maintain different network components [20]. Problems such as hardware failures, software bugs, wrong settings, or compatibility issues are also hard to detect and fix [40]. Using automation tools can help manage the network more efficiently, but they require advanced tools and skilled people to operate them [24]. Networks must also be designed

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to grow smoothly without affecting performance, security, or reliability. In addition, organizations must control the costs of hardware, software, and technical staff.

V. RESEARCH EFFORTS AND SOLUTIONS

This section of this paper is representing some research efforts and solutions in the field of fog and edge computing, which is shown in Figure 5.

5.1 Network optimization and communication protocol

Researchers are working on optimizing network protocols and communication strategies for efficient data transfer between edge devices, fog nodes, and the cloud. The of aim of all these solutions is to provide guaranteed QoS levels for different types of applications, which are running at the edge, to ensure responsiveness and reliability. For fog and edge computing environment, network optimization and communication protocols, refers to efforts and solutions aimed at improving the efficiency, reliability, and performance of communication. These environments are characterized by a diverse set of devices and nodes, often with limited resources, and they require specialized approaches to ensure effective communication. There are following research efforts and solutions in this domain.

- **Low-Latency Communication**

Researchers are focused on developing communication protocols and algorithms that minimize latency in fog and edge environments [10]. This is critical for real-time applications like autonomous vehicles and industrial automation [50]. Protocols like Message Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP) are designed to reduce overhead and improve responsiveness in IoT and edge scenarios.

Figure 5: Research efforts and solutions in the field of fog and edge computing

- **Scalable Communication**

Due to accommodation of multiple devices and nodes, scalability is a big problem in the field of fog and edge computing [9][8][14][5]. Researchers are working on solutions to handle this scalability problem effectively. Scalable communication refers to the ability of a communication system or technology to handle an increasing volume of data, users, or devices while maintaining performance, reliability, and efficiency [5][10].

- **Heterogeneous Device Communication**

Edge and fog environments contain multiple devices that operate at different performance levels and support distinct methods of communication. Research is focused on creating solutions that enable different device types to communicate with each other without interruption [20]. Heterogeneous device communication describes the process of devices that possess different hardware and software and communication protocols and operational capabilities exchanging data and information with each other [10]. The combination of protocol adaptation layers and middleware with standard communication protocols such as Hypertext Transfer Protocol (HTTP) and Hypertext Transfer Protocol Security (HTTPS) and WebSockets enables devices to achieve interoperability.

- **Security and Privacy-Enhanced Protocols**

Fog and edge environments require strong security measures. Researchers are developing secure and privacy-enhanced communication protocols to protect data and devices from threats [40]. According to [48], existing mechanisms for the cloud cannot be applied to edge environments. Roman et al. [51] describe the security threats which create challenges for both edge and fog computing environments. The use of end toend encryption together with authentication mechanisms and access control through Transport Layer Security (TLS) and OAuth enables edge communication to achieve better security and privacy protection.

- **Edge-to-Cloud Integration**

The process of combining edge and fog resources with cloud services requires effective communication protocols and methods. The system needs to create methods which will handle data processing by first selecting important information before sending it to the cloud. The system should delay sending data to the cloud until necessary. The system should first process important data while handling less important information through local processing to achieve better bandwidth management and lower latency times [34]. Researchers are developing hybrid communication protocols which will enable data synchronization and workload sharing

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between edge and fog and cloud systems. The system requires communication protocols which operate efficiently while using minimal resources in edge environments. The most common protocols for edge-to-cloud communication include MQTT and CoAP and HTTP/2 [52].

- **Quality of Service (QoS)**

Applications require different service quality levels in fog and edge environments. The researchers work to enhance the quality of service which exists in their communication systems. The researchers develop standard quality of service metrics together with measurement techniques which specifically suit fog and edge computing environments [53]. The metrics will measure performance through latency and throughput together with system reliability and availability and resource usage. The QoS-aware protocols together with traffic shaping mechanisms enable communication management which prioritizes application requirements [54].

- **Edge Caching and Content Delivery**

Data caching at the edge for frequently accessed information leads to decreased latency and enhanced communication efficiency [55]. The researchers conduct an investigation into algorithms and strategies which help them find the best methods to place content in edge locations. The process involves selecting the appropriate content to be stored at specific edge nodes according to access behavior and content popularity and importance. Fog and edge environments use content delivery networks together with Cloudflare and Akamai edge caching solutions to enhance their data delivery capabilities [55].

- **Machine Learning and AI for Network Optimization**

Machine learning and artificial intelligence techniques are being used to optimize network communication dynamically. Machine learning (ML) and artificial intelligence (AI) have emerged as powerful tools for network optimization in fog and edge computing environments. The technologies provide automatic decision-making capabilities together with predictive analysis and system automation features which improve network performance and operational efficiency and system reliability [56]. The ML algorithms enable network data analysis which allows real-time adjustments of communication settings to enhance operational efficiency and system dependability.

5.2 Resource Management and Allocation

The researchers create algorithms which optimize workload distribution between fog nodes and edge devices to achieve better resource utilization with shorter operational delays. Virtualization enables resource sharing through virtual machines and containers which helps reduce resource conflicts, yet virtual machines experience extended boot times and additional system management demands. B. Jia *et al.* [44] developed resource allocation methods for fog networks which function as a two-sided matching problem, and they utilized a double-matching deferred-acceptance method to achieve stable, cost-efficient resource distribution, while showing that the model can be expanded to include UAVs. The fog architecture developed by F. Bonomi *et al.* [57] allows users to virtualize all aspects of compute, storage, and networking through its policy-based provisioning system, which enables multiple applications to operate simultaneously, making it ideal for Big Data and IoT environments.

5.3 Data Management and Distribution Strategies

Researchers develop lightweight offloading and data-management techniques so edge devices, fog nodes, and the cloud share work efficiently while keeping latency low [58]. Approaches include fog-level aggregation, edge caching/replication, compression, and hybrid fog-cloud distribution to save bandwidth and speed access; examples include hybrid fog-cloud models [59], fog-assisted P2P sharing [60], and fog-aware replica placement with adaptive consistency (Fog Store) [61].

5.4 Security and Privacy Mechanisms

In recent years, there has been a significant surge in the volume of unstructured data, primarily hosted on cloud-based platforms. When using cloud storage, users relinquish complete control over their data, which introduces potential privacy vulnerabilities [13]. Traditional privacy protection methods primarily rely on encryption technologies. However, these approaches have become less effective in defending against internal attacks within cloud servers. To address this concern, an innovative three-layer privacy-preserving storage solution based on Fog computing was introduced in reference [62].

Wang *et al.* [63] introduce a power allocation approach of intermediate nodes that is formulated as a Bertrand game based on price competition to deal with the secure communication issues of wireless cooperative networks in the presence of multiple friendly but selfish intermediate nodes and prove that an optimal pricing scheme can maximize the secrecy capacity and achieve the optimal profits for the selfish friendly nodes. L. Lyu *et al.* [39] introduced a framework for smart metering aggregation known as the Privacy-Preserving Fog-Enabled Aggregation (PPFA) framework. This innovative framework is built upon the Fog computing architecture and leverages additive homomorphic encryption. PPFA empowers smart meters to enhance privacy by encrypting their data with

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the addition of concentrated Gaussian noise. The PPFA framework used a two layer encryption scheme. This scheme to keep aggregators unaware of individual data (first layer) and to authenticate participants (second layer). Tests show it preserves privacy while saving energy, easing bandwidth pressure, and lowering latency, but the authors note more evaluation is needed for distributed applications and heterogeneous queries.

Sohal *et al.* [40] proposed a cybersecurity solution with combination of a two-stage hidden Markov model, an IDS, and a virtual honeypot. This solution is used to classify edge devices as legitimate, sensitive, under attack, or compromised; a secure load balancer maintains resource fairness while the IDS continuously monitors and predicts breaches. Zhou et al. [64] present a context-aware task-allocation approach for mobile crowdsensing that assigns tasks at both edge and cloud levels to handle large-scale, real-time workloads in smart cities. Overall, while node-level processing helps privacy and performance, the decentralized edge architecture still increases the system's attack surface and demands strong security measures [47].

Edge devices broaden the attack surface and current edge frameworks still lack robust, widely deployed security, making data protection difficult and motivating ongoing research into integrity, confidentiality, and attack detection [13] [47]. Mohammed *et al.* [42] proposed FC-PA: Fog Computing-based Pseudonym Authentication scheme to secure 5G vehicular networks while keeping operations efficient. Al-Mekhlafi *et al.* [43] introduced a decentralized, fog-managed pseudonym-revocation approach using Chebyshev polynomials that lowers computational cost compared with elliptic-curve methods, improving scalability and suitability for real-time applications.

5.5 System Design and Management Approaches

The design and management of fog and edge computing systems require development of specific strategies and techniques and solutions which enable effective design and implementation and operation of these distributed systems. The following is a brief overview of research in this area: In studies [20,21,32] researchers have worked on optimal placement of edge and fog nodes considering aspects such as device capacity and workload distribution and latency requirements. The system requires development of placement algorithms which will help identify and distribute resources based on different workload types. Advanced techniques are being studied to ensure efficient management of resources such as CPU, memory, storage, and network bandwidth, so as to dynamically meet the demands of applications.

The edge orchestration systems develop systems which will automatically deliver resources and adjust workloads while handling capacity changes. Researchers are developing platforms which use auto-scaling and dynamic resource allocation to achieve optimal performance while reducing operational costs. The organization currently focuses on developing edge application development through adaptation of DevOps practices and CI/CD process for edge environments which will enhance development efficiency while decreasing time needed to deploy and update applications.

VI. FUTURE DIRECTIONS

Fog and Edge computing paradigms were driven by the need to process and analyze data closer to the source, which was becoming increasingly important with the growth of IoT devices and the demand for low-latency, real-time applications. Here are some potential future directions in the field of edge computing and fog computing:

6.1 Artificial Intelligence and Machine Learning at the Edge

The adoption of AI and ML technologies into edge networks has become a modern practice. This development allows operators to execute sophisticated computational frameworks on both edge devices and fog nodes which provide immediate operational insights without needing cloud services [65]. The field of big-data Internet of Things systems now depends on machine learning because it provides better data analysis methods than traditional data mining techniques. The research field involves developing AI-based solutions which enhance edge computing performance to meet the requirements of applications that demand low latency and stable network connections, which the cloud service fails to deliver [66].

6.2 Integration with 5G and Beyond

The deployment of 5G and future communication technologies will significantly impact fog and edge computing. The high bandwidth, low latency, and network slicing capabilities of 5G networks will enable new use cases and applications that require ultra-responsive edge processing [34]. 5G networks are the next generation of wireless cellular networks. 5G is characterized by low latency and high throughput, high amounts of data that are transmitted and generated, and the requirement to support a heterogeneous environment to allow for interoperability between various devices, network types, and quality of service (QoS) [67] requirements. Leveraging the high-speed connectivity of 5Gnetworks and the decentralized processing capabilities of fog computing enables real-time, non-contact autonomous

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healthcare monitoring within vehicular networks [68]. All these characteristics are unprecedented, never seen in previous generations' networks, and therefore require a new approach to fulfill the requirements, but also a vast number of new technologies, architectures, and innovations in mobile networks.

6.3 Edge-to-Cloud collaboration and Hybrid architectures

The upcoming future will bring about improved methods for uniting cloud services with edge computing capabilities. Applications will switch between edge and cloud environments according to workload requirements network state conditions and cost factors to achieve maximum performance and operational effectiveness [5]. Edge devices and edge servers execute their primary function by processing data with local resources to make instant decisions. The system sends important information which needs to be analyzed to the cloud for permanent storage and comprehensive decision-making processes. The edge and cloud components function together as a unified system to achieve better performance and resource efficiency. Hybrid architectures represent the combination of different computing environments. Businesses require specific computing solutions that operate on three separate environments which include on-premises infrastructure and private cloud and public cloud [4][12].

6.4 Edge Analytics and Intelligent Decision-making

Edge computing serves as an essential component which enables real-time analytics and anomaly detection operations. The system conducts its data processing and analysis functions at locations nearer to data sources which results in decreased response times and enables quick reactions to important incidents. The system reduces cloud data transmission requirements because its devices operate with autonomous decision-making capabilities. Autonomous vehicles use their sensor data processing capabilities to make immediate decisions about steering and braking functions. Intelligent decision-making processes rely on AI-based and machine learning-based models which organizations can implement at their operational sites [32] [66].

6.5 Standardization and Interoperability

The creation of standards and protocols aims to establish a unified edge ecosystem which connects edge and fog and cloud systems. The standard protocols used for data exchange include MQTT and CoAP and HTTP/HTTPS [52]. The hardware standards USB and PCIe establish dependable connection methods between devices. The security system depends on encryption technologies which include TLS/SSL and access control mechanisms that use OAuth. Interoperability enables different companies devices to operate together without interruptions while it also permits data transmission between edge and fog and cloud systems. This system provides essential support for AI/ML applications and smart services and real-time analytics. The future of fog and edge computing will deliver better solutions which combine security with advanced technologies through its ability to balance cloud and decentralized systems.

VII. CONCLUSION

This study provides an in depth evaluation of both fog computing and edge computing. The two computing models have developed their systems because data driven applications require low latency and high bandwidth capabilities which existing cloud-based solutions cannot deliver. The paper provides an in depth examination of their architectural systems which include the complete framework needed to connect with cloud services. Fog and edge computing enable organizations to achieve faster data processing capabilities which support instant operational decisions because they deliver computing resources to locations near their networks. The system builds from cloud resources to edge devices through its multiple improvements which include lower latency and better bandwidth effectiveness and greater system capacity. The actual significance of these technologies appears in autonomous vehicles and industrial automation and smart cities and healthcare applications. The paper includes a comparative analysis of existing research work along with an assessment of the existing opportunities and challenges which will lead to identification of future research areas. The research team wants to develop novel techniques and algorithms and architectural designs which will enhance the operational effectiveness of existing technologies according to ongoing research efforts.

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