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The Role of Edge Computing in IOT: Enhancing Real-Time Data Processing Capabilities

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ABSTRACT: The quick expansion of the Internet of Things (IoT) has produced exponential data production requiring efficient processing solutions. Because of too high latency, limited bandwidth, and security concerns, real-time applications find conventional cloud-based architectures less suitable. Edge computing addresses these restrictions by processing data nearer the source, thus reducing latency, improving response times, and so raising overall system efficiency. Edge computing—by leveraging localized computation—allows real-time decision-making for significant IoT purposes like smart cities, industrial automation, healthcare, and autonomous autos. Filtering and evaluating data at the edge before passing relevant information to the cloud helps to clear network congestion as well. This study addresses the importance of edge computing in IoT, its primary benefits, challenges, and future prospects in providing intelligent, real-time, scalable IoT systems.

KEYWORDS: Edge Computing, Internet of Things, Cloud computing, Real Time Data Processing

I. INTRODUCTION

The Internet of Things (IoT) facilitates bidirectional connection between smart devices via the use of sensors, enabling real-time data transfer [1]. The Internet of Things (IoT) is used in everyday life via "smart homes," "smart cities," and "smart healthcare." Internet of Things devices must comply with essential and standardized communication protocols, allowing enhanced identification, tracking, and administration of things. The International Telecommunication Union (ITU) defines the Internet of Things (IoT) as a worldwide framework that enhances services by connecting virtual and physical entities via communication networks. Applications developed for the Internet of Things (IoT) have issues with privacy, performance, security, and reliability because to the constrained storage and processing capabilities of IoT devices. The integration of Internet of Things (IoT) applications with cloud computing facilitates enhancements. Smart devices possess an abundance of data that may be sent across the network. This may often become an issue. Research from International Data Corporation (IDC) indicates that the quantity of Internet of Things (IoT) devices might attain 41.6 billion by 2025, generating 79.4 zettabytes of data. Issues related to volume, variety, velocity, legitimacy, and value are intrinsic to big data. Currently, the cloud oversees the management of all data generated by Internet of Things (IoT) devices. The integration of cloud computing with IoT has generated substantial expectations that the cloud alone cannot fulfil. The cloud networking architecture encounters many challenges including network utilization, data congestion, and cloud federation. The advent of IoT devices has heightened the significance of energy and resource conservation. Enhancing energy efficiency in smart devices and prolonging battery life are two issues posed by data transfer between IoT sensors and the cloud.

Several issues may emerge with cloud computing: All Internet of Things sensors transmit their data to a central data center over a network. Upon processing, the data is sent to the actuators. The co-location of sensors and actuators inside the same device results in increased delay, rendering control information ineffective. Cloud computing encounters challenges in data processing and providing suitable computing services; edge computing presents a viable solution. Proximity of computing workloads to intelligent devices on an edge server significantly decreases data transmission latency and network capacity demands for cloud collaboration. The elimination of long-distance data transmission ensures guaranteed data security. Consequently, intelligent devices need to use edge computing to do activities of a flexible nature [6].

The advancement of edge computing as an extension of cloud computing has resulted in enhanced opportunities, including reduced transmission costs and optimized network capacity usage. As a consequence, it leads to efficient utilization and processing, together with decreased energy use. Employing edge computing in clever, compact, real-time systems optimizes its effectiveness. Data security is assured as it precludes the potential for transmission via the network. The federal architecture of edge computing requires the positioning of edge devices between the cloud and terminal devices to provide cloud services to the network's perimeter. A contributing factor to addressing the requirements of IoT applications is the shift in service delivery from the cloud to the edge, resulting in enhanced scalability and energy efficiency for IoT devices. The terminal layer of the cloud-edge federation's three-tier architecture consists of sensors, cameras, and smartphones. The edge layer comprises base stations, access points, routers, switches, and gateways. Various types of devices, communication protocols, and services provide diverse methodologies for the implementation of edge computing. Although several advantages exist in transitioning processing to the network's periphery, certain challenges must be addressed when implementing edge computing. These include issues related to security, privacy, data abstraction, optimization, service administration, and the emphasis on the programmability of edge devices. Due of its interconnectivity, edge computing shares certain challenges with fog computing.

II. RELATED WORK

The proliferation of wireless communication techniques that are based on the Internet simplifies the process of selecting an appropriate medium for the exchange of information. Globally, the selection of mobile terminals is expanding. The interconnection of objects, which are frequently referred to as "gadgets," has enabled the advancement of wireless communication networks that are based on the Internet. On a daily basis, these networked devices generate an immense quantity of data. Conventional data storage and processing methods are rendered obsolete in an Internet of Things (IoT) environment [7]. As a result, it is imperative to establish a paradigm for decentralized computation that utilizes vast amounts of data. Cloud computing's extensive data analysis and storage capabilities enable end users to fully capitalize on the advantages of an Internet of Things (IoT) architecture.

Furthermore, cloud computing is endeavoring to resolve numerous challenges associated with real-time applications. Examples of computer applications that generate substantial amounts of data and necessitate context-specific and time-sensitive computation include industrial control, augmented and virtual reality, and others. It contributes to the computation of substantial quantities of data flow and is an essential element of future wireless communication systems that are based on the Internet. Reduced delivery delay and increased data velocities are essential components of wireless communication networks. The rapid execution of data flow is required by potent processing units, and a high data rate transmission connection is essential for Internet-based wireless communication networks [8].

An auxiliary computing paradigm is created to resolve the common challenges encountered in cloud computing, including high latencies and low bandwidth utilization. This model establishes a connection between computing resources and user devices, thereby enabling the computation of data [9] [10]. By decreasing the volume of data transmitted to the cloud, we can decrease communication latencies. At present, researchers are concentrating on methods to localize the processing capabilities that are located in vast data centers by bringing the network's periphery closer to end-users and sensors. "Edge computing" is a computational paradigm that utilizes resources situated at the network's periphery. The utilization of smart computation techniques, the management of data expansion, network traffic, and sustainable energy consumption, as well as the resolution of resource limitations in front-end devices, are all essential components of edge computing for IoT applications. Furthermore, low latency computation and decentralized cloud are indispensable. The objective is to enhance the quality of computing and communication services, with a particular emphasis on real-time applications [11].

2.1 Internet of Things and Challenges

An Internet of Things (IoT) network comprises a system of linked and varied devices, including vehicles and domestic appliances, capable of communicating and exchanging data with each other. These interlinked devices connect the physical and digital realms to enhance individuals' lives. Globally, billions of devices are interconnected via the

Internet to generate, collect, and transmit data. Any conceivable item may be connected to the Internet. The capacity to network, see, and identify may be inherent in ordinary objects [12].

Despite the potential advantages, IoT faces various challenges in relation to [13] [14] :

- **Scalability:** Scalability denotes the ability of a system, network, or process to effectively manage a growing workload. The extensive array of applications using raw data renders this a significant issue in the IoT. A substantial quantity of IoT devices that adjust and proliferate according to demand is crucial for several IoT applications, particularly in smart cities that have embraced an IoT-enabled ecosystem.
- **Self-organizability:** The network must possess the capacity to re-establish device-to-device connectivity in the case of failure of any nodes, connections, or communication methods. Network availability is improved by self-organizing capabilities.
- **Data Size:** There must be a sufficient mechanism for storing data and efficient protocols for transmitting data in IoT networks since the data produced by IoT devices is massive and diverse.
- **Timely Data Analysis**: Data analysis must be done immediately for real-time applications. This is why it's important to combine IoT networks with cutting-edge technology like edge computing.
- **Interoperability:** The sheer volume and variety of Internet of Things (IoT) devices, each with its own set of specifications and made by a separate company, presents a significant obstacle. Consequently, diversity and heterogeneity are two challenges that IoT networks must overcome.
- **Bandwidth Scarcity:** Bandwidth is needed for data collection and transmission by Internet of Things (IoT) devices. The need for bandwidth is rising in tandem with the number of IoT devices. Additionally, there has to be bandwidth available to handle the demands of IoT applications.

2.2 Cloud Computing & Challenges

Online services are provided using cloud computing. There are three major categories of these services depending on the benefits they provide: SaaS, or software as a service, is a business model whereby suppliers lease computer programs to customers for online access and use, often via a web browser. Although cloud architectures are crucial for the Internet of Things (IoT), cloud computing is not infallible and does not always make optimal decisions about processing and data storage, among other aspects. Meticulously recording each every temperature measurement is an inefficient use of space [15] [16]. Thus, a new architecture needs to be considered due to the following reasons:

- **Latency:** Applications like e-health management that rely on the Internet of Things (IoT) are latency-critical because of the way they sense and behave in response to their physical surroundings. Because of the physical distance between IoT devices and cloud computing resources, cloud computing alone is insufficient for IoT application integration. However, this problem is solved by combining cloud computing with edge computing.
- **Data size:** There is a growing need for more bandwidth to transmit data from the Internet of Things (IoT) to the cloud, particularly since smartphones can already upload videos and photos in real-time. To address this, companies are bringing cloud-like services closer to the consumer, which in turn reduces the bandwidth needed to transmit data from IoT devices.
- **Constrained resources:** Internet of Things (IoT) equipment, such sensors, have limited resources, including a battery life. In order to maintain a high level of service in IoT networks, it is necessary to put cloud services close to resource-constrained devices, since transmitting data to cloud servers drains batteries.
- **Availability:** While time-critical applications need that IoT devices be linked to the cloud, doing so requires constant internet connectivity, which may be taxing for devices with limited capabilities.

2.3 Edge Computing Frameworks

MAUI was among the first EC frameworks developed for the goal of offloading code from cellphones [17]. This system has three components: a decision engine that computes the offloading cost, a proxy that oversees the control and data transmission of offloaded processes, and a profiler that assesses the energy and data transfer requirements of the program. These functionalities are implemented on servers in both EDs and ECs. Authors provide a framework similar to ULOODF in a linked research. To get accurate estimates of execution time and energy consumption, the authors improve the performance of the decision engine component. Among EC designs and frameworks, ETSI Mobile Edge Computing (MEC) is preeminent. It provides the foundation for mobile edge systems, hosts, and networks. The MEC architecture fundamentally consists of the mobile edge host level, which is tasked with hosting and maintaining all edge applications. End users and third parties get an abstraction of the foundational MEC system at the mobile edge system level, while many access methods, including the Internet, local access networks, and 3rd Generation Partnership Project (3GPP) mobile networks, are available at the underlying network level [18].

Primarily designed for cognitive assistance applications, cloudlets reside at the intermediate level of a three-tier hierarchy. A cloudlet node comprises three separate types of virtual computers. The components of a cognitive virtual machine ensemble comprise application virtual machines for tasks such as facial recognition and augmented reality, a control virtual machine that manages sensor devices and allocates computations to other cognitive virtual machines, and a user guidance virtual machine. The virtual machine integrates the outputs of the cognitive virtual machines, subsequently generating output to assist the user. A key advantage of the architecture using a virtual machine is its flexibility [19].

In the traditional three-tier design, the cloud encompasses the application layer, while the edge contains the service administration layer. By extending both tiers to a three-tier design, FLEC may provide flexible EC services [20]. Flexibility is characterized by the system's ability to adjust to its environment and its capability to prioritize the requirements of its users. User orientation facilitates the delivery of services customized to individual users in real-time by considering comprehensive data (including user behavior, intent, and preferences) collected by IoT devices. Concurrently, environment adaptation autonomously determines the allocation of processing resources to either the edge or the cloud, based on the volume and quality of tasks, as well as their variability.

The authors propose a hierarchical approach that categorizes EC servers into many levels to more effectively handle peak demands [21]. Tier one, the fundamental level, comprises the servers that are geographically closest to ED. Level two is followed by level three, continuing sequentially to level n, which may denote traditional cloud computing. This strategy may leverage network congestion by aggregating and addressing peak requests that exceed the capacity of lower-tier EC servers.

Various circumstances need two-tier and three-tier designs. In scenarios when time is of the essence, a two-tier architecture is optimal. Many edge servers often cooperate to provide computing services for edge devices (EDs), since edge devices are much less powerful than cloud computing servers. The key problems of the two-tier architecture's design are application administration, performance optimization (including load balancing and execution latency), and edge server management. Tasks that are computationally intensive and time-critical are optimally managed by applications using a three-tier architecture. Computation-intensive procedures are executed in the cloud, and time-sensitive tasks are managed at the edge.

III. EDGE COMPUTING ARCHITECTURE

The fundamental architecture of edge computing posits that edge computing servers are much closer to the end user than cloud servers [22]. Consequently, the edge computing servers offer superior Quality of Service (QoS) and reduced latency to the end users, despite their reduced computational capacity in comparison to the cloud servers. Future reference architecture for IoT networks can employ a form of N-tiered Fog/Edge deployment by loosely coupling the best of these concepts without adding an additional layer of complexity to the entire system architecture [23]. A similar approach is presented in Figure1 by incorporating these concepts into the IoT architecture.

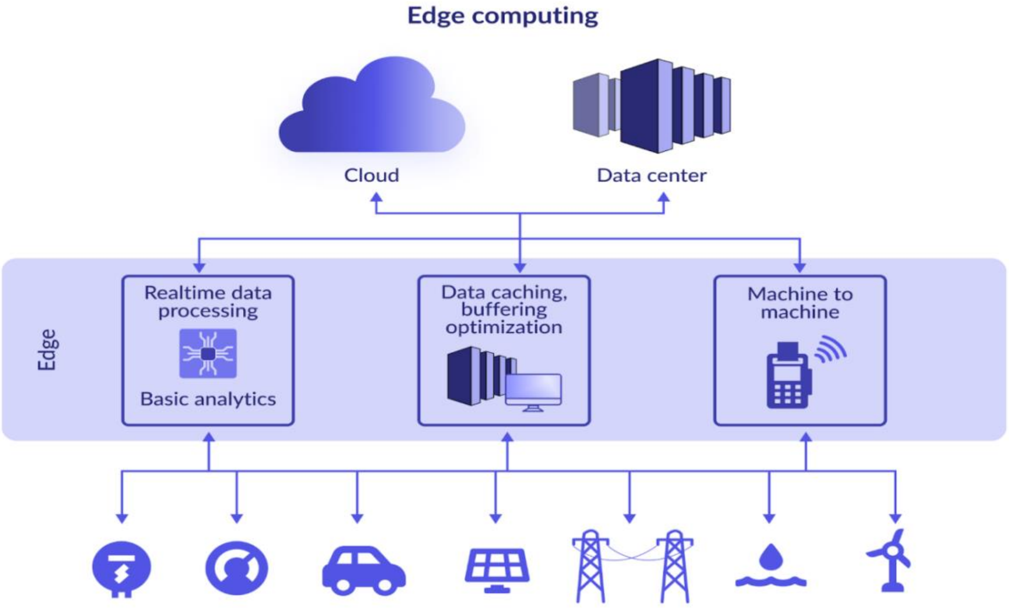

Figure 1: Edge Computing Architecture

- **IoT layer**

The IoT layer excels in closeness to the user's real surroundings. This layer comprises devices such as sensors, smart cars, mobile phones, drones, tablets, and others. Notwithstanding their computing capability, many of these gadgets function only as smart sensors inside this layer. These devices are distributed globally to perceive their surroundings and relay data to the subsequent layer for processing and storage. The foundational components of edge computing architecture are the end devices, including sensors and actuators. The front-end environment facilitates enhanced user involvement and greater responsiveness. Edge computing utilizes the substantial processing capabilities of proximate end devices to provide services for real-time applications. Nevertheless, the majority of requests remain unfulfilled due to the restricted capability of front-end devices. Consequently, in these instances, the end devices convey their resource requirements to the servers.

- **Edge Layer**

This layer, including several edge nodes, serves as the cornerstone of fog computing. The Open Fog Consortium defines an edge node as a physical or logical network device that implements fog services. Consequently, fog nodes may directly provide services to end devices. Gateways situated in the near-end environment regulate network traffic, while edge nodes interact with the cloud architecture to provide and obtain services. Edge or cloud servers need substantial resources to perform tasks such as offloading processing, caching data, and doing real-time analysis. Edge computing enhances end-user performance in data processing and storage with a little increase in latency by relocating the majority of data computation and storage to a proximate environment.

- **Cloud Layer**

The majority of the cloud's centralized infrastructure resides at this layer. A variety of services are accessible on the servers because to their advanced computation and storage capabilities. The edge model alleviates the burden on cloud resources and enhances productivity by efficiently transferring computational services from the cloud layer to the edge, in contrast to conventional cloud computing architectures. Due to the physical distance of cloud servers from end devices, transmission latency emerges as a crucial indicator for network performance. Nonetheless, the remote environment's cloud servers provide superior processing capabilities and data storage capacity. Cloud computing enables machine learning, large data analytics, data management, and massively parallel processing.

IV. ROLE OF EDGE COMPUTING IN IOT

This section focuses towards transmission, storage and computation characteristics in order to explain how edge computing improves the IoT performance [24] [25] [26].

- **Transmission**

Transmission time is wholly influenced by latency, bandwidth, and throughput, which are measurements that assess network performance. The "Live Video Analytics" initiative by Microsoft exemplifies a time-sensitive application that leverages the fast transmission capabilities of edge computing to fulfil quality of service standards. The primary objective of this project is to develop a real-time, cost-efficient system for analyzing live footage from all available cameras in a nearby open area. This system is designed to operate inside a globally distributed hierarchy of intelligent edges and large clouds. This research primarily aims to predict the time-sensitive vehicular traffic flow. Edge computing, by its hierarchical architecture, ensures the swiftest transmission times across all networks. Edge computing addressed the problem of network resource bottlenecks in the Internet of Things (IoT). Delegating data processing and storage to end users significantly decreases response time and traffic volume. The distributed and hierarchical architecture of edge nodes satisfies the substantial requirements of time-sensitive applications, including "Live Video Analytics," "Human Action Classification," and "Motion Estimation."

- **Storage**

Cloud computing's storage comprises centralized, multi-layered systems using commodity computers and disc drives. It serves as the central node where all other nodes in the network converge. Similarly, few edge nodes are explicitly engineered to address storage requirements. In contrast to traditional cloud storage, edge computing storage is distributed over the network's peripheral. It consolidates clusters of disc drives and allocates storage constraints among several edge nodes. Edge computing-based storage accelerates failure recovery and load balancing techniques to achieve QoS requirements. These load balancing strategies alleviate pressure on network connections by dispersing storage requests among several edge nodes. Moreover, edge computing storage is highly valued for failure recovery methodologies to identify data problems, including software, hardware, packet loss, noise, and power issues within extensive data streams from several sources.

- **Computation**

The bulk of IoT devices, constrained by their limited processing and power resources, are incapable of doing complex computational tasks on-site. In a standard situation, data is gathered by IoT devices and sent to more advanced computing nodes for further processing and analysis. Nonetheless, due to the constrained processing capacity of individual edge nodes, achieving scalable computational capabilities for edge computing is a significant challenge. Edge nodes can sufficiently fulfil the computational requirements of the Internet of Things (IoT), particularly for real-time applications, since IoT devices need little computing power. Moreover, by delegating computational tasks to edge nodes, IoT devices may decrease their energy consumption. In edge computing, the computational capacity of each node is inferior to that of cloud servers. Consequently, to fulfil the same requirements, the computational tasks are allocated across several edge nodes. Edge computing enhances the fulfilment of end-user requirements by relocating processing and storage to the network's perimeter; a fundamental element of this strategy is the task scheduling system. Task scheduling systems may be constructed with diverse objectives in consideration.

V. EDGE COMPUTING MODEL FOR SMART IRRIGATION

An edge computing enabled model for smart irrigation system will consist of following components

☐ **Sensors & IoT Devices (Edge Nodes)**

- Soil moisture sensors
- Temperature & humidity sensors
- pH sensors
- Water level detectors
- Weather data sensors

Computing Layer (Gateway/Edge Server)

- Edge Data preprocessing
- Local AI/ML models for real-time decision-making
- Connectivity: LoRa, Wi-Fi, 5G
- Actuation commands (e.g., turn on/off water pumps)

 Cloud & Analytics Layer

- Long-term data storage
- Advanced AI/ML training
- Dashboard for monitoring
- Remote control via mobile app

 Actuation & Control

- Automated water valves
- Drip irrigation control
- Notifications & alerts

IoT edge computing plays an significant role in cultivating the efficacy and effectiveness of IoT devices by bringing computational resources closer to data sources, there are other advantages of employing edge computing which includes,

- Improved Reliability and Reduced Latency – EC enables IoT devices to process and analyze data locally, thereby reducing latency and increasing reliability by eliminating the necessity of sending all data to the cloud for analysis. This speeds up the decision-making process and provides more efficient operations.
- Increased Responsiveness - The decentralized approach of IoT EC improves the responsiveness of IoT networks, ensuring that data is processed and analyzed in real time.
- Energy efficiency – IoT EC reduces energy consumption by allowing devices to perform tasks locally, thereby eliminating the necessity for constant communication with a centralized system.
- Security – While EC do not inherently offer a higher level of security than private clouds, the localized approach simplifies security management. It is primarily designed to ensure data sovereignty and compliance with local data protection regulations, thereby reducing the likelihood of data breaches.
- Bandwidth Optimization – Numerous IoT applications are fundamentally innovative monitoring systems that collect data, analyze it, and subsequently execute actions based on the insights that have been generated. Therefore, it is imperative to enhance bandwidth optimization.
- Optimizing Bandwidth Usage – EC can enable the processing and straining of IoT-produced data closer to the devices, thereby optimizing bandwidth by ensuring that only data necessary for long-term storage or analysis is transmitted to a centralized platform.
- Scalability – Modern peripheral devices can be connected to LAN or WAN, allowing for the integration of IoT devices into the network ecosystem and the facilitation of central management.
- Flexibility – IoT EC offers flexibility in data processing and analysis, enabling the customization of processing duties to meet the unique requirements of each IoT device.

For limited resources on edge devices to be used effectively and efficiently, edge resource management is essential. When assessing edge resource management, keeping the following metrics is important.

- Latency: Latency is a term that refers to the duration of time required to process data and generate a response. Reduced latency is indispensable for real-time applications, including industrial automation and autonomous vehicles.
- Throughput: The term "throughput" refers to the amount of data that an edge device can process in a specified amount of time. This is a critical point to consider for applications that generate a significant amount of data, such as high-resolution sensor data processing or video broadcasting.

- Resource utilization: This metric indicates the extent to which the periphery device optimizes its memory, storage, computing capacity, and network bandwidth. Although low utilization indicates the potential for optimization or consolidation, high utilization can lead to performance constraints.
- Uptime: This is expressed as a percentage of the entire operating and processing time of the edge device. High availability is essential for applications that are susceptible to significant consequences in the event of outage.
- Edge resource management system fault tolerance: This metric indicates the system's ability to recover from hardware or software malfunctions. It is equipped with self-healing techniques and automatic failover to ensure uninterrupted operation in the event of issues.

VI. CONCLUSION

With its creative edge computing, the Internet of Things (IoT) ecosystem has essentially fixed problems related to cloud-centric design. Edge computing facilitates real-time data processing close to the source, therefore providing faster response times, less bandwidth utilization, and lower latency. Applications depending on quick decision-making—such as smart cities, healthcare, autonomous systems, industrial automation—are likely to gain greatly from this change. Regardless of their advantages, we have to solve issues such security, infrastructure scalability, and device management if we are to get general adoption. Edge computing will become even more important in enhancing the accuracy, reliability, and complexity of IoT systems as 5G, distributed computing, and artificial intelligence advance. Future studies and development will improve edge designs, thereby strengthening their resilience, security, and adaptability to meet the increasing need for real-time data processing in the IoT. The Internet of Things (IoT) ecosystem's innovative edge computing allows cloud-centric design issues to be resolved. Edge computing delivers real-time data processing next to the source, therefore improving reaction times, bandwidth use, and latency. Applications that depend on quick decisions—smart cities, healthcare, autonomous systems, industrial automation—stand to benefit most from this change. If we want general acceptance regardless of its benefits, we must overcome obstacles such security, infrastructure scalability, and device administration. Edge computing will become ever more important in improving IoT systems' accuracy, dependability, and intelligence as 5G, distributed computing, and artificial intelligence keep develop. Future research and development will optimize edge designs even further, thereby enhancing their resilience, security, and adaptability to satisfy the growing requirement for real-time data processing in the IoT.

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