Towards Low-Latency Networking: A Hybrid Cloud–Edge Architectural Perspective

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Abstract*- The substantial increase witnessed over the last two decades in the use of applications characterized by high sensitivity to latency and intensive data requirements, such as Internet of Things (IoT) applications, has led to the development of a hybrid architecture that supports, on one hand, the requirements of latency-sensitive and real-time applications, and on the other hand, enables the use of cloud computing technology to provide large storage capacities and significant computational power. This development has resulted in the emergence of the Hybrid Edge-Cloud Architecture. This paper presents a review of the definition and concept of the Hybrid Edge-Cloud Architecture, benefits, components, and operational mechanisms. The paper focuses on the achievements of this architecture in reducing latency, optimizing resource utilization, enhancing scalability, and improving resource management. It also discusses the challenges associated with the adoption of this architecture, including task offloading, security and privacy, interoperability, and energy efficiency. Furthermore, the paper addresses the technologies and mechanisms that have been employed to overcome these challenges. At the same time, it reviews and analyzes future research directions, which are expected to focus primarily on the use of artificial intelligence-based techniques, reinforcement learning, and renewable energy solutions in an effort to mitigate these challenges.

Keywords— Cloud-Based Network, Low-Latency Applications, Internet of Things (IoT), Hybrid Cloud Networking, Latency Optimization, Edge Computing.

I. INTRODUCTION

The last two decades have witnessed the widespread adoption and remarkable development of several technologies. Among the technologies that have permeated various fields of digital systems are edge and cloud technologies. Most modern applications in critical spheres require quick response and minimal delay time [1]. The cloud-based systems have great computational features, are scalable, and cost-effective. The cloud-based and its centralized nature, in most cases, for most applications, cause a significant delay time for most delay-sensitive applications such as health care, smart cities, and autonomous systems because of the long distance that the transferred data has to travel [2].

The emergence of edge computing technology has been a game-changer in this field, since the processing of data collected from Internet of Things devices and sensors occurs near the source without the need to transfer that data over long distances via the cloud, which minimizes the delay time and improves the quality of provided services [3]. Moreover, the reduction of the delay time leads to improved and speed up the decision-making process in intelligent systems.

Complete reliance on cloud computing, with its centralized management, storage capacity, and high processing power, leads to a significant increase in latency and service quality. Conversely, relying solely on edge computing, with its high-speed data transfer, presents challenges related to storage space, processing power, and other constraints. Therefore, the optimal solution is to combine these two technologies by adopting a hybrid network architecture that integrates cloud and edge computing to leverage their advantages while minimizing their limitations [4, 5].

Using cloud computing and edge computing in a hyper cloud-edge architecture fulfills many of the requirements of modern applications, regardless of their nature or specific needs. Applications requiring fast execution, high-quality service, and sensitivity to latency can be handled through edge computing, while applications requiring large storage capacities and frequent analysis can be implemented on cloud computing. This architecture, in turn, provides the network with significant features, such as flexibility, scalability, low latency, and improved performance [6, 7].

The adoption of a hybrid cloud-Edge architecture still requires further investigation and analysis to address challenges related to latency management, security, resource allocation, and interoperability, despite its significant benefits.

This paper discusses the recent technologies introduced to network architecture from cloud computing and edge computing. It examines the hybrid system combining these two technologies, the benefits it offers, and the challenges arising from its use. It also explores its impact on producing an integrated system that ensures flexibility, low latency, sufficient capacity, and good overall network performance. The contribution of this paper provides architectural perspectives on a hybrid cloud-Edge environment to achieve low-latency application requirements.

II. BACKGROUND AND RELATED WORK

A. *Cloud computing and cloud networking concepts*

The concept and applications of cloud computing and cloud networks have constituted a highly impactful technological revolution on the structure and operation of network systems in most companies and business institutions [8]. Cloud computing has enabled the provision of services, including hardware, software, servers, and even platforms, via the internet, as shown in fig.1. Meanwhile, cloud networks have formed the infrastructure that ensures flexible connectivity between software and hardware, as well as the secure, centralized management of equipment and users [9]. Cloud networking contributed to solving many of the problems that traditional networks faced at the time, including scalability challenges, operational efficiency, management, and security.

Despite the advantages of cloud networking architecture, many problems and challenges have emerged that hinder meeting the needs of real-time applications and applications sensitive to latency in data transmission and processing [10]. The long distances data travels in a centralized cloud environment contribute to significant latency increases and negatively impact service quality. Therefore, it has become essential to find solutions to these challenges faced by systems adopting cloud architectures in their operations, aiming to reduce latency and other limitations as shown in [11].

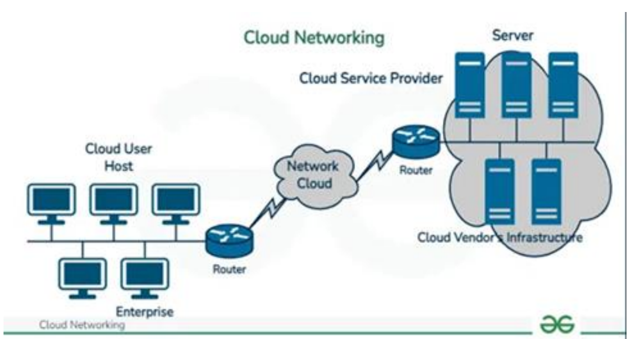

Figure 1. Cloud Networking Concept

B. *Standalone Edge Computing*

Taking advantage of this modern technology requires establishing the appropriate structure and approaching the system from a perspective different from the traditional one. Edge computing and IoT are considered among the most important technologies to have emerged in the last two decades [12]. The way of data processing is what distinguishes edge computing since the processing and analysis of data collected from the sources is performed on the source device or the nearby node, unlike the traditional network where the collected data is sent to a centralized server or cloud device for processing as depicted in fig.2. This new approach to processing reduces the delay time and minimizes the traffic workload on the bandwidth. IoT is one of the major application domains of edge computing, where smart devices rely on edge computing to process data rather than waiting for a remote central device to respond. These features require a different decentralized network architecture and another point of view for devices and location management [9].

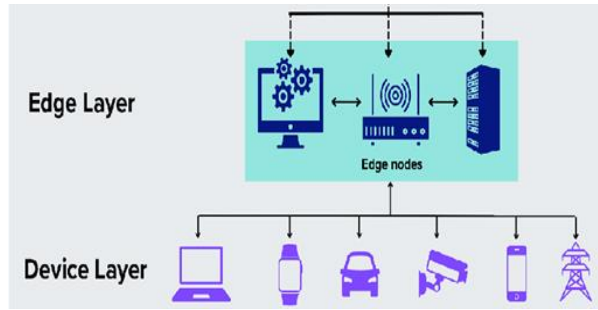

Figure 2. Standalone Edge Computing Architecture

As a result, edge computing enables quicker responses and improves the Quality of Service (QoS) for latency-sensitive applications. Consequently, modern networking environments require more decentralized architectures and flexible approaches for managing devices, resources, and data distributions.

III. HYBRID CLOUD–EDGE ARCHITECTURE

This architecture has emerged as a compromise solution that overcomes the disadvantages of cloud network architecture and Edge computing, making it more efficient and more responsive to real-time application requirements and quality of service [13]. At the same time, the hybrid Cloud-Edge architecture became distinguished, combining the computation power and scalability of the cloud and the low latency of Edge computing.

Much research has discussed the relationship between the two architectures as presented in [14, 15]. The relationship could be seen as cooperative or complementary, since each architecture provides the hybrid architecture with its own features. On its side, cloud architecture has sufficient storage, powerful processing, and centralized management. Edge computing, in its turn, can leverage the limitations of cloud architecture by implementing the computation required by real-time and low delay applications by local processing on the same device that collected the data or on a nearby device, avoiding the data from being transferred over a long distance to the cloud device.

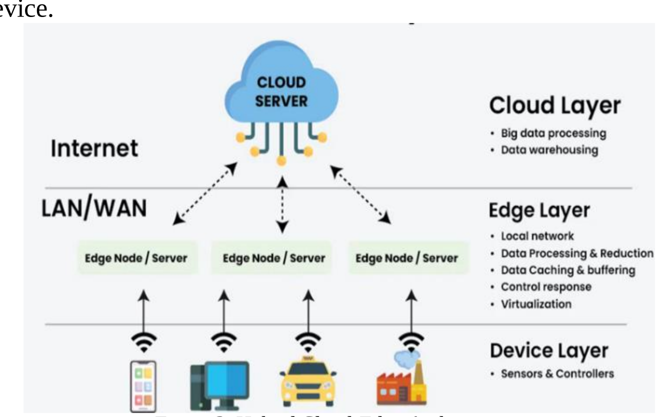

Figure 3. Hybrid Cloud-Edge Architecture

The mechanism of work in this architecture depends on distributing the tasks according to their requirements between the cloud and edge layers. Edge computing performs computation without relying on a centralized data center and minimizes the amount of data transmitted to the cloud, thereby reducing the response time for delivering results or feedback in real-time applications [16]. Consequently, the cloud layer performs the tasks for long delay tolerant application on the cloud.

IV. BENEFITS OF HYBRID CLOUD–EDGE ARCHITECTURE

Generally, the new architecture provides the networking environment with several advantages that fulfil the requirements of low-latency applications and improve service quality, while maintaining cloud architecture capabilities to support delay-tolerant applications [17]. The benefits of cloud-edge architecture can be explained as follows:

A. Scalability:

The cloud-edge architecture organizes the distribution of application tasks by type across different layers. Latency-sensitive application tasks are distributed to the edge layer, while delay-tolerant tasks are distributed to the cloud layer [18]. This, in turn, increases system efficiency, reduces the need for additional dedicated hardware or equipment with specific specifications, and supports additional devices and larger data volumes at a high level for the environment [19].

B. Improving Security:

Reducing the amount of sensitive data sent to the centralized cloud and keeping it at the edge layer or nearby, processing it there, enhances data privacy and confidentiality, and allows for all control measures to be implemented locally, rather than elsewhere, as in the cloud, which in turn minimizes the risk associated with transmitting the data to the cloud [20].

C. Reduce latency and improve the Response Time

More and more IoT applications over the last few decades have been used in the real environment, since these applications depend on actuators and sensors that collect data, making cloud environments less suitable for such applications because of the delay time [21]. Combining the Edge architecture resolved this problem by performing these tasks on the edge layer, reducing the distance for data transmission and minimizing latency.

D. Improve Quality of Services:

The hybrid cloud-edge architecture provides a suitable environment for various applications, as distributing tasks across the edge and cloud layers ensures optimal execution without network congestion or workload overload. Moreover, the mechanism of distribution improves the efficiency and productivity as a whole [22].

E. Efficient resource utilization

The cloud and edge architecture, by distributing the workload across more than one layer, provides optimal utilization of resources, devices, and storage capacity. Since the tasks coming into the network are distributed according to the type of application and its sensitivity to latency, this mechanism helps prevent the waste of existing network capabilities and reduces the need for increased resources [23].

V. CHALLENGES OF HYBRID CLOUD–EDGE ARCHITECTURE

The previous section reviewed the benefits of the cloud-edge architecture. While these significant advantages have improved and enhanced system performance, several challenges still hinder this architecture from operating at near-perfect efficiency. These challenges are listed below.

A. Security and Privacy:

One of the most serious challenges facing edge cloud networks is the security issues arising from the use of diverse technologies. In addition to the inherent security problems of cloud networks, there are also security issues arising from the use of virtual machine technology. Furthermore, problems related to running applications on different servers necessitate securing those servers [24, 25]. On the other hand, running user-generated tasks on nearby servers presents a new security challenge due to the easier accessibility of those servers.

B. Offloading and scheduling:

Offloading is the process of transferring a task to be executed, in whole or in part, on a device, whether in the cloud or on a terminal, to ensure execution at the target speed and meet execution requirements as shown in fig.4.

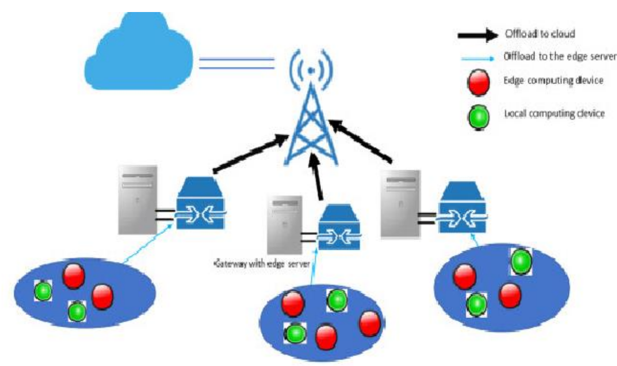

Figure 4. Offloading scheduling task. [26].

Scheduling offloading is one of the challenges facing edge cloud networks. It is necessary to determine which devices are most suitable for performing this task, along with their associated requirements, whether it will be performed on a cloud device, an edge device, or using a hybrid mechanism that includes performing part of the task on a local device and the other part on another device in the cloud. This requires considering the latency, execution capacity, and the security of the entire process. [25].

C. Managing the Complexity of Distributed Networks

The edge computing environment is one of the most resource-intensive environments, in terms of location, type, and operating method. This leads to difficulties in managing and controlling this diversity of devices. These difficulties also manifest in coordinating different processes, maintaining connectivity, securing resources, and ensuring communication between different levels within that environment [26].

D. Heterogeneity and Interoperability

The edge computing environment consists of multiple layers supporting a wide range of devices with varying capabilities and characteristics. These devices often generate data in different formats and rely on diverse hardware architectures, software platforms, communication protocols, and interfaces. Consequently, integrating and coordinating these heterogeneous components becomes a highly challenging task [27]. Ensuring seamless connectivity and compatibility between devices and systems across cloud and edge computing layers remains critical for delivering efficient and reliable services.

E. Energy Efficiency and Sustainability

Due to the nature of edge -cloud networks, which include a large number of edge devices, especially IoT devices, and the constant data supply required for their operation, leading to higher energy consumption, and considering that these devices are located in areas far from storage or processing points, providing energy resources for them to ensure continuous operation becomes crucial [28]. This highlights the need for load distribution and task scheduling as key steps to optimize energy use and reduce emissions while simultaneously ensuring the continued operation of these devices.

VI. DISCUSSION

The hybrid cloud-edge architecture has brought a significant transformation in the use of distributed networks, both in the technology employed and the services offered, most notably in meeting the demands of applications with high-latency sensitivity. This development has been accelerated by the adoption of smart cities, healthcare systems, and industrial IoT applications, among others, which rely on sensors, actuators, and other small devices that collect data [28]. The integration has driven the use of modern technologies that align with the advantages offered by this architecture, as stated in [29]. Modern communications, such as 5G, have significantly improved data transfer speed, reliability, and network efficiency. In addition, the use of AI-powered management tools has enhanced the process of managing and scheduling tasks, and enhancing resource allocation and availability. Consequently, the widespread adoption and growth of cloud-edge architecture lead to the complexity of this environment and require more advanced communication and AI management technologies.

As a result of the significant progress achieved using the edge cloud, several challenges have emerged due to complexity and scalability. These challenges include maintaining low latency, efficient use of resources, and ensuring security and privacy. On the one hand, the need for an intelligent mechanism for resource management and intelligent management of network resources, and improved data security and devices.

Table 1 presents the major technologies that have been exploited to enhance the hybrid cloud-edge architecture and the open issues that need more improvement.

TABLE 1. CHALLENGES AND RESEARCH GAP

Challenge Issue	Solution	Remained Issues
Energy and sustainability	Green Technologies	Restricted edge resources
Security	Encryption and Blockchain	Computational overhead
Scheduling and Offloading	Reinforcement learning	Complexity of decisions
compatibility	Standardized protocols	Compatibility between platforms

As shown from the previous table, despite the great progress made in the use of blockchain technology, artificial intelligence, and federated learning, there remains a gap, especially in resource management, compatibility, and security, which needs further research.

As mentioned previously, some advantages and technologies were used to provide a balance between the features it possesses from hybrid architecture, such as latency reduction and improved control over resource management, and more effective task scheduling .The above highlights the complexities of the hybrid cloud-edge environment and the need for further work to improve many aspects of its applications, such as enhancing security, scalability, and the deeper use of AI tools for resource management.

VII. FUTURE RESEARCH DIRECTIONS

The significant growth in the use of hybrid cloud-edge architecture and the subsequent widespread reliance on applications with high latency and real-time sensitivity have led to research trends that focus primarily on several aspects.

A. AI-driven Resource Management:

Modern machine learning and reinforcement learning can play a pivotal role in meeting the needs of network applications in a manner that is compatible with network conditions and status, as shown in [30].In addition to using artificial intelligence-driven resource management in managing and distributing loads, securing resources, and even making appropriate decisions in allocating tasks, whether on the cloud or the edge device.

B. Intelligent Task Offloading Mechanisms

The optimization of network resources will be an important target for future research direction, since the selection of a suitable offloading strategy for choosing the environment to implement tasks, taking into consideration the task requirements, such as delay time and needed resources. Many mechanisms can be considered for future solutions, or the core of solutions is reinforcement learning, where the main role of the agent is observing the network to learn the best policy for task offloading, considering latency, energy consumption, resource allocation, and security [31].

C. federated learning:

Security issues remain the most critical for the hybrid cloud-edge architecture. Developing and using new techniques will have a place in future research directions to enhance the procedures, data, and device security. This technique is based on bringing the intelligent model itself to the data to ensure that all security compliance is met.

D. Energy and Sustainability:

This is an emerging issue that researchers have begun to pay close attention to, given the global trend towards green technology and renewable energy generation. Since hybrid cloud-edge networks are no exception, the future is expected to see the adoption of several technologies, including renewable energy sources, carbon-free energy sources, energy-efficient power generation (using only what is necessary), and energy-saving cooling technologies [32].

VIII. CONCLUSION

The hybrid cloud-edge architecture is considered one of the most promising models in the network sphere and in modern environments. This model integrates cloud technology, which provides users, applications, and even companies with scalable storage, computational power, analytical capability, and application security, with networks and the Internet of Things (IoT) networks that support applications with high latency sensitivity, continuous and long data transfer, low power consumption, and limited storage space. Consequently, this model became important for many applications such as healthcare, smart cities, and Industrial IoT (IIoT).

Despite the advantages this model has provided to the modern network environment, many challenges have emerged and remain topics of research, including resource management, security and privacy, load and task distribution, ensuring sustainable energy and regulating its consumption, and other challenges.

The paper reviewed the technologies and mechanisms used to overcome these challenges, including the use of artificial intelligence-based mechanisms for resource management, modern communication technologies, and others. It also highlighted future research directions that will focus on developing solutions to the remaining challenges, relying on reinforcement learning, the latest generations of communication networks (5G and 6G), and renewable and sustainable energy technologies.

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I. Introduction

By moving data storage and processing closer to the point of origin, a novel paradigm known as "edge computing" has lately evolved to satisfy the growing demand for low-latency applications. Traditional cloud computing architectures aren't fast enough to meet the real-time processing needs of applications like smart grids, augmented reality, telemedicine, autonomous vehicles, and industrial internet of things (IoT), notwithstanding its scalability and adaptability. By spreading computation over a distributed network of nodes, which enhances data security, lowers bandwidth usage, and accelerates reaction times, new edge computing architectures offer inventive responses to these challenges. These systems combine several technologies and methodologies, including microdata centres, fog computing, and multi-access edge computing (MEC), so optimising resource allocation and allowing seamless interactions between edge devices and the cloud[1]–[3]. By moving processing duties from centralised infrastructure to local base stations or nodes in the network, MEC offers low-latency services at the periphery of a network thanks to 5G advances. New opportunities abound from this, including interactive gaming and real-time video analytics. Fog computing advances this concept by stressing proximity and scalability by creating a hierarchical ecosystem of resources including sensors, actuators, intermediate nodes, and the cloud. New edge architectures ensure real-time insights by depending more on artificial intelligence and machine learning models to do inferencing on-device and less on cloud processing[4].