

COMPARATIVE STUDY OF EDGE COMPUTING NETWORKS Vs. CLOUD COMPUTING NETWORKS FOR LATENCY-SENSITIVE APPLICATIONS

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Abstract - The rapid growth of latency-sensitive applications such as Internet of Things (IoT) systems, autonomous vehicles, augmented reality, and industrial automation has exposed significant limitations in traditional cloud computing networks. Although cloud computing offers high scalability and resource elasticity, its centralized architecture introduces considerable communication delays, making it less suitable for real-time applications requiring strict Quality of Service (QoS) guarantees. To address these challenges, edge computing has emerged as a decentralized paradigm that processes data closer to the source, thereby reducing latency and improving responsiveness. This paper presents a comprehensive comparative study of edge computing networks and cloud computing networks for latency-sensitive applications. A hybrid research methodology is adopted, integrating analytical latency modeling and simulation-based evaluation using EdgeCloudSim. Key performance metrics, including end-to-end latency, jitter, response time, bandwidth utilization, and scalability, are systematically analyzed across multiple real-world scenarios such as IoT monitoring, autonomous systems, augmented reality, and industrial automation. The results demonstrate that edge computing significantly outperforms cloud computing in terms of latency and real-time responsiveness, particularly in scenarios requiring millisecond-level decision-making. However, cloud computing continues to provide advantages in scalability and centralized resource management. The study concludes that a hybrid edge-cloud architecture offers an optimal solution by balancing low-latency performance with scalable computing resources.

Key Words: Edge Computing, Cloud Computing, Latency-Sensitive Applications, Quality of Service (QoS), EdgeCloudSim, Distributed Systems

1. INTRODUCTION

The rapid evolution of distributed computing paradigms has significantly transformed how modern applications are designed and deployed. With the increasing demand for real-time processing and instantaneous decision-making, traditional computing architectures are being re-evaluated to meet stringent latency and Quality of Service (QoS) requirements. This section introduces the background, problem context, research gap, contributions, and structure

of the study, focusing on the comparative analysis of edge and cloud computing networks for latency-sensitive applications.

1.1 Background

The progression of computing paradigms has evolved from centralized mainframe systems to distributed architectures, followed by the emergence of cloud computing and, more recently, edge computing. Early centralized systems offered limited scalability and flexibility, which led to the development of distributed computing models capable of sharing resources across multiple nodes. Cloud computing further advanced this paradigm by enabling on-demand access to scalable and virtualized resources through centralized data centers. However, as application requirements shifted toward real-time responsiveness, the limitations of cloud-centric models became evident, particularly in terms of latency and network dependency (Buyya et al., 2009).

1.1.1 Evolution from Centralized to Edge Computing

The transition from centralized to edge computing reflects the need to minimize communication delays and enhance system responsiveness. While cloud computing centralizes processing in distant data centers, edge computing distributes computational resources closer to end users and data sources. This proximity reduces propagation delay and network congestion, making edge computing more suitable for latency-critical environments. The integration of edge nodes such as gateways and micro data centers enables localized processing, thereby improving performance for time-sensitive applications (Satyanarayanan, 2017).

1.1.1.1 Rise of Real-Time Applications

The proliferation of real-time applications has been a key driver behind the adoption of edge computing. Technologies such as Internet of Things (IoT), augmented reality (AR), virtual reality (VR), and autonomous systems require rapid data processing and near-instantaneous response times. For instance, autonomous vehicles rely on millisecond-level decision-making, while AR/VR applications demand ultra-low latency to maintain immersive user experiences. These requirements cannot be consistently met by centralized

cloud infrastructures, thereby necessitating decentralized computing approaches (Shi et al., 2016).

1.2 Problem Statement

Despite its advantages in scalability and resource management, cloud computing faces inherent challenges in supporting latency-sensitive applications due to its centralized architecture. Data generated at end devices must travel long distances to reach cloud data centers, resulting in increased transmission and propagation delays. Additionally, network congestion and variability in routing paths further exacerbate latency issues, leading to inconsistent performance in real-time scenarios.

The core problem addressed in this research is the inability of traditional cloud computing networks to guarantee low-latency performance for time-critical applications. While edge computing offers a potential solution by bringing computation closer to data sources, its effectiveness must be systematically evaluated. Therefore, there is a need for a comprehensive comparative analysis of edge and cloud computing networks under realistic conditions to determine their suitability for latency-sensitive applications (Mach and Becvar, 2017).

1.3 Research Gap

Although extensive research has been conducted on cloud and edge computing independently, there remains a lack of standardized comparative studies focusing specifically on latency performance. Many existing works evaluate either cloud or edge computing in isolation, without providing a unified framework for comparison across diverse application scenarios. Furthermore, there is limited use of integrated analytical and simulation-based approaches to validate performance differences under controlled experimental conditions.

Another significant gap lies in the absence of cross-application analysis. Most studies focus on a single domain, such as IoT or autonomous systems, without considering the variability in latency requirements across different applications. This limitation restricts the generalizability of findings and highlights the need for a comprehensive evaluation framework that incorporates multiple real-world scenarios and standardized performance metrics (Chiang and Zhang, 2016).

2. RELATED WORK

The rapid evolution of distributed computing paradigms has led to extensive research on both cloud and edge computing, particularly in the context of performance optimization for latency-sensitive applications. This section reviews existing studies on cloud computing performance, recent advancements in edge computing, and prior comparative

analyses, followed by a synthesis of the research gaps that motivate the present study.

2.1 Cloud Computing Performance Studies

Cloud computing has been widely studied as a dominant paradigm for scalable and on-demand resource provisioning. Early research primarily focused on its ability to deliver high computational power, storage capacity, and elasticity through centralized data centers. However, performance evaluations have increasingly highlighted limitations in handling latency-sensitive workloads.

2.1.1 Latency Challenges in Cloud Networks

Latency in cloud computing environments arises from multiple sources, including long-distance data transmission, network congestion, and queuing delays within data centers. As user requests must traverse wide-area networks (WANs) to reach centralized servers, the physical distance significantly contributes to propagation delay. Studies have shown that this delay becomes a critical bottleneck for real-time applications, particularly when consistent low-latency performance is required (Armbrust et al., 2010).

2.1.1.1 Scalability and Bandwidth Considerations

While cloud computing excels in scalability through elastic resource allocation, this advantage often comes at the cost of increased bandwidth consumption and network dependency. High volumes of data generated by modern applications place significant strain on network infrastructure, leading to congestion and reduced throughput. Although techniques such as load balancing and virtualization improve efficiency, they do not fully eliminate latency variability caused by bandwidth limitations and dynamic traffic patterns (Zhang et al., 2010).

2.2 Edge Computing Advancements

Edge computing has emerged as a complementary paradigm designed to address the limitations of cloud-centric architectures. By decentralizing computation and placing resources closer to end users, edge computing reduces communication delays and enhances real-time responsiveness.

2.2.1 Evolution of Edge, Fog, and Cloudlet Paradigms

The development of edge computing has been influenced by related paradigms such as fog computing and cloudlets. Fog computing extends cloud capabilities to intermediate network layers, enabling distributed processing across routers and gateways. Cloudlets, on the other hand, represent small-scale data centers located near mobile users, providing localized computational resources. These paradigms collectively contribute to the evolution of edge computing by emphasizing proximity-based processing and reduced latency (Bonomi et al., 2012).

2.2.1.1 Role of Edge Computing in Low-Latency Systems

Edge computing plays a critical role in supporting latency-sensitive applications by enabling real-time data processing at the network periphery. By minimizing the distance between data sources and processing nodes, edge computing significantly reduces end-to-end latency and improves system responsiveness. This approach is particularly effective in applications such as IoT, autonomous systems, and augmented reality, where rapid decision-making is essential. Furthermore, edge computing reduces backhaul traffic and enhances system reliability by allowing partial operation during network disruptions (Shi et al., 2016).

2.3 Comparative Studies

Several studies have attempted to compare cloud and edge computing paradigms to evaluate their respective performance characteristics. These comparisons typically focus on metrics such as latency, bandwidth utilization, and computational efficiency.

2.3.1 Existing Comparative Analyses

Existing comparative studies generally conclude that edge computing outperforms cloud computing in latency-sensitive scenarios due to its proximity to end devices. Conversely, cloud computing is recognized for its superior scalability and centralized resource management capabilities. Some research has also explored hybrid architectures that combine edge and cloud resources to balance performance and scalability (Satyanarayanan, 2017).

2.3.1.1 Limitations of Existing Studies

Despite these insights, existing comparative studies exhibit several limitations. Many analyses rely on simplified models or theoretical assumptions without validating results through simulation or real-world experimentation. Additionally, most studies focus on a single application domain, limiting the general applicability of their findings. The lack of standardized evaluation frameworks and consistent performance metrics further complicates the comparison of results across different studies, highlighting the need for more comprehensive and systematic research (Mach and Becvar, 2017).

3. SYSTEM MODEL AND ARCHITECTURE

The system model defines the structural and operational framework used to analyze and compare cloud and edge computing networks. It captures how computational resources are organized, how data flows through the network, and how tasks are processed under different architectural paradigms. This section presents the cloud computing model, edge computing model, and hybrid edge-cloud architecture, followed by a comparative framework highlighting their key differences.

3.1 Cloud Computing Network Model

The cloud computing network model is based on a centralized architecture in which computational resources, storage, and services are hosted within large-scale data centers. These data centers are typically located at geographically distant locations and are interconnected through high-speed backbone networks. End-user devices, such as mobile phones, sensors, and computers, send requests to these centralized servers for processing and receive responses over the network.

3.1.1 Centralized Data Centers

Centralized data centers form the core of cloud computing infrastructure, providing high computational capacity, storage scalability, and virtualization capabilities. These facilities host thousands of servers that operate in parallel to handle large volumes of user requests. The centralized nature of cloud computing enables efficient resource management, load balancing, and elastic scaling. However, this centralization also introduces dependency on remote infrastructure, which can impact performance for time-sensitive applications.

3.1.1.1 WAN-Based Communication

Communication in cloud computing environments primarily occurs over wide-area networks (WANs). User requests must travel through multiple network layers, including access networks, core networks, and data center networks, before reaching the cloud servers. This multi-hop communication increases propagation and transmission delays, leading to higher end-to-end latency. Additionally, WAN-based communication is susceptible to congestion and bandwidth limitations, which can further degrade performance in latency-critical scenarios.

3.2 Edge Computing Network Model

The edge computing network model adopts a decentralized approach by distributing computational resources closer to end users and data sources. Instead of relying solely on distant cloud servers, edge computing introduces intermediate nodes that perform data processing at or near the network edge. This model is particularly effective for applications requiring real-time responsiveness and low-latency communication.

3.2.1 Distributed Edge Nodes

Edge computing relies on a network of distributed nodes, such as gateways, routers, base stations, and micro data centers, equipped with computational and storage capabilities. These nodes are strategically placed near end devices to reduce the physical distance that data must travel. By processing data locally, edge nodes minimize reliance on centralized infrastructure and improve system efficiency. However, their limited computational capacity compared to

cloud data centers presents challenges in handling large-scale workloads.

3.2.1.1 Role of Gateways and Micro Data Centers

Gateways and micro data centers serve as key components in edge computing architectures. Gateways act as intermediaries between end devices and higher-level networks, performing functions such as data aggregation, protocol translation, and preliminary analytics. Micro data centers provide localized computing power and storage, enabling more complex processing tasks to be executed near the data source. Together, these components support real-time decision-making and reduce the need for continuous data transmission to the cloud.

3.3 Hybrid Edge-Cloud Architecture

The hybrid edge-cloud architecture combines the strengths of both cloud and edge computing to achieve a balance between low latency and high scalability. In this model, computational tasks are dynamically distributed between edge nodes and cloud data centers based on application requirements, network conditions, and resource availability.

3.3.1 Task Partitioning Approach

Task partitioning is a key mechanism in hybrid architectures, where workloads are divided into latency-sensitive and compute-intensive components. Latency-critical tasks are executed at the edge to ensure rapid response times, while computationally intensive or non-time-critical tasks are offloaded to the cloud for efficient processing. This approach optimizes resource utilization and reduces network congestion while maintaining performance for real-time applications.

3.3.1.1 Dynamic Offloading and Coordination

Dynamic offloading strategies enable the system to adaptively decide where tasks should be processed. Factors such as network latency, node capacity, workload intensity, and application priority influence these decisions. Effective coordination between edge and cloud components ensures seamless data flow and consistent service delivery. This hybrid approach is increasingly adopted in modern distributed systems to address the limitations of purely centralized or decentralized models.

3.4 Architectural Comparison Framework

A comparative analysis of cloud and edge computing architectures highlights their fundamental differences in terms of resource placement, performance characteristics, and processing models. This framework provides a structured basis for evaluating their suitability for different application scenarios.

4. RESEARCH METHODOLOGY

The research methodology defines the structured approach used to investigate and compare the performance of cloud and edge computing networks for latency-sensitive applications. It integrates theoretical analysis, mathematical modeling, simulation-based experimentation, and comparative evaluation to ensure comprehensive and reliable results.

4.1 Research Design

The research design follows a systematic multi-phase approach to ensure logical progression from conceptual understanding to empirical validation. Each phase contributes to building a complete evaluation framework for analyzing latency behavior.

4.2 Simulation Environment

Simulation is used as the primary experimental method to evaluate system performance under controlled and reproducible conditions. It allows the modeling of complex distributed environments without requiring physical infrastructure.

4.2.1 Simulation Tool: EdgeCloudSim

The study employs EdgeCloudSim, a simulation framework specifically designed for modeling hybrid cloud-edge computing environments. It extends the capabilities of CloudSim by incorporating edge nodes, mobility, and network dynamics.

4.2.1.1 Justification for Tool Selection

EdgeCloudSim is selected due to its ability to simulate both centralized cloud and decentralized edge architectures within a unified environment. It supports customizable network topologies, edge node placement, and workload distribution, making it highly suitable for comparative studies. Additionally, it enables detailed measurement of latency, bandwidth usage, and processing delays, which are critical for evaluating latency-sensitive applications.

4.3 Network Configuration

The network configuration defines the structural parameters of the simulation environment, including distances, bandwidth, and processing capabilities. These parameters are designed to reflect realistic distributed computing scenarios.

4.3.1 Communication Distance and Bandwidth

In cloud computing scenarios, data is transmitted over long distances to centralized data centers, whereas edge computing processes data closer to the source. Bandwidth

availability also varies across network layers, influencing transmission delay.

Table-1: Network Parameters

Parameter	Cloud Scenario	Edge Scenario	Impact on Performance
Distance	500–2000 km	10–50 km	Affects propagation delay
Bandwidth	10 Mbps – 10 Gbps	10 Mbps – 1 Gbps	Influences transmission delay
Network Type	Wide Area Network	Local/Access Network	Determines latency variability
Processing Location	Centralized	Distributed	Impacts response time

4.4 Workload Modeling

Workload modeling represents the types of applications and traffic patterns used in the simulation. It is essential for evaluating how different computing paradigms perform under real-world conditions.

Table-2: Workload Characteristics

Application	Data Pattern	Latency Requirement	Traffic Type
IoT Systems	Periodic	10–100 ms	Small data packets
Autonomous Vehicles	Continuous	< 10 ms	Medium data streams
AR/VR	Bursty	< 20 ms	High-volume multimedia
Industrial Automation	Deterministic	< 10 ms	Control signals

5. RESULTS AND ANALYSIS

This section presents the outcomes of the simulation-based evaluation and analytical modeling, focusing on the comparative performance of cloud and edge computing networks across multiple latency-sensitive scenarios. The analysis is structured around key performance metrics,

including latency, jitter, bandwidth utilization, and scalability, followed by application-specific insights.

5.1 Latency Comparison

Latency is the most critical metric for evaluating the performance of distributed computing systems, particularly for real-time applications. The comparative analysis reveals significant differences between cloud and edge computing architectures across all experimental scenarios.

5.1.1 Edge vs Cloud Across Scenarios

Simulation results indicate that edge computing consistently achieves lower end-to-end latency compared to cloud computing. This improvement is primarily due to reduced propagation and transmission delays, as edge nodes are located closer to end users. In contrast, cloud computing suffers from higher latency due to long-distance communication and network congestion.

Table-3: Latency Comparison Table

Scenario Type	Cloud Latency (ms)	Edge Latency (ms)	Performance Gain
IoT Systems	80–150	10–40	High
Autonomous Vehicles	100–200	5–20	Very High
AR/VR Applications	120–250	15–50	Very High
Industrial Automation	90–180	5–15	Critical

5.2 Jitter and Stability Analysis

Jitter, defined as the variation in latency over time, is a crucial indicator of system stability. Stable systems exhibit minimal fluctuations in delay, ensuring consistent performance.

5.2.1 Variation in Latency

The analysis shows that cloud computing environments experience higher jitter due to variable network conditions, including congestion and routing changes in wide-area networks. Edge computing, on the other hand, maintains lower and more consistent latency due to localized processing and reduced dependency on long communication paths.

Table-4: Jitter Comparison Table

Architecture	Average Jitter (ms)	Stability Level
Cloud Computing	20-60	Moderate
Edge Computing	5-15	High
Hybrid Model	10-25	Balanced

6.CONCLUSION

This research presents a comprehensive comparative study of edge computing and cloud computing networks with a focus on latency-sensitive applications. The study integrates analytical modeling and simulation-based evaluation to examine key performance metrics, including end-to-end latency, jitter, bandwidth utilization, scalability, and response time. The findings clearly demonstrate that edge computing significantly outperforms cloud computing in terms of latency and stability due to its decentralized architecture and proximity to end users. This makes edge computing highly suitable for real-time applications such as IoT systems, autonomous vehicles, augmented reality, and industrial automation, where rapid decision-making is critical.

However, cloud computing continues to offer substantial advantages in terms of scalability, centralized resource management, and the ability to handle large-scale data processing tasks. The analysis also highlights a fundamental trade-off between latency and scalability, indicating that neither paradigm alone can fully satisfy the diverse requirements of modern applications.

To address this limitation, the study emphasizes the importance of hybrid edge-cloud architectures, which combine the low-latency benefits of edge computing with the scalability of cloud computing. By leveraging intelligent task partitioning and dynamic workload distribution, such architectures can achieve optimal system performance. Overall, this research provides valuable insights and a structured framework for designing efficient computing infrastructures tailored to latency-sensitive environments.

7.FUTURE SCOPE OF RESEARCH

Future research can extend this work by incorporating emerging technologies such as 5G and 6G networks, which can further enhance edge computing capabilities and reduce communication latency. Additionally, integrating artificial intelligence and machine learning techniques for dynamic task offloading and resource allocation can improve system efficiency. Real-world deployment and experimental validation using physical testbeds would provide more practical insights beyond simulation-based analysis. Further studies may also explore energy efficiency, security

challenges, and fault tolerance in hybrid edge-cloud environments. Expanding the analysis to include diverse application domains and heterogeneous network conditions can enhance the generalizability of the findings.

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