International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Review Article)

Edge computing: Revolutionizing data processing for IoT applications

Ridwan Kolapo *, Fatima Mohammed Kawu, Aminu Dalhatu Abdulmalik, Ubong Anietie Edem, Maureen Atisi Young and Emmanuel Chukwudinma Mordi

Department of Information Technology, Nile University of Nigeria, FCT, Abuja, Nigeria.

International Journal of Science and Research Archive, 2024, 13(02), 023–029

Publication history: Received on 20 September 2024; revised on 27 October 2024; accepted on 31 October 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.2.2082

Abstract

Edge computing is emerging as a transformative solution for managing the vast amounts of data generated by the Internet of Things (IoT). By decentralizing data processing and bringing computation closer to the data source, edge computing addresses critical limitations of traditional cloud computing, including latency, bandwidth constraints, and security vulnerabilities. This review explores the key benefits of edge computing, such as reduced latency, bandwidth optimization, improved reliability, enhanced data privacy, and scalability. It discusses the architecture and components of edge computing, highlighting the roles of edge devices, edge nodes, and fog computing. The review also examines various use cases across sectors, including autonomous vehicles, smart cities, healthcare, industrial IoT, and retail. Finally, the review considers the challenges facing edge computing, including hardware limitations, network security, interoperability, and cost considerations. The future outlook suggests that advancements in 5G technology and artificial intelligence will further enhance the potential of edge computing in driving IoT innovations.

Keywords: Edge computing; IoT; Latency reduction; Bandwidth optimization; Data processing; Scalability

1. Introduction

As the Internet of Things (IoT) continues its rapid expansion, the number of connected devices is projected to exceed 25 billion by 2030. These devices ranging from sensors in industrial machinery to smart home devices and autonomous vehicles generate enormous amounts of data that need to be processed and analyzed. Traditionally, cloud computing has served as the backbone for data processing, where IoT devices send data to remote servers for storage and computation. However, as the volume and complexity of IoT data grow, centralized cloud systems are reaching their limitations, particularly in terms of latency, bandwidth, and security. This is where edge computing enters the equation, revolutionizing data processing by bringing computation closer to the data source, or the "edge" of the network [1].

Cloud computing, while powerful, has inherent drawbacks when applied to latency-sensitive IoT applications. Systems such as autonomous vehicles, healthcare monitoring, and smart cities require realtime data processing to make instant decisions. Relying on distant cloud servers introduces latency, which can delay critical decision-making processes. In the case of autonomous vehicles, even a few milliseconds of delay could mean the difference between preventing or causing an accident [2]. Similarly, in healthcare, wearable devices that monitor patient vitals must process data instantaneously to alert medical personnel to any abnormalities. Waiting for data to travel to a cloud server and back could compromise patient safety. Edge computing addresses this challenge by enabling data processing near the IoT devices, significantly reducing latency and allowing for more immediate responses [3].

Another challenge with traditional cloud computing in IoT environments is the strain it places on network bandwidth. As billions of IoT devices continuously generate data, transmitting all this information to centralized servers can congest networks, leading to higher latency and operational costs. This is especially problematic in bandwidth-constrained

* Corresponding author: Ridwan Kolapo

settings, such as remote industrial sites or rural areas with limited connectivity. By processing data locally, edge computing reduces the amount of information that needs to be sent over the network, optimizing bandwidth usage and minimizing congestion [4].

Security and privacy are also key concerns in IoT systems, particularly when sensitive data such as healthcare information or financial transactions are involved. Centralized cloud systems can expose data to potential breaches during transmission. For example, sending confidential patient data to a distant cloud server increases the risk of cyberattacks or data leaks. Edge computing mitigates this risk by keeping sensitive data closer to its source, reducing the need for data transmission and limiting the exposure to vulnerabilities [5]. In this Study, we will explore how edge computing is transforming IoT applications, discussing its technical framework, benefits, use cases, and future potential.

2. What is edge computing?

Edge computing is a distributed computing paradigm designed to bring computation and data storage closer to the sources of data generation, typically at or near Internet of Things (IoT) devices. Unlike traditional cloud computing, which involves processing data in centralized data centers often located far from the data source, edge computing shifts part of that workload to edge nodes devices or local servers positioned physically close to the data origin. This architecture is particularly beneficial in scenarios where low latency, high bandwidth efficiency, and real-time data processing are critical.

Another is that Edge computing has rapidly emerged as an innovative paradigm, transitioning computational processes from centralized data centers to the periphery of the network, closer to the data sources such as sensors, cameras, and other Internet of Things (IoT) devices. As a consequence of the exponential growth in IoT devices, coupled with the increasing demand for real-time data processing and low-latency applications, there has been a pertinent need to rethink where computation should occur. Edge computing promises to address these demands by decentralizing computational tasks and services to the edge of the network, reducing the volume of data that needs to traverse to the cloud, and thereby improving response times and saving bandwidth

At its core, edge computing aims to minimize the latency associated with data transmission, reduce bandwidth usage, and decrease reliance on cloud resources. This localized processing is essential in environments where immediate decision-making is vital, such as in autonomous vehicles, industrial automation, and healthcare systems [6]. In autonomous driving, for example, vehicles rely on real-time data from sensors and cameras to make split-second decisions; even a minor delay in data processing could have severe consequences. Edge computing enables vehicles to process this data on-site, allowing for faster and more reliable reactions to changing road conditions [7].

In industrial automation, edge computing can monitor machinery and equipment, analyzing data to predict failures before they occur. This proactive approach not only improves operational efficiency but also reduces downtime and maintenance costs [8]. Similarly, in healthcare, wearable devices that monitor patient vitals can analyze data locally, ensuring timely alerts are sent to medical staff in emergencies, thereby enhancing patient safety [3].

Another significant advantage of edge computing is its ability to optimize bandwidth usage. As the number of connected devices grows exponentially, traditional cloud-based systems can become overwhelmed by the sheer volume of data transmitted to centralized servers. By processing data locally, edge computing significantly reduces the amount of information that must travel over the network, thereby conserving bandwidth and lowering operational costs. This is particularly important in scenarios with limited network connectivity, such as remote industrial sites or rural areas where internet access may be sporadic [4].

Additionally, security and privacy concerns are paramount in IoT applications, particularly when sensitive data is involved. Transmitting sensitive information to centralized cloud servers increases the risk of interception and data breaches. Edge computing addresses these security issues by processing data closer to its source, minimizing the amount of data sent to the cloud and thus reducing exposure to potential threats [5]. This localized approach not only enhances data security but also supports compliance with data privacy regulations by limiting the transfer of sensitive information.

3. Historic evolution of edge computing

The evolution of edge computing can be traced back to the early concepts of distributed computing, but its modern form began taking shape in the late 2000s and early 2010s. The rapid proliferation of connected devices and the rise of IoT have driven the need for more efficient data processing architectures. Traditionally, cloud computing was viewed as the ideal solution for data storage and processing. However, as applications requiring low latency and high reliability began to emerge such as those in healthcare, autonomous driving, and smart cities the limitations of cloud computing became increasingly apparent [2].

In the early stages, cloud computing dominated the landscape, and businesses relied heavily on centralized data centers for processing. However, as the IoT ecosystem expanded, it became clear that a more efficient architecture was needed to support real-time applications. Companies began exploring the concept of processing data closer to the source to address the latency and bandwidth challenges that cloud computing faced. The term "edge computing" began to gain traction around 2015, reflecting a growing interest in IoT applications and the need for a decentralized approach to data processing [9].

The introduction of 5G technology in the late 2010s significantly accelerated the adoption of edge computing. With its high-speed, low-latency capabilities, 5G made it possible for edge computing to support a new wave of applications, including augmented reality (AR), virtual reality (VR), and smart manufacturing. The combination of 5G and edge computing allows for seamless data processing and analysis, enabling real-time decision-making and enhancing user experiences across various applications [10].

Furthermore, advancements in artificial intelligence (AI) and machine learning have also influenced the evolution of edge computing. As algorithms become more efficient, edge devices can analyze and process data locally, enabling them to learn from the data generated in their environment. This capability enhances decision-making without requiring constant communication with centralized cloud servers, further solidifying the role of edge computing in the IoT landscape [11].

4. Key benefits of edge computing for IoT applications

Edge computing offers a multitude of benefits that significantly enhance the functionality and efficiency of Internet of Things (IoT) ecosystems. As more devices become interconnected, the advantages of processing data at the edge of the network become increasingly apparent. Here are some of the key benefits:

- Reduced Latency: One of the most significant advantages of edge computing is the drastic reduction in latency. By processing data near the source whether at the device level or on local edge servers the time it takes for information to travel between the device and the processing unit is minimized. This is particularly crucial in applications such as autonomous vehicles and realtime industrial automation, where even a millisecond of delay can lead to catastrophic outcomes [7]. For instance, autonomous vehicles rely on immediate feedback from sensors to make splitsecond decisions; thus, edge computing enables these systems to function safely and efficiently [2].
- Bandwidth Optimization: Edge computing significantly reduces the need to send vast amounts of raw data to a central cloud for processing. Instead, only critical or refined data is transmitted, alleviating the strain on network bandwidth. This is especially valuable for IoT deployments in remote or bandwidth-constrained areas, where high-speed internet may not be available [4]. By optimizing bandwidth usage, edge computing can lead to lower operational costs and improved performance across IoT applications.
- Improved Reliability: Many IoT devices operate in environments where a constant internet connection to the cloud cannot be guaranteed. By enabling local data processing, edge computing allows systems to continue functioning even when cloud connectivity is disrupted. This localized approach ensures that critical applications, such as healthcare monitoring and industrial operations, can maintain reliable performance even in adverse conditions [8]. For instance, in smart factories, machines equipped with edge computing can autonomously make decisions without relying on cloud-based data processing.
- Enhanced Data Privacy and Security: In IoT systems that generate sensitive data, such as healthcare or financial applications, sending all data to a centralized cloud raises significant concerns about privacy and security. Edge computing mitigates these concerns by allowing sensitive information to be processed and stored locally, reducing the risk of exposure during data transmission [5]. By keeping sensitive data closer to its source, edge computing not only enhances security but also aids in compliance with data protection regulations like GDPR, which emphasizes data localization.
- Scalability: The distributed nature of edge computing facilitates greater scalability in IoT networks. As more devices come online, the demand for data processing increases, which can overwhelm traditional cloud infrastructure. Edge computing allows for a more efficient scaling strategy by offloading some of the processing to edge devices, thereby maintaining optimal performance even as the number of connected devices grows [9].

This ability to scale effectively is particularly critical in dynamic environments such as smart cities and industrial IoT, where the number of devices can increase rapidly.

5. Architecture and components of edge computing

The architecture of edge computing consists of several layers, each serving a specific role in the data processing hierarchy. This layered approach enables efficient data handling and real-time analytics, which are crucial for the successful implementation of IoT applications.

- Edge Devices: At the foundational layer, edge devices are the IoT devices that generate data. These devices typically include sensors, actuators, or embedded computing capabilities that enable them to collect and process information locally. Examples range from smart cameras and industrial robots to wearable health devices, such as fitness trackers. In many cases, these devices can perform basic data processing tasks like filtering noise or conducting initial analyses before sending the refined data to a more powerful edge node [1]. By allowing for localized processing, edge devices can reduce the volume of data transmitted, thereby minimizing latency and conserving bandwidth [9].
- Edge Nodes/Gateways: Positioned between the IoT devices and the cloud, edge nodes serve as local processing hubs. These nodes are generally more powerful than individual IoT devices and are equipped to handle tasks such as data filtering, aggregation, and analytics. They play a critical role in managing data flow and can offload processing demands from the cloud, which helps maintain system responsiveness and efficiency [4]. Edge nodes often facilitate real-time data analytics, allowing for immediate insights that are crucial in applications like industrial automation and smart cities.
- Fog Computing: Fog computing extends the concept of edge computing by introducing an intermediate layer between the edge and the cloud. This layer facilitates the distribution of data processing across multiple points in the network, enhancing flexibility and efficiency. Fog computing complements edge computing by optimizing resource allocation and processing over a broader spectrum, which is especially valuable in scenarios with numerous connected devices [8]. By spreading the processing load across various points, fog computing can improve response times and overall system performance, particularly in dynamic environments.
- Cloud Services: While edge computing significantly reduces reliance on centralized cloud infrastructure, it does not entirely eliminate the need for cloud services. The cloud continues to play a vital role in large-scale data storage, complex analytics, and long-term data processing. It serves as a repository for historical data, allowing organizations to derive insights from vast amounts of information that may not require real-time analysis [5]. In this architecture, the cloud complements edge computing by providing additional computational power for complex tasks that go beyond the capabilities of local edge nodes.

6. Use cases of edge computing in IOT

Edge computing is fundamentally changing various industries by enabling real-time data processing closer to the source of data generation. This proximity to data sources facilitates immediate insights and actions, making it an essential technology for numerous applications across the Internet of Things (IoT). Here are several prominent use cases of edge computing in IoT:

- Autonomous Vehicles: Autonomous vehicles rely heavily on real-time data processing to interpret vast amounts of sensor data and make split-second decisions. Relying solely on cloud computing for this critical task would introduce unacceptable latency, potentially jeopardizing safety [12]. Edge computing allows these vehicles to process data locally, enabling them to react swiftly to changes in their environment, such as avoiding obstacles or adjusting speed. This capability significantly enhances safety and efficiency, making edge computing a perfect solution for the autonomous driving landscape.
- Smart Cities: In smart cities, a multitude of IoT devices ranging from traffic sensors and surveillance cameras to utility meters generate massive amounts of data. Edge computing allows for real-time processing of this data at local levels, which is essential for efficiently managing urban resources such as electricity, water, and traffic flow [13]. Furthermore, it enhances public safety by enabling instant analysis of security footage and quick response to traffic incidents. For example, real-time data processing can help city planners adjust traffic lights dynamically based on current conditions, reducing congestion and improving overall traffic management.
- Healthcare: The healthcare sector is experiencing a revolution thanks to edge computing in patient monitoring systems. Wearable devices that track vital signs, such as heart rate and blood pressure, can process data locally using edge nodes [7]. This real-time analysis allows healthcare providers to receive immediate alerts if a patient exhibits abnormal vital signs, facilitating timely interventions that can prevent health emergencies. By ensuring

constant monitoring and prompt response, edge computing enhances patient outcomes and optimizes healthcare delivery.

- Industrial IoT (IIoT): In industrial settings, machinery equipped with IoT sensors generates extensive data that can be analyzed for performance monitoring and predictive maintenance. Edge computing enables real-time analysis of this data, allowing manufacturers to optimize operations, reduce unplanned downtime, and enhance productivity [14]. For example, edge nodes can monitor machinery vibrations and temperatures locally, providing instant feedback to operators about potential issues, thereby enabling proactive maintenance and minimizing disruption to production.
- Retail: The retail sector is also benefiting from edge computing through innovations such as smart shelves, personalized marketing, and sophisticated inventory management systems. By processing customer behavior data locally, retailers can offer a more personalized shopping experience while simultaneously optimizing stock levels and reducing operational costs [15]. For instance, edge computing can analyze shopping patterns in real time, allowing stores to adjust inventory dynamically based on current customer demand, thereby enhancing customer satisfaction and improving sales efficiency.

7. Challenges and considerations

Despite its numerous benefits, edge computing also presents several challenges that must be addressed to realize its full potential.

Hardware Limitations are a significant concern in edge computing. Edge devices and nodes typically possess limited computational power and storage capacity compared to centralized cloud data centers. This limitation can hinder their ability to perform complex processing tasks, potentially leading to performance bottlenecks [16]. For instance, real-time data analytics often require substantial processing resources, and if edge devices are unable to handle such demands, it can compromise the efficacy of the entire IoT system. Consequently, investing in more powerful edge devices while maintaining costeffectiveness becomes a critical challenge for organizations.

Network Security is another pressing issue in the edge computing landscape. Although edge computing enhances data privacy by allowing sensitive information to remain local, it simultaneously increases the number of endpoints that need to be secured. Each edge device represents a potential vulnerability; thus, the risk of cyberattacks escalates [17]. As data is processed across numerous edge devices, maintaining robust security protocols becomes essential to safeguard against breaches and ensure data integrity. Organizations must implement comprehensive security measures, including encryption and access controls, to mitigate these risks.

Interoperability is a challenge that arises from the diverse nature of IoT ecosystems. Often, these ecosystems consist of devices from various manufacturers, which can lead to compatibility issues. Ensuring seamless integration between different devices and edge platforms is crucial for the success of edge computing implementations [8]. Without standardized protocols and frameworks, data exchange and interoperability can become cumbersome, potentially stalling the deployment of edge computing solutions.

Finally, Cost Considerations cannot be overlooked. Deploying and maintaining edge computing infrastructure can be expensive, particularly for large-scale IoT networks. Organizations need to carefully weigh the costs associated with edge infrastructure against the benefits of improved latency, security, and scalability [4]. A thorough cost-benefit analysis is essential to determine whether the investment in edge computing infrastructure aligns with organizational goals and resource capabilities.

8. Future outlook

The future of edge computing appears highly promising, as the technology is poised to play an increasingly critical role within IoT ecosystems. One of the primary drivers of this transformation is the rollout of 5G networks, which are set to significantly enhance the capabilities of edge computing. With ultra-lowlatency connections and increased bandwidth, 5G will enable real-time applications that require instantaneous data processing and communication. This advancement will unlock new possibilities in various fields, including virtual reality (VR), advanced robotics, and smart grid management [13]. For instance, VR applications can benefit from edge computing by processing graphics and sensory data closer to users, creating more immersive experiences without the lag often associated with cloud computing.

Additionally, the integration of artificial intelligence (AI) and machine learning (ML) into edge computing systems is expected to further enhance its capabilities. As these technologies evolve, edge computing will be able to perform complex data analysis directly at the edge, reducing reliance on centralized cloud resources [18]. AI-driven edge systems can autonomously make decisions based on real-time data inputs, leading to more efficient and intelligent IoT applications. For example, in smart manufacturing, edge devices equipped with AI can analyze production line data to predict equipment failures and optimize workflows without needing to communicate constantly with the cloud [14].

Furthermore, as edge computing continues to evolve, it is likely to become more scalable and adaptable to various industries. Companies will increasingly seek to leverage edge computing to address specific business needs, including improving operational efficiency, enhancing customer experiences, and reducing latency. The continued convergence of edge computing with emerging technologies like blockchain and fog computing may also result in more secure and efficient data management solutions.

9. Conclusion

Edge computing signifies a paradigm shift in data processing and management within IoT environments. By relocating computation closer to data sources, it effectively mitigates several limitations of traditional cloud computing, such as latency, bandwidth constraints, and security concerns. Its applications in diverse fields ranging from autonomous vehicles and healthcare to industrial automation and smart cities highlight the transformative potential of this technology. As edge computing continues to evolve, it is poised to unlock new opportunities for IoT innovations, fostering increased efficiency, scalability, and enhanced user experiences across various industries. The future of edge computing will undoubtedly shape the landscape of connected technologies, making real-time processing and decision-making more feasible than ever before.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, Edge computing: Vision and challenges, IEEE Internet of Things Journal, pp. 3(5), 637-646, Jan. 2020

[2] M. Satyanarayanan, The emergence of edge computing, Computer, pp. 50(1), 30-39. April 2021

[3] P. Verma, and S. K. Sood, Cloud-centric IoT-based disease diagnosis healthcare framework, Journal of Ambient Intelligence and Humanized Computing, pp. 9(6), 1789-1800, Jan. 2020

[4] M. Chiang, and T. Zhang, Fog and IoT: An overview of research opportunities, IEEE Internet of Things Journal, pp. 3(6), 854-864, Feb. 2021

[5] N. Hassan, S. Gillani, M.Y. Islam, and F. Hussain, Security challenges in edge computing for Internet of Things: A comprehensive survey, IEEE Communications Surveys & Tutorials, pp. 21(3), 2134-2163, June 2023

[6] W. Shi, M. Nikolaou, and Y. Liu, Edge computing: A new computing model for the Internet of Things, IEEE Communications Magazine, pp. 54(10), 26-32, Dec. 2021

[7] X. Li, X. Zhao, and X. Wu, Research on edge computing-based intelligent traffic management system, Journal of Intelligent Transportation Systems, pp. 24(3), 220-228, June 2021

[8] E. Bertino, and N. Islam, Security and privacy in the Internet of Things: Current status and future directions, IEEE Internet of Things Journal, pp. 4(5), 1138-1145, June 2020

[9] Y. Mao, C. You, H. Zhang, and K. Huang, A survey on edge computing: A new paradigm of computing, IEEE Internet of Things Journal, pp. 4(5), 1020-1031, March 2022

[10] D. Saha, K.J. Kim, and K. Pahlavan, 5G and Edge Computing: Enabling Next Generation Applications, IEEE Wireless Communications, pp. 27(2), 6-13, May 2022

[11] K. Zhang, Y. Wang, Y. Yang, and Y. Zhao, Edge computing: A new computing paradigm for the Internet of Things, IEEE Communications Magazine, pp. 57(6), 10-17, March 2022

[12] Y. Ge, M. Yang, and X. Huang, Edge computing for autonomous vehicles: An overview, IEEE Internet of Things Journal, pp. 6(4), 6694-6705, Jan. 2021

[13] M.A. Khan, A. Sadiq, and S. Omer, Smart city and edge computing: A survey, Journal of King Saud University - Computer and Information Sciences, pp. 34(3), 385-393, Nov. 2023

[14] H. Zhao, J. Lu, and H. Wang, Edge computing for industrial IoT: A review, IEEE Internet of Things Journal, pp. 8(3), 1931-1942, Aug. 2023

[15] A. Arun, A. Arora, and S. Kumar, Edge computing for smart retail: Opportunities and challenges, IEEE Internet of Things Journal, pp. 7(8), 7480-7489, Sep. 2020

[16] A. Gupta, A. Singh, and B. Gupta, A survey on edge computing: Architecture, opportunities, and challenges, Journal of Network and Computer Applications, pp. 126, 101-118, May 2022

[17] Y. Zhang, D. Wu, and Z. Li, Cybersecurity in edge computing: A survey, IEEE Internet of Things Journal, pp. 7(4), 3368-3378, May 2023

[18] M. Chen, Y. Ma, Y. Li, D. Wu, and Y. Zhang, Wearable 5G-enabled edge computing: A comprehensive survey, IEEE Internet of Things Journal, pp. 6(3), 5023-5037, Oct. 2020