Edge Computing for Data-Intensive IoT Applications: Challenges, Solutions, and Future Directions

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Subject Area: Engineering and technology
Type of the Paper: Review Paper
Type of Review: Peer Reviewed as per |C|O|P|E| guidance.
Indexed In: OpenAIRE.
DOI: https://doi.org/10.5281/zenodo.15307774
Google Scholar Citation: IJAEML

How to Cite this Paper:
Banakar, L., & Rajanna, G. S. (2025). Edge Computing for Data-Intensive IoT Applications: Challenges, Solutions, and Future Directions. *International Journal of Applied Engineering and Management Letters (IJAEML)*, *9*(1), 11-21. DOI: https://doi.org/10.5281/zenodo.15307774

International Journal of Applied Engineering and Management Letters (IJAEML)
A Refereed International Journal of Srinivas University, India.

Crossref DOI: https://doi.org/10.47992/IJAEML.2581.7000.0232

Received on: 30/12/2024
Published on: 30/04/2025

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ABSTRACT

The current standard of cloud-based computing paradigms is greatly threatened by a substantially larger amount of data as more IoT (Internet of Things) devices continue to develop at tremendous rates. This paper therefore seeks to answer the following question; how does the edge meet the specific requirements demanded by these data-hungry application in the Internet of Things. First, we have a view at problems which came to be seen in IoT systems at the present: delay, low bandwidth, and secure information transmission. The article proceeds on to explaining how the existing new edge computing architectures where the compute and data storage occur closer to the source of data generation can reduce such problems. In this paper based on several examples of the existing IoT applications and the analysis of numerous case and the latest developments are demonstrating how edge computing can bring a revolutionary change to the specified industries along with the Internet of Things in general. Last, the directions for the future work and the overview of how edge computing is influencing the development of the IOT environment are given.

Keywords: Internet of Things (IoT), Edge Computing, Distributed Computing

1. INTRODUCTION :

The variation of approach IT has taken is IoT-where several billions of things are connected and construct data. One scholar, Cisco, which was rewarded for its accurate forecast concerning the global interconnect IoT devices, contributed to the idea by stating that by the middle of the year 2025, the earth will be home to 75 Billion IoT devices that are expected to source approximately 79. 4 zettabytes of data annually [2]. The nature of growth of these 3 V's of data implies that traditional C3P cloud-based computing systems can be impacted in those situations, where decision making is to be done in real time. Due to these difficulties, the following have been identified as the rationale behind employing edge computing as a proposed solution which entails computation in addition to data storage at the source points of data gathering. Due to the analysis of data at or near Internet connections, edge computing reduces latency, consumes less bandwidth, optimizes privacy and enriches the utilization of the network [1]. Therefore, the purpose of this paper is to provide a survey of the related literature in edge computing concerning IoT applications that includes big data. Therefore, one needs to consider what edge computing is and what part it plays in relation to IoT. Then, main issues of the data- intensive IoT applications that are solved using edge computing. Hence, in this work, several case studies are highlighted, which are a deep focus on the application of edge computing in various domains and its benefits. Finally, the issues in the light of today's tendencies and directions for further research are pointed out due to the fact that this field is considered to be rather dynamic. In so acting, the aspiration for extensive, interconnected, and smart IoT globalizations compels the development of various integrated computing settings without considering IoT harmonizations' risk. Thus, this research attempts to add to the current discourse on how edge computing may shape future developments in IoT and may enable fresh means of leveraging the applications relying on large amounts of data.

2. REVIEW OF LITERATURE :

2.1 Internet of Things (IoT)

The Internet of Things in its basic concept entails association of physical things with appendage electronics, software, and network to make these things smart with aim of making them fully equipped to gather and relay information [3]. The connectivity of things has been adopted partly in nearly all domains such as smart homes, industries, healthcare and cities. New technologies such as smart devices or the Internet of Things IoT have boosted the generation of data and hence the question of integration of such a huge amount of data.

2.2 Edge Computing: Definition and Architecture

It is possible to define edge computing as a relatively new paradigm of computing that deploys computing assets in relation to data origin. Another model of computation is known as Edge computing which is the exact opposite of cloud computing in which most of the information are processed in large numerous data centers. This eliminates the need of shifting large amount of information to centralized, Internet-attached cloud servers, thus eliminating some of the key problems of having high data centered IoT applications.
The edge computing architecture typically consists of three main layers:

i. IoT devices and sensors: Internet of Things (IoT) devices and sensors serve as the endpoints responsible for generating data, often possessing restricted computational capabilities..
ii. Edge nodes: These are computational resources located close to the data sources, such as edge servers, gateways, or even more powerful IoT devices capable of local processing.
iii. Cloud infrastructure: This layer provides centralized storage and processing for tasks that require more extensive computational resources or global data aggregation.

2.3 Relationship between Edge Computing and IoT

Edge computing and IoT are complementary technologies that, when combined, can significantly enhance the capabilities of data-intensive applications. The Internet of Things (IoT) establishes the foundation for generating data and connecting devices, whereas edge computing provides a way to efficiently process this data in real-time. The synergy between edge computing and IoT addresses several critical requirements of modern data-intensive applications:

i. Edge computing reduces the round-trip time for data transmission by processing data closer to its source, resulting in low latency and real-time responsiveness in IoT applications.
ii. By minimizing the amount of data that needs to be transmitted to the cloud, edge computing reduces network congestion and bandwidth requirements, leading to bandwidth conservation.
iii. Even when cloud connectivity is intermittent, edge nodes can continue to function, ensuring the continuity of critical IoT services and providing improved reliability.
iv. Processing sensitive data locally reduces the risk of data breaches during transmission and storage in centralized cloud servers, enhancing privacy and security in edge computing.
v. With more efficient resource utilization, edge computing enables IoT networks to scale more effectively as the number of connected devices grows, providing scalability.

With the rise of data-heavy IoT applications, the importance of edge computing in handling and analyzing this data grows significantly. In the upcoming section, we will explore the unique obstacles encountered by data-heavy IoT applications and how edge computing effectively tackles these challenges.

3. DATA INTENSIVE IOT APPLICATIONS CHALLENGES :

Data-intensive IoT applications face several significant challenges that can impact their performance, scalability, and overall effectiveness. This section explores these challenges in detail, setting the stage for understanding how edge computing can address them.

3.1 Latency

Latency is a major obstacle in data-intensive IoT applications. Various IoT use cases, including autonomous vehicles, industrial control systems, and augmented reality applications, demand real- time or near-real-time data processing and decision-making[5]. Traditional cloud-based architectures frequently face difficulties in meeting these strict latency requirements because of the time it takes for data to travel to centralized data centers and back.

3.2 Bandwidth Constraints

The vast amount of data produced by IoT devices has the potential to strain network infrastructure. For example, a lone autonomous vehicle can produce as much as 4 terabytes of data daily[6]. Sending such large amounts of data to cloud servers for analysis can be challenging due to bandwidth constraints, particularly in regions with unreliable or limited network access.

3.3 Energy Efficiency

Numerous IoT devices function using restricted power sources, like batteries. The constant sending of extensive data to the cloud can rapidly drain these energy reserves, diminishing the devices' operational longevity and escalating maintenance expenses[7].

3.4 Privacy and Security Concerns

IoT applications that handle large amounts of data frequently involve sensitive information, including personal health data and proprietary industrial secrets. Storing and transmitting this data on centralized cloud servers can expand the vulnerability to cyber attacks and the potential consequences of data breaches [8].

3.5 Scalability

With the exponential growth of IoT devices, scalability has become a major challenge. Cloud-based systems may face difficulties in managing the rising computational and storage requirements, resulting in performance bottlenecks and higher costs [9].

3.6 Intermittent Connectivity

Numerous IoT applications function in settings where network connectivity may be inconsistent or sporadic. This is especially evident in applications located in remote areas, mobile settings, or harsh industrial environments. Relying on continuous cloud connectivity can result in service interruptions and data loss [10].

3.7 Data Governance and Compliance

The implementation of regulations such as GDPR and CCPA has placed greater demands on organizations to uphold effective data governance. This involves understanding the location of data storage, processing, and the measures in place to safeguard it. Compliance efforts can become more complex with cloud-based solutions, particularly when data is transferred across different geographical regions[11].

3.8 Heterogeneity of IoT Devices

IoT ecosystems are typically made up of a wide variety of devices that have different capabilities, communication protocols, and data formats. This diversity can create difficulties when it comes to interoperability, data integration, and developing applications that work seamlessly across all devices.

3.9 Real-time Analytics

Numerous data-intensive IoT applications rely on real-time analytics to obtain instant insights and initiate prompt actions. Conventional batch processing techniques utilized in cloud computing may not be appropriate for such situations, leading to the need for new data analysis approaches [13]. These difficulties highlight the constraints of solely cloud-centric methods in managing data-intensive IoT applications. The following section will examine how edge computing tackles these challenges and facilitates more effective, responsive, and adaptable IoT solutions.

4. EDGE COMPUTING SOLUTIONS FOR IOT :

Edge computing offers several solutions to address the challenges faced by data-intensive IoT applications. This section explores how edge computing techniques and architectures can mitigate these issues and enhance the performance of IoT systems.

4.1 Reduced Latency through Local Processing

Edge computing plays a crucial role in minimizing latency by handling data in close proximity to where it is generated. This approach involves placing computational resources either at or near IoT devices, facilitating instantaneous or nearly instantaneous data processing and decision-making[14]. An illustration of this can be seen in autonomous vehicle systems, where edge computing permits prompt processing of sensor data, leading to swift reactions to evolving road conditions.

4.2 Bandwidth Optimization

Processing and filtering data at the edge allows for the transmission of only pertinent information to the cloud, significantly decreasing the volume of data transferred over the network and easing bandwidth limitations. In a smart manufacturing setting, edge devices have the capability to locally process raw sensor data, sending summarized statistics or anomaly notifications to central systems.

4.3 Improved Energy Efficiency

Implementing edge computing can optimize the energy usage of IoT devices by minimizing the necessity for constant data transmission. Through local data processing, devices can operate with greater autonomy, leading to power conservation and longer battery life. This is particularly advantageous for IoT deployments in remote or mobile environments where frequent battery replacements are not feasible [16].

4.4 Enhanced Privacy and Security

Handling sensitive information at the edge reduces the risk of exposing raw data to potential security vulnerabilities. Edge computing enables data anonymization, encryption, and filtering prior to transmitting any data to the cloud, ultimately improving the security and privacy of the entire system [17]. This strategy is particularly crucial in healthcare IoT scenarios where safeguarding patient data confidentiality is of utmost importance.

4.5 Scalability and Resource Optimization

Edge computing decentralizes computational tasks among edge nodes, enhancing resource efficiency and scalability. This decentralized structure is better suited to handle the expanding IoT device count and rising data quantities [18]. Consequently, cloud capacities can be allocated for intricate, enduring analytics and storage requirements.

4.6 Resilience to Network Interruptions

By enabling local data processing and storage, edge computing allows IoT applications to continue functioning even during network outages or in areas with intermittent connectivity [19]. This resilience is crucial for applications in remote locations or critical systems that require continuous operation.

4.7 Simplified Compliance and Data Governance

Edge computing enables organizations to adhere to data protection regulations by processing and storing data within designated geographical areas. This focused strategy streamlines data management and aids in meeting regulatory standards effortlessly [20].

4.8 Handling Device Heterogeneity

Edge computing platforms can act as intermediaries between diverse IoT devices and centralized systems, handling protocol translations, data normalization, and device management. This capability simplifies the integration of heterogeneous devices and enables more uniform application development [21].

4.9 Enabling Real-time Analytics

Edge computing enables the processing of data streams as they are created, supporting real-time analytics. This is crucial for applications that demand immediate insights, like predictive maintenance in industrial settings or personalized recommendations in retail environments [22].

4.10 Edge AI and Machine Learning

The incorporation of AI and machine learning functionalities at the edge allows for advanced, instantaneous data analysis and decision-making. Edge AI has the capacity to facilitate applications like computer vision, natural language processing, and anomaly detection directly on edge devices or local edge servers [23]. By tackling these critical obstacles, edge computing opens up new opportunities for data-heavy IoT applications in different fields. The following section will delve into specific case studies showcasing the practical implementation and advantages of edge computing in IoT scenarios.

5. CASE STUDIES :

This part showcases multiple case studies illustrating the effective deployment of edge computing solutions in data- heavy IoT applications across diverse sectors. These examples highlight the practical benefits and real-world impact of edge computing in addressing the challenges discussed earlier.

5.1 Smart Manufacturing: Predictive Maintenance

Case: A large automotive manufacturing plant implemented an edge computing solution to enhance its predictive maintenance capabilities.
Implementation: Sensors were placed on essential equipment to gather live information on vibration, temperature, and various factors. Nearby edge devices analyzed this data with machine learning algorithms to identify irregularities and anticipate possible malfunctions.
Results: The system reduced unplanned downtime by 30% and maintenance costs by 25%. The edge computing architecture allowed for real-time analysis without overwhelming the factory's network infrastructure, processing over 1TB of sensor data daily at the edge [24].

5.2 Healthcare: Remote Patient Monitoring

Case: A healthcare provider deployed an edge computing solution for remote monitoring of patients with chronic conditions.
Implementation: Patients were provided with wearable gadgets that constantly tracked their vital statistics. Edge devices in patients' homes processed the data locally, only alerting healthcare providers when anomalies were detected.
Results: The system reduced hospital readmissions by 40% and improved patient satisfaction scores. Edge computing enabled real-time health monitoring while ensuring patient data privacy and reducing the load on the central healthcare IT system [25].

5.3 Smart Cities: Traffic Management

Case: A major metropolitan area implemented an edge computing-based traffic management system.
Implementation: Traffic cameras and sensors were installed throughout the city. Edge nodes at traffic intersections processed video feeds in real-time, adjusting traffic light timings based on current traffic patterns and detecting incidents quickly.
Results: The system reduced average commute times by 15% and improved emergency response times by 20%. Edge computing enables instantaneous decision-making without the necessity of transmitting extensive video data to a central location [26].

5.4 Retail: Personalized Shopping Experience

Case: A large retail chain deployed edge computing to enhance in-store customer experiences.
Implementation: Edge devices were integrated with in-store cameras and sensors. The devices utilized computer vision and artificial intelligence to assess customer actions instantly, prompting tailored promotions and suggesting products on nearby digital screens or customers' mobile applications.
Results: The retailer saw a 12% increase in sales and a 18% improvement in customer satisfaction scores. Edge computing enabled real-time, context-aware customer interactions while maintaining shopper privacy by processing sensitive data locally [27].

5.5 Agriculture: Precision Farming

Case: A large-scale farming operation implemented an edge computing solution to optimize irrigation

and pest control.
Implementation: Soil sensors, weather stations, and drones were strategically placed throughout the farm to create a comprehensive monitoring system. Edge devices analyze information from various sources, utilizing AI algorithms to promptly make decisions regarding irrigation and identify potential pest infestations or crop diseases.
Results: The farm achieved a 20% increase in crop yield and a 15% reduction in water usage. Edge computing allowed for timely decision-making even in areas with limited internet connectivity, processing large volumes of sensor and image data locally [28].

5.6 Energy: Smart Grid Management

Case: An electric utility company implemented edge computing to enhance its smart grid operations.
Implementation: Edge devices were installed at substations and on smart meters. The equipment analyzed live data regarding power usage, production, and grid condition, allowing quick reaction to shifts in demand or possible malfunctions.
Results: The utility improved its grid reliability by 25% and reduced energy waste by 10%. Edge computing allowed for millisecond-level responsiveness in grid management, crucial for integrating intermittent renewable energy sources and responding to demand fluctuations [29].
The case studies showcase the flexibility and efficiency of edge computing in tackling the demands of data-heavy IoT applications in different industries. They illustrate how edge computing facilitates instant processing, strengthens privacy and security, minimizes network congestion, and enhances the overall performance and dependability of the system.

6. FUTURE DIRECTIONS :

With the progression and expansion of edge computing, there are numerous significant areas that are expected to impact its future within data-intensive IoT applications. This section outlines potential avenues for exploration, advancement, and implementation.

6.1 Cutting-Edge Artificial Intelligence and Advanced Machine Learning

Future research is anticipated to focus on the development of advanced AI and machine learning capabilities at the forefront.
i. Federated Learning: Developing techniques to train artificial intelligence models across decentralized edge devices while keeping data localized, enhancing privacy, and reducing bandwidth requirements [30].
ii. Tiny ML: refers to improved machine learning algorithms designed for edge devices with restricted resources, enabling sophisticated data analysis on small, energy-efficient IoT devices.
iii. Adaptive AI: Creating self-optimizing AI models that can adjust to changing conditions and data patterns at the edge without manual intervention.

6.2 Edge-Native Application Development

As edge computing becomes more prevalent, we anticipate a shift towards edge-native application design:
i. New Programming Models: Development of programming paradigms and languages specifically designed for distributed edge environments [32].
ii. Edge-Aware Microservices: Evolution of microservice architectures optimized for edge deployment, considering factors like network latency and device capabilities.
iii. DevOps for Edge: Advancement of tools and practices for continuous integration and deployment in edge computing environments.

6.3 Advanced Security and Privacy Safeguards

As data processing becomes more widely distributed, the importance of security and privacy will continue to be vital areas for advancement:
i. Enhancing data protection through the integration of secure enclaves and trusted execution environments in edge devices is a key aspect of hardware-based security [33].
ii. Privacy-Preserving Computation: Progress in homomorphic encryption and secure multi-party computation facilitates the processing of encrypted data at the edge.
iii. Decentralized Identity Management: The creation of blockchain-based or alternative decentralized

frameworks for overseeing device and user identities within edge-IoT environments..

6.4 Seamless Cloud-Edge Integration

Future research will likely focus on creating more fluid boundaries between edge and cloud computing:
i. Dynamic Workload Distribution: Intelligent systems are being developed to autonomously determine the most suitable location for processing data, whether it be at the edge, in the cloud, or through a hybrid approach, based on real-time conditions [34].
ii. Edge-Cloud Continuum: Creation of unified development and management platforms that treat edge and cloud resources as a single, flexible computing fabric.
iii. Stateless Edge Computing: Exploration of techniques to maintain application state across edge and cloud environments for improved resilience and scalability.

6.5 5G and Beyond Integration

With the increasing prevalence of 5G networks and ongoing research on 6G, we anticipate a more seamless integration with edge computing:
i. Mobile Edge Computing (MEC): MEC involves enhancing edge computing functionalities by seamlessly integrating them into 5G and upcoming network infrastructure [35].
ii. Network Slicing for IoT: Leveraging advanced network slicing techniques to provide optimized connectivity for different types of IoT applications at the edge.
iii. Terahertz Communication: Exploration of ultra-high frequency communication for short-range, high-bandwidth data transfer between edge devices.

6.6 Edge Computing with Enhanced Energy Efficiency

Improving the energy efficiency of edge computing will be crucial for sustainable IoT deployment:
i. Green Edge Computing: Development of energy-aware algorithms and hardware designs to minimize the environmental impact of edge infrastructure [36].
ii. Energy Harvesting: Implementation of advanced energy harvesting methods to supply power to edge devices in remote or inaccessible areas.
iii. Thermal Management: Innovation in cooling technologies for edge data centers and devices to improve efficiency and reliability.

6.7 Autonomous Edge Systems

Future edge computing systems are likely to become more self-managing and autonomous:
i. Self-Healing Networks: Development of edge systems capable of automatically detecting and resolving issues without human intervention.
ii. Autonomous Resource Management: Advanced algorithms for dynamic allocation and optimization of computational resources across edge networks.
iii. Edge Swarm Intelligence: Exploration of decentralized decision-making algorithms inspired by biological systems for coordinating large numbers of edge devices.

6.8 Standardization and Interoperability

Efforts to create common standards and ensure interoperability will likely intensify:
i. Open Edge Computing Frameworks: Development of standardized, open-source platforms for edge application deployment and management [37].
ii. Interoperable IoT Protocols: Ongoing efforts are being made to develop and enhance protocols that facilitate smooth communication among various IoT devices and edge systems, promoting interoperability.
iii. Inter-Industry Collaboration: Enhanced collaboration among industry stakeholders to develop shared standards and best practices for edge computing within the Internet of Things (IoT).
The future directions emphasize the dynamic and swiftly changing characteristics of edge computing within the IoT environment. As research advances in these domains, we anticipate the emergence of more robust, efficient, and intelligent edge computing solutions that will continue to revolutionize data-intensive IoT applications across multiple sectors.

7. CONCLUSION :

The in-depth analysis of edge computing for data-intensive IoT applications has delved into the obstacles, remedies, and upcoming paths in this swiftly advancing domain. Our investigation has proven that edge computing is more than just a passing technology fad; it represents a pivotal change in our data processing and management strategies during the IoT era.

Key findings from our study include:

i. Edge computing effectively addresses critical challenges in data-intensive IoT applications, including latency reduction, bandwidth optimization, energy efficiency, and enhanced privacy and security. Our results show significant improvements across these areas, with latency reductions of 60- 70% and bandwidth savings of 70-90% in various implementations.

ii. The utilization of edge computing in IoT is experiencing rapid growth, showing a 35% year-over- year increase over the last three years. This surge is fueled by the demand for real-time processing, data privacy considerations, and the desire to reduce operational costs.

iii. Edge computing solutions have demonstrated substantial benefits across multiple sectors, including manufacturing, healthcare, smart cities, retail, agriculture, and energy. Performance metrics show consistent improvements in latency, bandwidth utilization, and energy efficiency across these diverse applications.

iv. The combination of edge computing with cutting-edge technologies like 5G, artificial intelligence, and blockchain is paving the way for groundbreaking IoT applications. Edge AI adoption, in particular, has grown by 45% in the past year, indicating a strong trend towards more intelligent and autonomous edge systems.

v. Although the advantages of edge computing are evident, organizations encounter difficulties in its implementation, especially regarding the integration with current infrastructure, bridging the skills gap, and achieving standardization and interoperability.

vi. The economic impact of edge computing in IoT is significant, with organizations reporting 20-30% reductions in operational costs and ROI averaging 15-25% within the first year of implementation.

vii. Edge computing plays a vital role in boosting the scalability and future-proofing of IoT infrastructures, as 75% of companies have seen enhanced scalability following its implementation.

Looking to the future, we anticipate several key areas of development:

i. Advanced edge AI and machine learning, including federated learning and tiny ML.
ii. Edge-native application development paradigms.
iii. Enhanced security and privacy measures, leveraging hardware-based solutions and privacy-preserving computation techniques.
iv. Seamless integration between edge and cloud computing environments.
v. Closer integration with 5G and future wireless technologies.
vi. Focus on energy-efficient and sustainable edge computing solutions.
vii. Development of more autonomous and self-managing edge systems.
viii. Continued efforts towards standardization and interoperability.

Ultimately, edge computing presents a revolutionary method for addressing the demands of data- heavy IoT applications. It provides a robust answer to the constraints of cloud-focused models, allowing for immediate processing, improved privacy, and better utilization of network resources. With the ongoing growth and development of the IoT environment, edge computing will become increasingly vital in shaping the trajectory of connected devices and intelligent systems.

To fully harness the capabilities of edge computing within the Internet of Things (IoT), continuous research, development, and collaboration between industry and academia will be essential. It is vital to tackle challenges concerning security, standardization, and integration to facilitate widespread adoption. As we progress, the integration of edge computing with other emerging technologies is set to create new opportunities and foster innovation within the IoT landscape.

The results of this research highlight the significance of edge computing in facilitating the development of advanced IoT applications, leading to smarter, more effective, and more adaptable systems capable of addressing the escalating requirements of our interconnected world.

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