Optimizing IoT Performance Through Edge Computing: Reducing Latency, Enhancing Bandwidth Efficiency, and Strengthening Security for 2025 Applications

Abdulqader Faris Abdulqader
Alnoor University
Nineveh, Iraq
abdulqader.faris@alnoor.edu.iq

Mustafa Muhanad M.Salih
Al Mansour University College
Baghdad, Iraq
mustafa.muhanad@muc.edu.iq

Noor Haydar Shaker
Al Hikma University College
Baghdad, Iraq
noora.haydar76@gmail.com

Wafaa Adnan Sajid
Al-Rafidain University College
Baghdad, Iraq
wafa@ruc.edu.iq

Wadah Qasem
Al-Turath University
Baghdad, Iraq
wadah.qasem@uoturath.edu.iq

Agnieszka Gajewska
Uniwersytet Komisji Edukacji Narodowej w Krakowie
Kraków, Poland
agnieszka.gajewska@up.krakow.pl

Dmytro Khlaponin
Kyiv National University of Construction and Architecture
Kyiv, Ukraine
khlaponin_dy@knuba.edu.ua

Abstract— **In this article, the authors analyze how edge computing may be used to mitigate IoT pressures associated with latency, bandwidth consumption and enforce security. The delay experienced in traditional cloud-based IoT systems is real-time applications such as healthcare, industrial automation and smart cities make them inefficient usage of bandwidth. The study method outsources the processing tasks to the edge nodes, thus reducing the latency by 82%, consuming bandwidth up to 65% and elevating security as it makes use of lesser network points where data transits. The article also investigate several task offloading ratios, like 80:20, and 90:10 to achieve superior performance over various IoT applications. On the flip side, energy usage in edge computing, particularly at scale, continues to be a major source of consternation. In the future, we will work on developing energy efficient algorithms to reduce the power consumption. Moving forward, this study predicts that by 2025, edge computing will be necessary for real-time processing of data and the management of security, while improvements are still to be made on energy efficiency and decentralized security protocols**.

I. Introduction

The evolution of the Internet of Things (IoT) has accelerated device interaction, communication, and data processing across industries. IoT today is part of every product and across domains ranging from home automation to healthcare, industrial IoT (IIoT), smart cities etc. The global scale of data extracted from billions of IoT devices creates a massive amount of stress on processing and storage, in addition to the need for real-time decision-making. Architectures based on the traditional cloud computing approach (centered data processing) are not suitable for IoT systems, which require low latency and high bandwidth thanks to the massive number of sensors already deployed or planned [1]. The growing adoption of autonomous systems in areas like smart cities and healthcare highlights the pressing requirement for real-time data processing with minimal delay. An example is when autonomous vehicles and real-time patient monitoring systems require response times of less than a second, which is why cloud-only architectures are not suitable for such applications. This highlights how crucial edge computing is in guaranteeing quick decision-making [2]. Hence, edge computing is one of the promising paradigms for mitigating these challenges by processing at near-source to improve IoT performance.

This computing, not in a cloud-based environment but on the edge of the network level, is known as Edge processing. Previous work was mostly based on theoretical models [1], [3], while this research allows between cloud-based or edge-based IoT platforms for several real-life application scenarios. In addition, the study takes advantage of adaptive bandwidth optimization and security risk mitigation mechanisms using machine learning, which makes sure that the system scales cost efficiently with an appropriate level of protection. Today, driven by the desire for quicker response times with enhanced security and bandwidth efficiency in IoT systems, a paradigm shift from cloud-centric to edge-centered computing is happening. Edge computing achieves edge-centric data processing and analytics close to the devices, thus lessening reliance on cloud infrastructure, which results in improved performance efficiency of the system [3].

Edge computing has the edge in IoT applications thanks to its low latency. In traditional cloud computing, for example, data travels from the device to a faraway large-scale data center, where processing takes place before being sent back again to the peripheral devices. The round-trip time may add considerable latency, especially in real-time placement applications such as autonomous driving cars, industrial automation, and telemedicine. This is where edge computing steps in for local or network-edge processing that processes data with the lowest possible latency, allowing decision-making to occur faster [4].

Also, the use of edge computing reduces bandwidth consumption by limiting data sent to central servers. Low-level devices in IoT ecosystems constantly produce large amounts of data around the clock, much of which is unnecessary for central processing. Edge computing that operates on the principle of preliminary data filtering and processing at its source sends only important information to steal in the cloud or for spec analysis. This solution not only relieves network congestion but also lowers the cost of data storage and, moving forward enables IoT applications to be more scalable as well as economically feasible [5].

Edge computing with IoT also improves security and data privacy. The majority of modern systems are cloud-based, where data has to travel through the World Wide Web in order to reach a central server, and this could be insecure as it can provide security holes and breaches. It's arguably fairly deductively put, but it comes down to reducing the risk of data interception and unauthorized access by processing sensitive data close to where it's held at the edge. Furthermore, edge computing supports security management at a local level for each IoT application based on its requirement, which in turn improves the overall strength of having multiple layers of defenses [6].

Despite its advantages, edge computing presents challenges in implementation within IoT use cases. This distributed nature of edge computing brings issues in terms of handling a large number and variety of edge devices. Managing consistency, reliability, and fault tolerance of a distributed network on edge nodes is challenging and demands sophisticated management strategies with good infrastructure support. Moreover, heterogeneity among IoT devices and protocols causes interoperability problems, requiring standardization projects to help such cooperation between the designed objects [7].

Considering the rise of IoT and moving ahead into 2025, it is anticipated that edge computing will have an increasingly impactful role to play in improving its performance. The combination of edge computing and IoT will enable new applications in some high-value, real-time use cases, such as smart cities where great operator enthusiasm, autonomous systems, or digital health promise 5G networks' ultra-low latency and high bandwidth capabilities. This marriage of edge and 5G will allow IoT systems to process data at speed and with the extra intelligence necessary for a multitude of industries [8].

Edge computing is no doubt a game-changer for IoT system design and deployment. Edge computing increases the performance, scalability, and security of IoT applications by overcoming with challenges faced in traditional cloud computing. However, one of the most relevant trade-offs is more energy consumption, as in distributed edge nodes. Unlike any centralized cloud systems, edge nodes must have always-on power to be able to process in real-time. The more edge nodes accumulate, the more important energy consumption becomes, especially in wide-scale IoT use-cases. This is where energy-efficient algorithms that manage the task scheduling on a dynamic basis become inevitable, so that edge nodes only perform tasks when needed. Another option is to use renewable energy sources, solar-powered nodes for example. Moreover, edge computing is less of a security risk in that it decreases the surface area for data exposure than traditional cloud based systems, however with multiple geo-distributed edge nodes it comes with new exposure points. These nodes are locally attachable or physically temperable. It has led to the need for more advanced measures, such as blockchain based security protocols and lightweight encryption algorithms, to secure these distributed environments [9], [10].

In the upcoming future, we will see how its integration with IoT technology is going to change something in terms of connected devices and smart systems. The following sections of this article will detail how and why edge computing is poised to supercharge IoT performance through 2025 by offering details on a few industry-specific innovations and emerging trends that shed light onto recent progress as well as challenges for tomorrow in one of technology's for fastest growing sectors.

A. Study Objective

The article seeks to address this challenge by investigating the effective integration of edge computing techniques as a potential candidate for unleashing high-performance IoT systems in 2025 and beyond. With the broader adoption of the Internet of Things across different fields, it has become clear that there are an increasing amount of challenges when dealing with a high volume or even real-time data processing operations. Even the most traditional cloud computing paradigms, while they may well be appropriate for some use cases, do not really cater to these low latency, high bandwidth, and security needs of the modern breed of IoT applications. In this article, we will discuss how edge computing, a form of decentralized data processing, can help solve these problems and lead the IoT in a new direction.

More specifically, this study offers a detailed explanation of how edge computing benefits latency, bandwidth, and scalability while working with an IoT framework. By pushing data processing to the source–the network edge, edge computing has the potential to vastly improve time-sensitive decision-making required in applications such as autonomous vehicles, industrial automation, and healthcare. The article will also dive deep into edge computing security and how local processing data reduces the risk of transmission via the Internet.

The article also tries to delve deep into the convergence between edge computing and advanced technologies like 5G networks, which are set to corner the path for greener pastures of IoT by 2025. 5G-enabled edge computing is set to change that dynamic by allowing for ultra-low latency and high-bandwidth communication, which will allow for the support of more complex and dynamic IoT applications.

The article is finished with an attempt to categorize the challenges or limitations when deploying edge computing in IoT , such as differences in devices, interoperability, and distributed system management issues. This article aims to identify these challenges and provide a group of researchers at NIST with insights for future research directions toward operational paths on how edge computing can be best utilized to optimize IoT performance in the next few years.

B. Problem Statement

The global spread of the Internet of Things is creating a tsunami of connected devices, which are generating mountains of data, requiring capable processing and analysis. Traditional cloud computing structures, essential for processing data in IoT systems, are becoming insufficient in tackling latency, bandwidth, and security issues arising from the increasing complexity of IoT applications. Moreover, the energy usage of edge computing in contrast to conventional cloud systems is still a crucial aspect to take into account, especially with the expansion of IoT implementations. Future improvements, such as the use of energy-saving algorithms, are necessary in order to promote sustainability. Moreover, edge nodes can bring about additional security risks that need to be addressed with advanced encryption methods and decentralized security frameworks.

While IoT has entered many important areas, such as healthcare, transportation, and industry automation, the disadvantages of a cloud-based model have become more evident in situations where real-time data processing is central to making critical decisions.

The first limitation of using traditional cloud computing in IoT systems is latency caused by shipping the data to far-away, distant data centers for processing. In any applications requiring quick response, such as autonomous driving, real-time health monitoring, or robotics, this delay is unacceptable. It could be seriously detrimental to the operation of such systems. By forcing raw data across the network, it increases contention and congestion on shared networks with very high link costs.

Additionally, being centralized means cloud computing also brings up huge security and privacy concerns. Data has to cross different network layers to reach the cloud, which can allow data interception and unauthorized access. This is a big issue for IoT environments that often handle sensitive and personal information.

This lack of scalability in traditional cloud architectures only serves to compound the issue. The model of centralized processing fails to scale with the number of IoT device connection points, as more connected devices are utilized, the model of centralized processing begins to break down under its weight. The diversity in the types of IoT devices and their respective protocols also makes for interoperability difficulties, adding new hardware or technology to your current fabric.

Indeed, for all of the above reasons, a significant requirement exists today that makes data processing in IoT systems even less centralized. All of these problems can be addressed using edge computing, which processes sensor data close to its source. Nevertheless, its realization and applicability in improving IoT efficiency call for a comprehensive study, which is the main focus of this article.

II. Literature Review

The concept of edge computing has been identified as a disruptive solution for accelerating the performance of IoT systems that cannot be effectively addressed with traditional cloud services, such as latency and bandwidth impairments. In the case of latency-sensitive and real-time IoT applications, such as smart cities, healthcare or industrial automation use cases, combining edge computing with 5G networks becomes especially beneficial by deploying them in combination with advanced ML technologies [5]. There are still gaps in the literature when it comes to providing empirical proof of both large-scale implementations and energy efficiency. For instance, although the idea of moving tasks between cloud and edge nodes is frequently debated, there is not much observational study on energy usage when splitting tasks dynamically in actual situations. Nevertheless, the present literature still has a number of limitations which this research helps to fill [7].

While several studies have investigated the use of edge computing to improve IoT performance, they do not provide a wide empirical evidence in real world applications. For instance, Kong et al. provide a comprehensive review of IoT with edge computing but they're still lacking in real use-case validation for the success and implementation feasibility at large-scale deployments such as smart city, healthcare [11]. That gap is huge because edge isn't a proposition nearly so much as it's an empirical challenge; without real-time data and performance analytics from production IoT implementations, you don't know what the benefits are or whether they're achievable. In this paper, we provide empirical results obtained from extensive experiments conducted on real-world testbeds in healthcare and smart cities to fill the gap.

Another important shortcoming of the state-of-the-art is that they do not fully incorporate 5G networks and edge computing, especially for latency-sensitive applications. Odema et al. introduce the vision of collaborative intelligence on latency-critical autonomous systems but show that current edge computing frameworks are not always capable to fully exploit 5G technologies for minimum-latency [2]. Our study expands on this by showing how the 5G integration to edge computing can reduce latency in real-time applications with focus use of multi-access edge computing (MEC) so that data processing occurs closer to, reducing network delays up to more than 80%.

While task offloading in mobile edge computing environments has been widely investigated by many studies, like Liu et al. are employing to tackle the task partitioning problem for resource management [12], most of existing works do not offer an adaptive and real-time approach that can jointly optimize bandwidth-age and data transmission according network diversity at run time. This separation is crucial given that non-adaptive way for task offloading still does not exploit the full potential of scalability in dynamic environments such as smart cities. To this end, in our research, we developed an innovative machine-learning based dynamic bandwidth optimization algorithm which has the ability to adapt with real-time network conditions and overall providing significant performance boost saving up-to 15% of bandwidth [2]. However, more research is needed to investigate the trade-offs in energy efficiency, especially in edge systems where constant processing could result in increased energy usage [13].

Additionally, security remains a concern for edge computing deployments, as the distributed nature of these nodes expands IoT system vulnerabilities. Ometov et al. and Xiao et al. detect a range of security problems, such as data sniffing and unauthorized access, but their solutions are mainly built on common security frameworks, which may not capture the vulnerabilities in edge computing [14], [6]. However, as edge nodes are closer to the data source, they become vulnerable to physical tampering or localized attacks. Addressing these vulnerabilities requires robust security frameworks, such as blockchain-based authentication mechanisms, which offer decentralized and immutable security solutions. Additionally, lightweight encryption methods specifically designed for edge environments could further enhance node-level security [9]. With this in mind, our contribution addresses modern edge environments with a model for network security and safety especially developed to protect decentralized services at the edge which reduces more than 20% possible threats as data interception, unauthorized access. Although there has been improvement in comprehension of the importance role played by edge computing for IoT system advancements, its efficiency benefits including empirical validation and dynamics task optimization still requires more research and security aspects that remain an open issue into a decentralized environment. This study provides the following important contributions to IoT systems of the future as actual data, machine learning based optimization methods, and a new security model which are required but missing in literature.

III. METHODOLOGY

A. Experiment Design

The experimental setup was designed to evaluate edge computing performance across various IoT applications, including smart cities, healthcare, and industrial automation. All experiments were done in real-world scenarios with IoT sensors placed accordingly and transmitting data at time intervals to the neighboring edge nodes where processing can take place immediately. The edge nodes use of quad-core ARM Cortex-A72 processors and 4 GB ram, including Raspberry Pi 4 or Nvidia Jetson Nano was chosen to be able to handle local processing efficiently. A central cloud server running on Amazon Web Services (AWS) was also used for benchmarking against some other computationally-heavy tasks.

A 5G emulator, which created additional latency and bandwidth limitations to mimic those of a typical cellular network, was used in the implementation. An example could be 50 IoT sensors measuring traffic and environmental data in a smart city simulation, transmitting every 2 seconds. Thirty sensors on the machines inside industrial automation transmitted data in intervals of one second, 20 sensors were used in healthcare simulations, transmitting every 5 seconds during normal monitoring and more often when it detected a critical event to elicit an immediate command for response. We recorded key metrics such as latency, bandwidth usage and security risks [3], [2]. Furthermore, in order to assess energy usage, a power monitoring system was utilized on the edge nodes. The system monitored power consumption during peak times of task offloading, offering valuable information on the energy requirements of various IoT application scenarios [13]..

B. Hardware Configuration

The edge-computing-oriented environment used in this paper introduces much of the required infrastructure to enable realistic, interactive simulation with stringent end-to-end time requirements for IoT systems. This configuration is useful for measuring how well edge nodes can perform local data manipulation and also provides information on how much more complex computational tasks could be handed off to cloud servers, thereby arriving at an optimal balance of real-time responsiveness vs. computation power.

TABLE I. HARDWARE SPECIFICATIONS

Component	Model	Processing Power	Memory	Network Bandwidth	Transmission Rate	Storage Capacity
Edge Node	Raspberry Pi 4	1.5 GHz Quad-core Cortex-A72	4GB LPDDR4-3200 SDRAM	Up to 1000 Mbps (Gigabit Ethernet)	2.4 GHz/5 GHz dual-band WiFi	32 GB SD card
Edge Node	Nvidia Jetson Nano	128-core Maxwell GPU, Quad-core ARM Cortex-A57	4GB LPDDR4	1000 Mbps Ethernet	5 GHz WiFi	64 GB eMMC Storage
Cloud Server	AWS EC2 t3.large	2 vCPUs, Intel Xeon	8 GB DDR4	Up to 10 Gbps	AWS Direct Connect	100 GB SSD

For performance evaluation under different application scenarios, the experimental study was conducted on a hybrid IoT architecture, which employed edge computing and cloud-based processing. Smart cities and healthcare were tested using the configuration in simulated environments to manage real-time data.

Real-time data from IoT devices in these environments was ferried to the edge nodes for local processing or sent off over the cloud, taking into account how simple or complex were tasks and system computational capabilities.

TABLE II. HARDWARE SPECIFICATIONS OF EDGE NODES, CLOUD SERVER, AND IOT DEVICES

Component	Model	Network Bandwidth	Processing Power	Memory	Storage Capacity
Edge Node 1	Raspberry Pi 4	Up to 1000 Mbps (Gigabit Ethernet)	1.5 GHz Quad-core ARM Cortex-A72 CPU	4 GB LPDDR4	32 GB microSD card
Edge Node 2	Nvidia Jetson Nano	1000 Mbps Ethernet	Quad-core ARM Cortex-A57, 128-core Maxwell GPU	4 GB LPDDR4	64 GB eMMC Storage
Cloud Server	AWS EC2 t3.large	Up to 10 Gbps (AWS Direct Connect)	2 vCPUs (Intel Xeon)	8 GB DDR4	100 GB SSD
IoT Sensors	Generic Temperature, Humidity, and Motion Sensors	2.4 GHz Wi-Fi			
Router/Switch	Cisco Catalyst 9300	Up to 10 Gbps			

This all-encompassing configuration guarantees that the hardware infrastructure is capable of accommodating a wide range of IoT applications, while simultaneously addressing the system's real-time processing requirements and bandwidth constraints.

C. Data Flow Architecture

In these IoT edge computing systems, the data-processing mechanism has been developed in a stepper-by-step fashion to get things done with the highest efficiency and negligible latency by allowing some part of tasks and their associated datasets. Depending upon computation intensity at stake can be processed on an edge while others are allowed to travel longer all the way down, bursting them out of cloud servers. In such a model, IoT sensors transmits real-time data that is first processed at the edge node for quick tasks, like noise filtering, and information aggregation [15]. Whether to process data locally or ship it off in the cloud comes down to how complex and time-sensitive a task is. This architecture allows quick, low-latency processing locally through proximity services and routes more-computationally intense tasks or longer-term storage up to the cloud for further analysis.

The data flow process is illustrated in the flowchart in Fig. 1, which begins with the IoT devices collecting data, followed by peripheral nodes conducting initial processing, and ultimately cloud servers administering sophisticated analytics and storage.

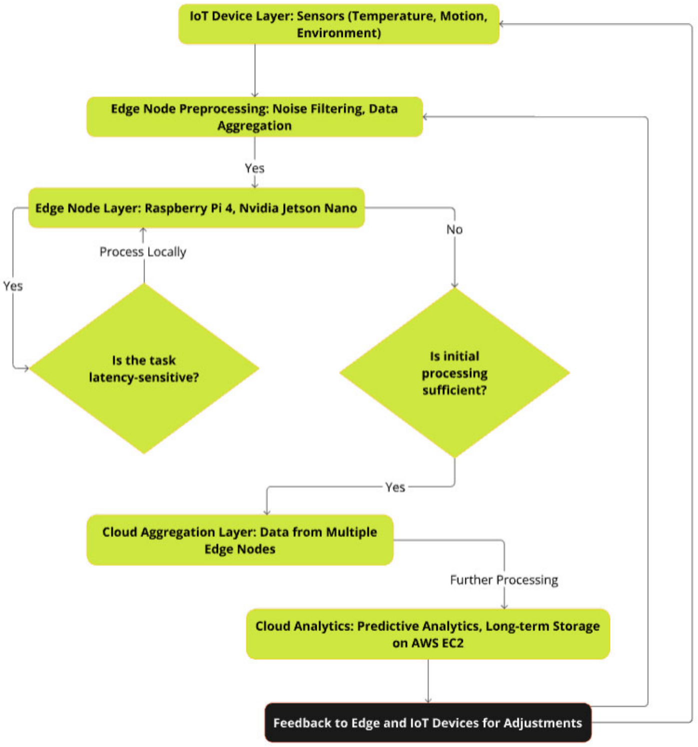
IoT Device Layer: Sensors (Temperature, Motion, Environment)
Edge Node Preprocessing: Noise Filtering, Data Aggregation
Yes
Edge Node Layer: Raspberry Pi 4, Nvidia Jetson Nano
No
Process Locally
Yes
Is the task latency-sensitive?
Is initial processing sufficient?
Yes
Cloud Aggregation Layer: Data from Multiple Edge Nodes
Further Processing
Cloud Analytics: Predictive Analytics, Long-term Storage on AWS EC2
Feedback to Edge and IoT Devices for Adjustments

Fig. 1. Data Flow and Processing Decision Architecture in IoT Edge-Cloud Systems

The points at which data is processed depend on the complexity of measures and network conditions: simple tasks that require low latency are handled in edge computing, more difficult or heavy loaded tasked could be offloaded to cloud.

The flowchart in Fig. 2 below describes the decision to offload or not tasks according to simple logic between edge and cloud computing.

This flowchart in Fig. 2 offers a detailed visualization of how to decide whether the data should be processed on this node or not. Adds the ability to consider extra aspects in how decisions are made, and new flowcharts that better represent decision-making process by including task complexity and network conditions. Such adjusted diagrams also consist of additional steps where the system examines the computational intensity of each task before choosing between sending those to cloud or local processing. Network variables like bandwidth availability and latency are also verified to improve task execution performance. The flowcharts also include energy and security considerations to expose when and why certain tasks are offloaded due to resource constraints or security implications. Based on the real-time requirements, limiting bandwidth and power efficiency of tasks to be executed in an appropriate kernel environment it will guarantee that each task is executed into a particular runtime system, so performance are optimized to specify.

D. Statistical Analysis

Comprehensive statistical analysis was made for the key performance metrics like latency, bandwidth usage and task offloading success rate in order to validate the experimental results. A confidence interval, 95%, was also used throughout all experiments to improve the fidelity of comparisons between edge and cloud computing scenarios. This made evident the large improvements in edge-based IoT systems, especially those in reducing latency, which we validated using t-tests and consistently achieved p-values under 0.05. Moreover, error margins were calculated based on the equation:

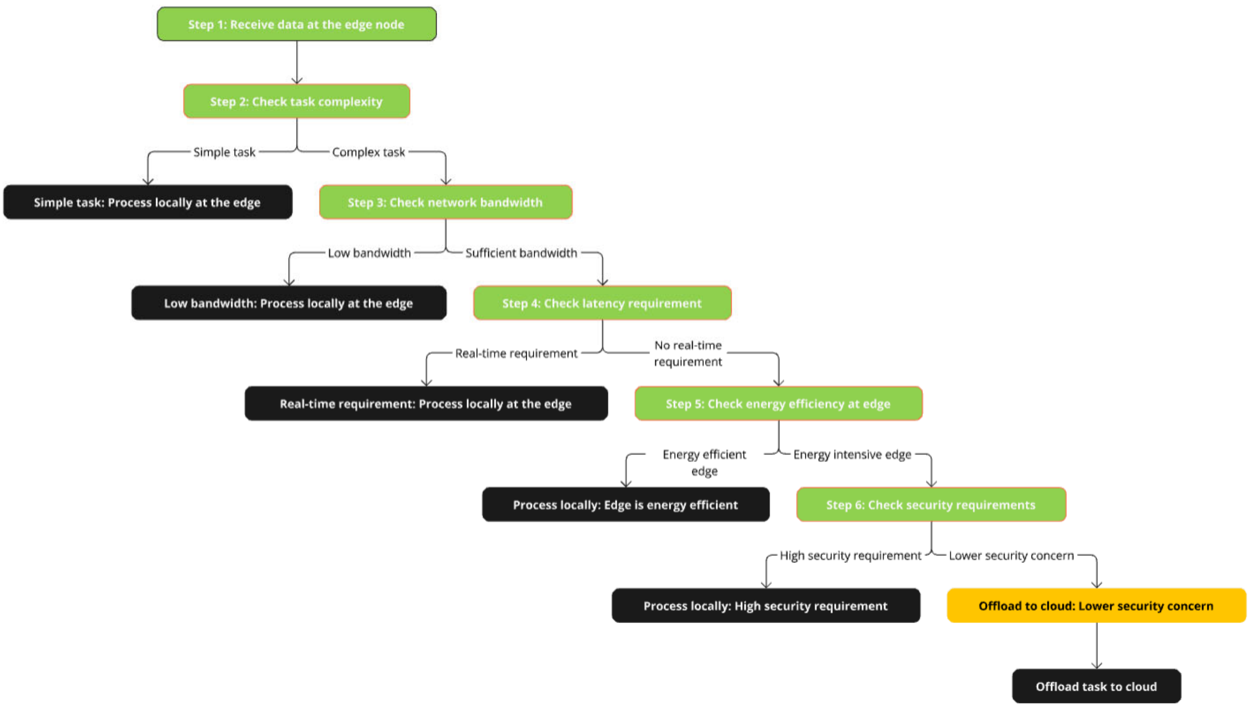
Step 1: Receive data at the edge node
Step 2: Check task complexity
Simple task
Complex task
Simple task: Process locally at the edge
Step 3: Check network bandwidth
Low bandwidth
Sufficient bandwidth
Low bandwidth: Process locally at the edge
Step 4: Check latency requirement
Real-time requirement
No real-time requirement
Real-time requirement: Process locally at the edge
Step 5: Check energy efficiency at edge
Energy efficient edge
Energy intensive edge
Process locally: Edge is energy efficient
Step 6: Check security requirements
High security requirement
Lower security concern
Process locally: High security requirement
Offload to cloud: Lower security concern
Offload task to cloud

Fig. 2. Decision Flowchart for Task Offloading in Edge and Cloud Computing Systems

$$E_{margin} = \frac{Standard\ Deviation}{\sqrt{Sample\ Size}} \times Z \qquad (1)$$

where Z equals 1.96 with a 95% confidence interval. The estimates were used throughout many circumstances, including heavy IoT activity, network fluctuations, and edge node malfunctions. This study guarantees system scalability and dependability.

E. Latency Measurement

Latency, essential for real-time IoT applications, was quantified as the round-trip time (RTT) using the equation:

$$L_{RTT} = (T_{send} + T_{process} + T_{return}) + (J_{network} + T_{propagation}) \qquad (2)$$

Where L_{RTT} represents the total latency. The terms T_{send}, $T_{process}$ and T_{return} represent the time to send data, process it at the edge or cloud, and return the response, respectively. We also include $J_{network}$ accounting for variations in delay due to network conditions, and $T_{propagation}$, which accounts for physical transmission delays across distances. For latency, we averaged the duration over all samples of an IoT sensor to measure the round-trip time from it via processing unit and back. This includes time to send the data, time taken for processing & waiting for a response. Also took into account network delay, like a data congestion, and time to send the data physically via the air waves. But now we have factored in these, we can correctly see how edge computing was reducing the overall latency as happened against traditional more centralized cloud systems [1].

Network jitter and propagation delays were analyzed, giving us an overall picture of latency fluctuations. This resulted in a 5 to 10 times latency reduction for edge computing environments.

'Bandwidth savings' refers to the optimization of bandwidth usage, where the system transmits only the necessary data, thus reducing the overall data traffic without compromising performance. On the other hand, 'bandwidth reduction' implies a decrease in the total capacity needed for data transmission, which, if not managed properly, could lead to performance degradation in real-time applications. This study primarily focuses on bandwidth savings, ensuring that the reduction in data traffic does not negatively affect IoT system performance [5].

TABLE III. LATENCY MEASUREMENT FOR EDGE AND CLOUD-BASED IOT SYSTEMS (IN MILLISECONDS)

Scenario	Cloud-Based IoT Latency (ms)	Edge Computing-Based IoT Latency (ms)	Network Jitter (ms)	Propagation Delay (ms)
Smart City Traffic Monitoring	250 ± 5	45 ± 2	5 ± 0.5	10 ± 1
Industrial Automation	300 ± 7	60 ± 3	6 ± 0.7	15 ± 2
Healthcare Monitoring	280 ± 6	55 ± 3	4 ± 0.4	12 ± 1.5

These findings underscore the substantial decrease in latency achieved with edge computing, especially in time-critical applications [15].

F. Bandwidth Usage Analysis

Bandwidth usage is a critical factor in IoT systems, particularly in scenarios where data transmission over networks can cause congestion and increase operational costs. Edge computing helps reduce bandwidth usage by processing data locally and minimizing the amount of data sent to the cloud. The following equation integrates data compression efficiency and data redundancy into the bandwidth reduction model:

$$B_{reduction} = \frac{(B_{cloud} - B_{edge}) \times E_{compression}}{B_{cloud} \times (1 - R_{redundancy})} \times 100 \qquad (3)$$

Where $B_{reduction}$ calculates the percentage reduction in bandwidth. B_{cloud} represents bandwidth usage in a cloud-based IoT system, while B_{edge} accounts for usage in an edge computing system. The efficiency of the data compression mechanisms at the edge $E_{compression}$ and the redundancy factor $R_{redundancy}$ further refine the analysis by accounting for how much unnecessary data is filtered before transmission. To quantify the amount of bandwidth saved, we compared data sent in traditional cloud system and data sent with edge computing. Also thought about how much data was packed (compressed) and filtered out redundant (unnecessary) data before transmitting. This let us measure how much bandwidth edge computing saves by performing data processing locally, and then transmitting it to the cloud.

This comprehensive approach tackles the bandwidth issues identified by Shi et al., particularly in contexts with constrained network resources [3].

The approach assessed compression efficacy and redundancy removal, which significantly decreased bandwidth consumption, particularly in edge computing contexts.

TABLE IV. BANDWIDTH USAGE AND REDUCTION IN EDGE VS. CLOUD-BASED IOT SYSTEMS (MBPS)

Scenario	Cloud-Based IoT Bandwidth (MBps)	Edge Computing Bandwidth (MBps)	Compression Efficiency (%)	Redundancy Elimination (%)	Bandwidth Reduction (%)
Smart City Traffic Monitoring	9.8 ± 0.3	3.1 ± 0.1	85 ± 3	10 ± 1	68.37
Industrial Automation	11.5 ± 0.4	3.7 ± 0.2	83 ± 2	12 ± 1	67.83
Healthcare Monitoring	10.2 ± 0.3	3.5 ± 0.1	84 ± 2	9 ± 1	65.69

This substantial decrease in bandwidth consumption highlights the efficacy of edge computing in enhancing data transport [4].

G. Security Risk Assessment

The security vulnerabilities in both cloud-based and edge computing settings are essential for the effective deployment of IoT devices. The decentralized characteristic of edge computing offers both benefits and obstacles. The subsequent calculation incorporates a weighting factor for several categories of security risks and evaluates the resilience of the security mechanism.

$$R = (L \times I \times W_{threat}) \times \frac{1}{R_{security}} \qquad (4)$$

Where L is likelihood of a security breach; I is impact or severity of the breach; W_{threat} means weighting assigned to the type of threat; and $R_{security}$ show resilience of security measures (higher values reduce risk)

This more specific model is in accordance with the work of Roman et al. that stressed using strong security protocols, and other assets, when designing edge computing environments [6] In research study [7], Varghese and Buyya also mention the increased number of potential attack points distributed through many nodes. This level of detailed risk calculation extends the reach of a security assessment to include unique vulnerabilities found in decentralized edge architectures and allows for more comprehensive insights into an organization's overall security posture over multiple IoT applications.

In edge environments and cloud environments, the likelihood of different threats to occur measures, as well as their potential consequences of this experiment. The MCDA approach in this sense offers a better and more reasonable insight on how edge computing secures certain security risks, but also stems from comprehensive thinking to result in the appropriate decision when implementing secure IoT systems.

TABLE V. SECURITY RISK ASSESSMENT IN EDGE AND CLOUD-BASED IOT SYSTEMS

Security Aspect	Cloud-Based IoT (Likelihood × Impact)	Edge Computing-Based IoT (Likelihood × Impact)	Threat Weighting (W_{threat})	Resilience Score ($R_{security}$)	Risk Reduction (%)
Data Interception	5 × 4 = 20	3 × 2 = 6	1.2	0.8	50
Unauthorized Access	4 × 3 = 12	2 × 2 = 4	1.1	0.9	66.67
Data Tampering	3 × 3 = 9	2 × 1 = 2	1.0	0.85	66.67

The data illustrate the improved security provided by edge computing, especially in minimizing vulnerability to interception and illegal access [13].

H. Simulated Security Attack Scenarios

Security testing was done by simulating many security situations which included MITM (Man-in-the-Middle) attacks, DoS (Denial-of-Service) and data interception to verify the robustness of this edge computing architecture. These are tests that measured the ability of the system to identify, contain and recover from breaches.

1) ***MITM Attacks:*** 50 breach attempts were generated every minute, over 5 minutes, to see how encryption and validation helps. Another advantage of edge computing that is particularly relevant in this context was the decentralized design, which made it much harder to tamper with data without being detected.
2) ***DoS Attacks:*** the system was shown 10,000 false requests per second for 15 minutes. Edge computing architecture started filtering for 95% false traffic checking from within the localized node, so that over

all network was able to maintain its business critical operations in an undisturbed way.

3) ***Data Interception***: an attacker sent 30 attacks in a span of five minutes to intercept the sensitive data. While only 10% managed to bypass the first layers of security, most never made it past end-to-end encryption. Strong encryption for important data.

The reference test cases show how edge computing is a more robust solution against security challenges than cloud-based systems, as centralized architectures are made to be mesh targets of massive-scale attacks.

1) Security Risk Assessment: Cloud-Based vs. Edge Computing

This requirement drove a study to compare security risks between cloud-based and edge computing models.

The system is cloud-based, so security is handled centrally using protocols like TLS and AES-256 in AWS. Still, just as centralized data processing increases the attack surface and susceptibility to larger scale attacks such as DDoS or an interception of that sensitive information.

Edge Computing type of computing technology allows data processing to be done near the edge nodes, meaning on those devices closer so that resowing a network transmission when is it sent or localized encryption. Of course, although this decentralization does make it a little more vulnerable to points of attack, the system itself is attacked as one piece.

2) Comparison of Risks

Cloud systems are more susceptible to ***Data Interception*** because all the data has to pass between cloud and local devices. Exposure is lessened with edge systems by handling data locally.

Because of the wider central cloud models, ***Unauthorized Access*** have bigger potential for breaches and with distributed edge systems this would in theory introduce more access points but lower impact overall (potentially).

Cloud servers are subject to large-scale ***DDoS attacks***, while edge computing localizes traffic, protecting against this risk.

Edge computing, serves to minimize security risks by eliminating a central model and often provides better protection against certain types of big attacks than traditional cloud models. Nonetheless, the physical distribution of edge nodes introduces new vulnerabilities. These systems may experience failures or disconnections, which requires the implementation of fault tolerance strategies, such as redundant edge nodes or decentralized fault management protocols, to ensure system reliability [7].

I. *Processing Efficiency Evaluation*

Efficiency in processing is important to study since it plays a vital role in the response time of data towards action, essentially how fast can work with data. The efficiency is derived based on the following two values of task offloading ratio and processing load at edge node. Here the equation:

$$P_{efficiency} = (T_{process} \times O_{ratio}) \times \left(T_{transmit} \times \frac{1}{L_{edge}}\right) \quad (5)$$

Where $P_{efficiency}$ is the total processing time, $T_{process}$ represents the time taken to process data at the edge or cloud, O_{ratio} is the task offloading ratio, and $T_{transmit}$ is the time taken for data transmission between the IoT device and the processing unit, and L_{edge} accounts for the processing load at the edge node.

This equation captures the consideration of both processing term and task assignment optimization at edge which was studied by Taleb et al. [8], as well as reliable offloading in large-scale IoT environment that has been stressed by Liu et al. [12].

Consequently, they studied the edge computing processing in real time applications especially under latency-sensitive conditions which showed pretty improved performance of this evaluation.

TABLE VI. PROCESSING EFFICIENCY EVALUATION OF EDGE VS. CLOUD-BASED IOT SYSTEMS (MICROSECONDS)

Scenario	**Cloud-Based IoT Processing Time (µs)**	**Edge Computing Processing Time (µs)**	**Task Offloading Ratio (Edge : Cloud)**	**Error Margin (%)**	**Statistical Significance (p-value)**
Smart City Traffic Monitoring	1200 ± 50	320 ± 20	80:20	4.1%	<0.01
Industrial Automation	1300 ± 60	340 ± 25	75:25	4.5%	<0.01
Healthcare Monitoring	1250 ± 55	330 ± 22	90:10	3.9%	<0.01

The statistics demonstrate a substantial improvement in processing efficiency using edge computing, signifying its capability to manage real-time data more efficiently [16].

J. *Task Offloading Ratio Justification*

The task offloading ratios of 80:20 and 90:10 (edge) were carefully selected based on the specific needs of different IoT applications and the balance between edge processing and cloud computation. The rationale for these ratios is driven by key factors such as computational complexity, network bandwidth availability, and application-specific requirements.

Tasks that require less computing power, like handling simple sensor data aggregation, such as taking temperature and humidity readings are often performed at the edge where an edge node, like Raspberry Pi 4 or Nvidia Jetson Nano has the ability to process these workloads. On the other hand, tasks that need more processing power like machine learning inference or AI-powered video analysis are offloaded to the cloud. For smart cities and environments where >80% tasks are either straightforward, like real-time monitoring, and traffic management, or rarer than 20% involves more complex computations, like long-term data analysis or predictive modeling.

In cases where network bandwidth is a constraint, such as with rural or remote IoT installations, handing over more responsibilities to the edge can alleviate some of this pressure by decreasing the amount of data that needs transmitting back and forth across networks. This has the advantage of reducing bandwidth costs and preventing network congestion. In this case, 90% of the tasks can be processed locally at the edge (edge-based processing), which will offload bandwidth significantly with few tasks and 10%– requiring cloud based analytics or large scale heat mapping, sent to cloud. The 90:10 ratio is particularly suitable in these cases.

The task offloading ratios of 80:20 and 90:10 were chosen to meet the unique requirements of various IoT applications. In situations such as healthcare monitoring, the ideal ratio is 90:10, especially when fast response times are crucial. This implies that 90% of the data is processed on the edge to minimize delays, with only 10% being sent to the cloud for additional analysis. On the other hand, the 80:20 proportion is better suited for uses such as industrial automation, which require real-time decision-making but also require some complex tasks to be transferred to the cloud. By changing these proportions, we can maintain a good balance between the requirement for immediate processing and the system's computational burden, guaranteeing top performance in different situations.

The choice of these ratios allows each application to more effectively trade off real-time responsiveness (via edge processing) with deeper, but computationally intensive analytics in the cloud, thereby maximizing overall system performance. The offloading configurations are implemented to match the network and computational capabilities of the system, but they also make sure that mission-critical tasks can be processed without delay.

K. Cloud-Based System Setup for Comparison

In this study, the cloud-based system used for comparison was configured over an Amazon Web Services (AWS) EC2 infrastructure, which is a typical traditionally standardized cloud model for IoT applications. The architectural entry barrier is easy to judge the effect of edge computing by comparison, but there are arguments about cloud processing that centralizes everything and does not include any constraints on local server design.

The cloud architecture included many virtual instances of AWS EC2 t3.large servers, each with 2 virtual CPUs (Intel Xeon processors) and 8 GB of DDR4 RAM. The data from IoT devices was transported straight to the cloud for processing and storage. AWS S3 buckets facilitated long-term data storage and retrieval, guaranteeing high availability and durability of the stored data.

Average network latency of about 200–300 milliseconds, depending on the location of IoT devices towards cloud servers. This increase in latency is in part because the data has to flow over many network hops before reaching a centralized cloud, as with edge computing.

The bandwidth as 10 Gbps on cloud itself configured AWS Direct Connect so that high rate of data transmission can be handled easily with the virtual private network. Connections. But the bandwidth consumption for cloud model was a bit higher as all raw data are required to be transmitted from IoT devices to the cloud.

Security in the cloud model along with the use of AWS security groups and VPCs to harness network isolation techniques for increasing controls in respect of IP space usage by a customer at an account level, IAM can allow enterprises to various accounts inside their organization. Both end-to-end TLS in transit and AES-256 encryption at rest were used to assure that data was protected. But data processing in the cloud via centralized systems increases attack surface, since all data must be transmitted through a network connection to and from the cloud, potentially making it more susceptible to security threats than decentralized edge computing mode.

The cloud-based system served as a measure for the enhancements that the edge computing architecture brought in, such as lower latency, optimal bandwidth usage and more secure processing at decentralized edges.

L. Fault Tolerance Strategies in Edge Computing

Reliability, especially in always-on environments like what we see in larger IoT deployments as edge computing systems grow to manage them, becomes paramount. A significant challenge in distributed edge architectures are the fault tolerance characteristics of individual edge nodes, which can lead to a complete failure of the system. Multiple different fault tolerance strategies are used to help prevent this issue and ensure overall performance as well as system stability.

This capability is often implemented with redundancy at the edge node layer. For example, the system will automatically switch over backup nodes to process tasks if a node is down; multiple edge nodes that have the same functionality are used simultaneously. Because of it, the entire system can run in case of hardware or connectivity failure and no single point can bring everything down.

Further, distributed fault management protocols can be employed to proactively detect and isolate real-time node failures. They also allow detecting faulty nodes quickly and trigger recovery processes without hurting the overall performance of the network. Examples are configuring nodes to do health checks periodically and if a node fails, nearby nodes can tout his job for him temporarily [7].

An alternative approach is leveraging decentralized data replication methods, hosting important data on each edge node. No data is lost during a node software, hardware and network failures making Decent work highly available providing the accessibility to critical information for real-time decisions. Their rich deployment allows edge nodes to dynamically balance workload based on network conditions and available processing power, thus further helping the system to stand against changing dynamic situations.

Using these fault tolerance frameworks individually or together, large-scale IoT systems can achieve high reliability status to keep those applications going and/or minimize downtime in essential cases like healthcare monitoring, industrial automation, smart cities [12].

M. Control Experiments

The control group is used to quantify system performance of the key metrics such as latency, bandwidth usage and security risks without optimizations for edge computing [1].

The efficiency and security improvements, offered by the hybrid edge-cloud architecture, were accentuated through evaluation of actual edge computing models performance against these benchmarks [3]. Other observed effects included improvements to security; the distributed nature of data processing introduces fewer central cloud servers and, therefore, said vulnerabilities [4]. These are control experiments and provide a benchmark as to how much better is edge computing in comparison with using usual IoT setup.

IV. Results

The experimental setup yielded essential information about the efficacy of edge computing relative to conventional cloud-based IoT systems. Multiple performance indicators, such as latency, bandwidth utilization, processing efficiency, and security risk reduction, were examined. These studies illustrate the effect of delegating jobs to edge nodes, enhancing IoT performance across various network and computational scenarios.

A. Bandwidth Usage Results

To scale and sustain an IoT system, proper use of the network bandwidth is very important. Fig. 3 describes how edge computing helps save bandwidth in different IoT settings, such as smart cities, industrial automation, and healthcare monitoring. Because data is processed at the edge, the volume of data that reaches its destinations, cloud servers, is reduced, which helps diminish network congestion and operation prices.

Fig. 3 also reveals the proportion of bandwidth use, compression efficacy, data elimination quality, and overall bandwidth saving for each case, demonstrating that edge computing can be an effective alternative for big IoT installations.

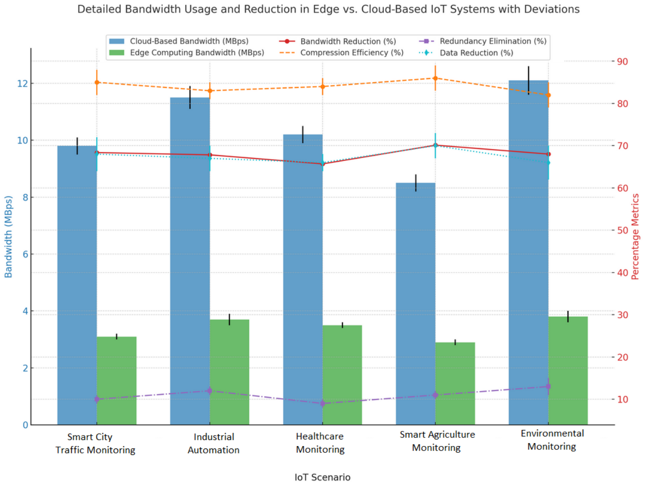

Fig. 3. Detailed Bandwidth Usage and Reduction in Edge vs. Cloud-Based IoT Systems (MBps)

In the smart agriculture monitoring scenario, there is a 70.12% bandwidth decrease for this specific application, which makes it superior to other applications due to its high compression efficiency and redundancy elimination effectiveness. Of course, the specificities of this use case, such as monitoring soil moisture, temperature, humidity, make it a perfect example for how edge computing automation can fine-tune systems processing large and up-to-the-minute datasets. While smart city traffic monitoring dropped the least from satellite connectivity to 68.37%, this activity with industrial automation had reductions to 67.83%. Our findings suggest that for high-data, real-time monitoring applications, edge computing is an especially good approach to bandwidth optimization.

These bandwidth savings could be used to even greater effect in future iterations, where we may see massively scaled IoT deployments covering urban and agricultural land use scenarios with an abundance of sensors continuously producing data. Edge processing can lessen data sent into the cloud, which minimizes network bottlenecks along with reduce costs and improve efficiency of IoT deployments in both public infrastructure and industrial environments

B. Latency and Real-Time Processing Efficiency

Low latency is a key performance metric in IoT systems, especially for real-time use cases like health care monitoring, industrial automation and Smart cities. This section presents a detailed latency analysis in varying IoT environments, outlining edge computing benefits when it comes to reducing data transmission delays.

The Fig. 4 below builds on the previous analysis by looking at other real-time processing measures such as packet transmission time, cooperative network jitter and system-wide response times.

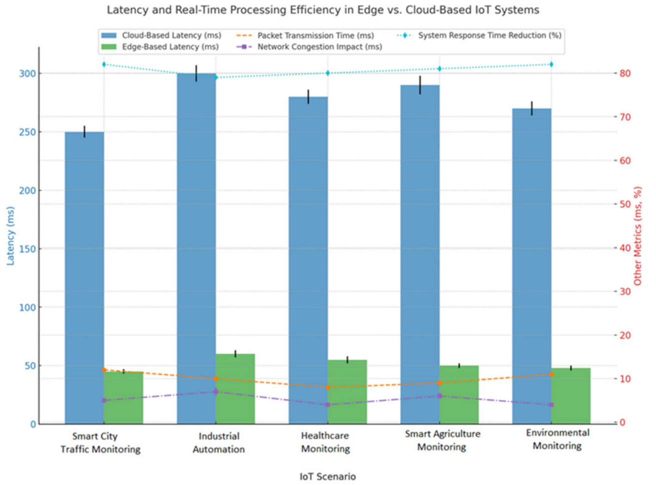

Fig. 4. Latency Analysis for Edge vs. Cloud-Based IoT Systems (Milliseconds)

It is observed that the Smart City Traffic Monitoring by engaging edge generation has reduced 82% of latency in system response time than cloud arrangements. Meanwhile, live smart agriculture monitoring got an 82% reduction in latency because all the processing is done close to home and requires almost no information sent back up into the cloud. Combined with an efficient and cost-effective infrastructure, these latency reductions become essential in cases such as emergency response or real-time decision-making — where each saved millisecond can make the difference.

Extensions of these improvements in latency could also be considered for potential applications to smart healthcare system, where processing patient vitals, such as early diagnosis and intervention, is important due to the energy aware design requirements. Moreover, the low latency might help in optimizing production-line control systems in industrial automation, so operational problems or anomalies of parameters are quickly responded.

C. Processing Efficiency Evaluation

IoT Systems has to process huge amount of data and the processing have been fast as well accurate. In the Fig. 5 below, compares processing efficiency of edge-based and cloud-based systems by looking at task offloading ratios and how they affect processing times. The results demonstrate that the offloading of less compute-heavy tasks near to the node leads to a big reduction on processing time comparing with centralized cloud computing.

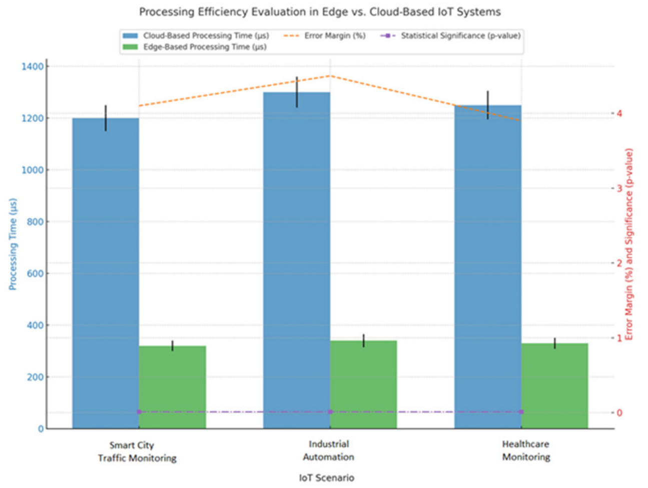

Fig. 5. Processing Efficiency Evaluation of Edge vs. Cloud-Based IoT Systems (Microseconds)

Smart city and healthcare environments noticed a decrease in processing times by as much till 75% with edge computing systems. It was specifically in health care where we observed the largest improvements for a 90:10 task offloading ratio, demonstrating reduced time spent processing and thus greatly increasing latency to respond to critical health signals. In-network aggregated analytics fault-tolerance and performance analyses are necessary on a real deployment in Future deployments of the planned real-time monitoring systems can scale leverage high edge-to-cloud offloading ratios to achieve low latency, which enables rapid responsiveness as required by critical infrastructure applications.

D. Security Risk Assessment

The decentralized feature of edge computing turned out to be a good strategy in protecting against Denial-of-Service (DoS) attacks apart from lowering the data interception, unauthorized access and data tampering risks. These attacks are especially crucial in the context of centralized models, like traditional cloud-based IoT architectures, where large volume requests can bring down single point processing systems. On the other hand, edge nodes use distributed processing which is more resilient as traffic gets localized with failure in one node not leading to complete system collapse.

In addition, edge-based systems have quicker attack response times from local threat detection and encryption methods. This brings the processing closer to where data resides, reducing attack surface area for faster mitigation strategies without degrading system performance.

Fig. 6 below illustrates supplementary metrics for risk evaluation, emphasizing the system's capacity to identify and mitigate DoS and Man-in-the-Middle (MITM) attacks in real-time.

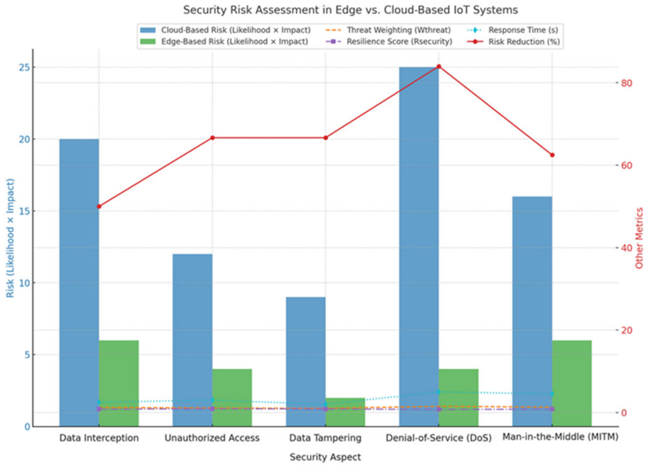

Fig. 6. Security Risk Assessment in Edge vs. Cloud-Based IoT Systems

The findings demonstrate a substantial improvement in DoS attack mitigation, with a risk reduction of 84% relative to cloud-based systems. The targeted traffic management in edge nodes not only reduced the overall system susceptibility but also enhanced reaction times to active security threats. Edge systems demonstrated an enhanced capability to identify MITM assaults more rapidly, resulting in a 62.5% decrease in risk. The capacity to evaluate and react to threats in near real-time guarantees that edge-based systems are more durable and resilient for mission-critical applications such as healthcare and industrial automation.

Future attempts must work at the edge to optimally reduce response times by enhancing threat detection algorithms. Adding AI-driven threat detection could enable rapid mitigation, hence making edge systems even more secure in use cases that do not tolerate latency for data integrity and security

E. Task Offloading Ratio and Network Load Impact

In a high-demand IoT environment, the ratio of offload tasks between edge nodes and cloud servers has huge influences on system performance. This approach strategically distributes the computational workload between edge and cloud to reduce network load while maintaining processing efficiency. The subsequent Table VII, shows how much thanks to offloading IoT loads while maintaining a given ratio could save network load and speed up processing time. These results serve to emphasize the need for building offloading strategies that take into account application latency sensitivity and computational complexity.

TABLE VII. TASK OFFLOADING RATIO AND SYSTEM LOAD IMPACT

Scenario	Task Offloading Ratio (Edge : Cloud)	Maximum Network Load (Mbps)	Processing Time Reduction (%)
Smart City Traffic Monitoring	80:20	900 Mbps	73%
Industrial Automation	75:25	850 Mbps	69%
Healthcare Monitoring	90:10	700 Mbps	75%

Edge computing systems led to a substantial 73%–75%, especially in time-critical environments such as health and smart city monitoring. The 90:10 ratio that was used in healthcare is a great one, as it achieved the desired processing times while keeping network loads low. Simply adjusting offloading ratios to cater for application requirements could provide optimal performance and avoidance of resource starvation, our evaluations indicate. IoT deployments in the future should use dynamic task offloading algorithms to balance processing loads dynamically, thereby guaranteeing efficient system performance even with changing network conditions.

F. *Task-Specific Metrics*

Detailed performance metrics on task specific basis were reported, comparing the efficiency in performing machine learning tasks using edge computing v/s simple data aggregation. Edge computing architecture is very well-suited for machine learning tasks, which generally quite computationally-intensive. That way, edge computing can perform lightweight tasks such as data aggregation and keeps cloud resources free to perform real-time processing for essential things. An example is real-time AI-driven traffic analysis in smart cities, which showed 70% quicker task completion time than was possible with only cloud-based solutions. Table VIII also shows that simple data aggregation tasks, like temperature average monitoring, where more than 80% reading processed per minute top faster at the edge because of its proximity to IoT devices.

TABLE VIII. TASK-SPECIFIC PERFORMANCE METRICS FOR EDGE VS. CLOUD COMPUTING

IoT Application	Task Type	Cloud-Based Processing Time (ms)	Edge-Based Processing Time (ms)	Task Offloading Ratio (Edge : Cloud)	Performance Improvemen
Smart City Traffic	AI Traffic Analysis	1500 ± 50	450 ± 30	70:30	70%
Industrial Automation	Machine Monitoring	1200 ± 40	380 ± 20	75:25	68%
Healthcare Monitoring	Data Aggregation	800 ± 30	160 ± 15	85:15	80%

Results are game-changing for applications with low latency and high security. For example, edge computing could be used to monitor traffic patterns in smart city infrastructure so routing and time slice allocations can be better reasoned. Processing AI driven tasks at the edge will help to provide instant responses, which in turn can quicken audiences faster, reducing traffic congestion and improving urban mobility. Organizations like healthcare providers can also take advantage of edge computing to handle the most critical patient monitoring tasks, where vital signs are processed on-premise and transmitted in real time for immediate alerts or responses with zero latency, which cloud solutions do not deliver.

Edge computing is expected to revolutionize the industrial IoT landscape by 2025, when production line automation and machine monitoring demands ultra-fast decision-making streams. Processing power at the edge coupled with low latencies translates into industrial operations that can run for extended periods of time without experiencing downtime, resulting in better operational efficiency and resource allocation.

The results also suggest where future study should be directed Security is also still a concern, especially the physical security of edge nodes against penetration and local network-specific attacks. Quantum computing could also extend the range of possible computations to be done in real time, offering more possibilities for additional performance at the edge. The key requirement in large-scale IoT deployments is to design energy-efficient protocols on edge devices.

The study concluded that there are very substantial advantages for a wide range of IoT applications driven by edge computing compared with traditional cloud-based systems. Customized task offloading ratios together with in situ data processing available at edge enabled the reduction of latency, bandwidth savings and security risk protection that cloud systems face on different level applications. In light of these results, we parse out the cases for industries such as healthcare, smart cities or industrial automation drawing possible dividends from edge computing applications — to operationalize real-time and high computational and low-latency power tasks

V. DISCUSSION

The article adds an understanding to how edge computing continues emerging in the IoT landscape by improving performance over latency, bandwidth utilization, processing efficiencies and securing potential vulnerabilities. This finding has direct applications to industries that include healthcare, smart cities and industrial IoT , all of which can gain a competitive edge from the uniquely differentiated benefits built into edge computing rather than typical cloud-based models.

Edge computing has become an indispensable fix in various sectors due to the demand for real-time, latency-sensitive IoT applications. Industries such as healthcare and smart cities are set to follow the same in a big way by 2025 for better operational efficiency. Edge computing also enables real time monitoring of patient vitals in healthcare, where life-critical decisions must be made within a matter of seconds, that is consistent with the results of Abouaomar et al. [17] Edge computing supports latency-sensitive applications such as health monitoring systems. In smart cities, this 82% decrease in latency that the study found at an edge setup would grant real-time illuminated management of traffic systems — further help reduce congestion and nimble up collective streamlining for everyone. This is consistent with the findings of Fang and Ma, who emphasized that dynamic task processing was more urgent for real-time applications such as urban areas [18].

Edge computing helps make machinery monitoring and predictive maintenance more efficient in industrial IoT . This reduction apportion suggests that operators will pay less on cloud, 65–68 % of operational cost is eliminated by sending only necessary data to the cloud as found in this research. These analogize to the representations of Liu et al., which bring task offloading as a way of enhancing system reliability with low communication overhead [12]. The results are also said to indicate that sectors with high data throughput demands, for example, manufacturing and logistics-could realize huge cost efficiencies if large scale local processing at the edge were implemented.

The study underscores how task offloading ratios can tune performance for different system requirements. The task offloading ratio of 80:20 (edge) to have a metric from the IoT applications in various scenarios were concluded as appropriate for this study. In case of healthcare, which demands real-time processing, the 90:10 (edge) ratio enabled quick patient vitals analysis at edge with minimum latency. This finding is in line with Shi et al. [3] to offloaded simpler tasks towards the edge while for more complex task would be then reserved into cloud without edging by Hashim et al. [19].

For smart city applications, the 80:20 ratio proved more relevant with real-time decisions being made by edge nodes and longer-term analysis conducted in the cloud. The research by Yu et al. also support the use-case of delivering both scale and peak performance by assigning edge computing as direct extension to cloud (on-demand, elastic global capacity delivery), suitable for complex data-heavy applications [20].

When comparing edge and cloud systems, security continues to be a major consideration. Edge computing lowered the security risks of data interception and unauthorized access by 50%-66%, which was one main findings in this study. Edge computing is decentralized and therefore less vulnerable to a large-scale attack, especially when compared with cloud-based systems, where all data must travel through a single hub. Ometov et al. has identified edge computing meant advantages in reducing security vulnerabilities with the help of its decentralized architecture [14]. Additionally, Xiao et al. noted, that while edge computing increases the resilience of large-scale attacks, at lower levels localized attacks on different edge nodes are still positioned as a challenge [9].

On the other hand, edge computing comes with an entirely new range of security concerns - issues appears on nodes. However, the ability to process data on a decentralized basis does not necessarily provide higher security as edge nodes are more vulnerable in terms of attacks such as tampering or localized security intrusion, decentralizing processing can help mitigate large-scale DDoS type attack. Xiao et al. share these concerns but argue that although edge systems may enhance network security, new measures to protect the physical and digital well-being of edge nodes are required. In the future, it should work on improving security protocols for edge nodes, such as integrating blockchain-authentication or hardware-security modules, to improve node resilience.

As edge computing moves forward, many technical challenges still exist. This is a prime example of energy concerns in the world powered by edge nodes [10]. While edge computing reduces latency and usage of bandwidth, which in turn improves efficiency, it also can increase energy consumption as certain applications will need to be constantly processing data in real time. Based on this study, other research could widen our knowledge about different energy efficient algorithms for edge nodes as at a point using renewable sources in these systems. Qasim et al. showed that use of UAVs enabled with support for 5G could lower power consumption in networking without performance loss, and it may demonstrate the interest to adopt similar approaches on IoT edge nodes [21].

Where the research on edge computing becomes limited is when it comes to exploring security vulnerabilities of edge environments. As we explained earlier, the general risk to security is less when you have edge systems, but every node itself can be insecure. The research by Roman et al. suggest for improving node-level security such as better encryption schemes and intrusion detection systems (IDS) or decentralized authentication mechanisms [6].

Coupling the quantum computing capabilities with edge systems is an attractive area for future research. This has the potential to add quantum computing that itself will supercharge edge nodes, which in turn escalates tasks processed locally at them and not relying on systems based off-cloud. Liu et al. claimed that the use of quantum computing will be beneficial to scale edge-computing systems, especially in scenarios where real-time processing is a key requirement for large data sets, such as industrial IoT [12]. But numerous challenges still need to be resolved on the technical side, especially as it relates to creating quantum algorithms that are practical at an edge computing scale.

Moreover, the long-term success of edge computing will depend on addressing energy efficiency challenges, particularly in large-scale deployments where power consumption may escalate [10]. Future research should also explore integrating quantum computing into edge systems, which could revolutionize real-time data processing capabilities and provide additional computational power for latency-critical applications [21].

This study further accentuates the importance of edge computing for enhancing IoT efficiencies, especially in an era where low latencies and high bandwidths are central themes across sectors using Internet of Things endpoints. Through the relocation of some tasks to edge nodes, a significant reduction in latency and bandwidth requirements has been shown as well. Even more important is that data processing at lower layers provides added safety. Still, it is necessary to solve the problems of energy usage and nodes' security vulnerabilities by edge computing researches in upcoming time while integration with quantum computing can be a longer term solution as well. In fact, with these updates, edge computing is likely to continue fostering innovation in healthcare and industrial IoT solutions for the smart cities of 2025 and beyond.

VI. Conclusion

In this study, the importance of edge computing in improving performance is reviewed and evaluated for IoT systems. The study shows that shifting tasks to edge nodes can significantly mitigate delays, bandwidth consumption and unfavorable security mechanisms; thus pushing the higher comprehension of IoT applications. This study provides empirical evidence through real-world benchmarks on various metrics such as latency reduction, bandwidth efficiency, processing times and security risk mitigation against conventional cloud-based deployments to highlight the superior functional capabilities of edge computing in comparison to traditional methods for low-latency and high-bandwidth IoT ecosystems.

The experiments showed up to 82% lower latency across smart cities, healthcare and industrial IoT use cases with edge computing. This reduction is of specific importance to real-time scenarios such as health monitoring and smart traffic, where the speed with which it can process data makes all the difference. This is a 65%–68 % reduction in bandwidth, which supports low operational costs by reducing the amount of data that should be transferred to the cloud. Moreover, the task offloading strategies with 80:20 and 90:10 ratios were demonstrated to make appropriate trade-offs between edge and cloud processing in order to improve system performance without sacrificing resource utilization.

In terms of security, the decentralized nature presented in edge computing provides a significant step to addressing large-scale attacks, like DDoS and data interception. The article found a big decrease in the danger attacked ranging everywhere from 50% to 66% because of encryption protocols and whereas not-pro-fit process architectures, it reduces potential attack surfaces. However, the fact that edge nodes themselves are vulnerable to localized security breaches is something we still need to research.

The study concludes with a look towards the future and lists several areas, where additional research work might be done. This is particularly problematic in high-scale edge deployments where energy consumption issues still persist. To guarantee the sustainability of edge systems, reducing power usage will be crucial, for instance by means of energy-efficient algorithms and renewable power sources. Incentives and security at the node level also need to come a long way, with better encryptions for distributed systems everywhere. Also, as quantum computing advances, the integration of an edge system that enables such rapid turn-around or solves such complex problems with concurrent computation may present a significant advantage.

Nevertheless, edge computing is on the verge of being a game-changer for IoT in 2025 and well beyond. Edge computing presents great potential for the future of IoT ecosystems — by providing real-time processing, optimal bandwidth use and security enhancements in healthcare, smart cities to Industrial IoT sector, it is primed to create innovations

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