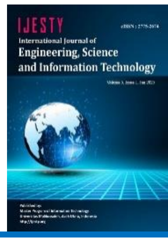
International Journal of Engineering, Science and Information Technology
Volume 5 No. 1 (2025) pp. 595-599
ISSN 2775-2674 (online)
Website: http://ijesty.org/index.php/ijesty
DOI: https://doi.org/10.52088/ijesty.v5i1.1490
Research Paper, Short Communication, Review, Technical Paper



Low-Latency Edge Computing for Real-Time Applications in Wireless Sensor Networks

Awakash Mishra[1*], Abhinav Rathour[2], Dheeravath Raju[3], Shashikant Patil[4], M.A. Muthiah[5], Bichitrananda Patra[6], Aravindan Munusamy Kalidhas[7]

[1]Maharishi School of Engineering & Technology, Maharishi University of Information Technology, Uttar Pradesh, India
[2]Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India
[3]Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India
[4]uGDX, ATLAS SkillTech University, Mumbai, India
[5]Department of Electronics and Communication Engineering, Sathyabama Institute of Science and Technology, Chennai, India
[6]Department of Computer Applications, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India
[7]Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka, India

**Corresponding author Email: awakash.mishra@muit.in*

The manuscript was received on 10 August 2024, revised on 15 October 2024, and accepted on 30 January 2025, date of publication 13 May 2025

Abstract

Real-time data processing with Edge Computing, such as Low Latency Edge Computing (LLEC), allows for functioning at the network boundary or edge, which enhances responsiveness and reduces latency in WSNs. This approach is helpful for most time-critical needs in innovative city applications, healthcare, industrial automation, and other areas where prompt actions are crucial. In contrast to conventional cloud models, LLEC processes data at the collection site to reduce the transmission time, improving bandwidth efficiency. Moreover, LLEC increases the height of scalable walls and energy efficiency by shifting the computational burden to the edge nodes. This document focuses on the most critical problems in WSNs, such as restricted resources, limited scalability, and security issues. We offer a distributed edge framework with real-time processing features and minimal security protocols to address these gaps. Localized computation at cluster heads diminishes network congestion while prolonging sensor life. This paper presents multiple case studies demonstrating LLEC's effectiveness in practical applications. Finally, the paper discusses the widening scope of research and the importance of LLEC in future distributed systems.

Keywords: *Low-Latency Edge Computing, Wireless Sensor Networks, Real-Time Applications, Edge Architecture, Scalability.*

1. Introduction

Innovative health services, industrial surveillance, and environmental monitoring are examples of emerging real-time applications. These applications require data to be processed with minimal delay, thereby increasing the demand in the context of WSNs (wireless sensor networks). Furthermore, traditional cloud-based computing models are time-sensitive because of high transmission delays, low bandwidth, and the constant need for connectivity [14]. To address these issues, LLEC (Low Latency Edge Computing) has emerged as a new paradigm that is robust enough to provide computation and data storage in sensitive locations where data is generated, significantly improving response times and system efficiency.

A WSN is a wireless network of spatially distributed sensor nodes that monitor and collect data about physical or environmental conditions. The collected data is then sent to a central node or server. Nonetheless, the effectiveness of these networks in supporting real-time applications suffers as they need fast and local data processing [15]. In this regard, LLEC facilitates the real-time need by allowing edge nodes or gateways to execute remote procedure calls, which lowers the need for centralized infrastructure and mitigates latency issues.

This document details LLEC's contribution to the advancement of real-time applications in WSNs. It explains the basics, revisits recent issues, and proposes some architectural and algorithmic approaches toward optimum low-latency performance. This research demonstrates the effectiveness of edge-based approaches through practical case studies and performance evaluations. Additionally, it recognizes open areas for further exploration and progress in this advancing domain.

Key Contribution

1. I suggested a distributed edge framework for real-time data streaming in wireless sensor networks, which would achieve lower latency and faster response time.
2. Developed an adaptive load-balancing algorithm to improve the utilization of computing resources and avoid node overload while ensuring real-time service delivery.

3. Incorporated lightweight security protocols at the edge to secure sensitive information while maintaining optimal performance levels, energy consumption, and efficiency.
4. The system's effectiveness was demonstrated through case studies and analytic evaluation, which demonstrated that traditional model benchmarks were surpassed in latency and energy usage.

This paper aims to present and assess a Low-Latency Edge Computing (LLEC) framework designed for Wireless Sensor Networks (WSNs), paying attention to real-time responsiveness for critical applications. Motivation and scope are presented in Section 1, stating the urgency of active data processing in specific fields. Edge computing and other associated data latency minimization techniques are discussed in Section 2. Section 3 describes a novel distributed architecture with local processing at the cluster head level and adaptive task allocation. In Section 4, the system's performance is evaluated from the efficiency perspective, comparing latency with node count. In Section 5, the main properties of the system are summarized along with its prospects, drawing attention to LLEC as a low-cost, easily expandable solution for practical WSN issues.

2. Literature Review

The newest developments in low-latency edge computing have notably improved the efficacy of real-time applications in Wireless Sensor Networks (WSNs). By positioning computational resources closer to the data source, edge computing helps to reduce transmission time and enhance the performance of time-sensitive applications. Edge-enabled framework for Wireless Networked Control Systems (WNCSs), where data is first processed at the edge for communication efficiency. Their adaptive transmission model showed 58.16% latency reduction in a 5G testbed, demonstrating the potential of low-latency edge frameworks [1].

Incorporating this, Haque et al. (2024) introduced SAWEC, a sensing-assisted wireless edge computing model that identifies environmental changes and selectively transmits data from video streams [2]. This approach improved mobile deep learning tasks by more than 90%, reduced channel usage and latency [13]. Another work by Li et al. (2023) [7]addressed the problem of high latency during access point handover in SDN-based edge computing environments [6]. Their low-latency AP handover protocol, integrated with a resource scheduling policy, improved handovers without negatively impacting performance [3].

Patel (2024) studied smart cities and examined the importance of edge computing in urban-scale IoT deployments [9]. He noted that service response times were significantly improved, and public services could be managed with much greater precision in real time when edge nodes were placed closer to the data sources [4]. Also, Rahim (2024) researched scalable architectural designs for IoT-integrated WSNs [5]. He pointed out that real-time data processing is best done with distributed edge computing models concerning latency, scalability, and throughput [10].

Collectively, these additional works showcase the transforming prospects of real-time edge computing as a crucial driver of WSN applications with remarkable responsiveness [8]. They illustrate both architectural changes and other system-wide enhancements that affect the development and deployment cycles.

3. Methods

The growing demand for immediate responses to actions within a WSN (Wireless Sensor Network) is targeted for mitigation by creating a Low Latency Edge Computing (LLEC) framework designed for distributed sensor environments. It intends to minimize latency by processing data at the network edge where it resides. This model avoids delays from sending all data to remote servers or cloud systems. In smart cities or industrial automation, and healthcare, these domains are time-sensitive, so the model aids faster response and reliable operations. The movement of the computation closer to the source of data improves responsiveness to the system, reduces required bandwidth, alleviates network traffic, and addresses deployment problems associated with large-scale WSNs.

The suggested system utilizes a combination of distributed edge computing architectures and WSNs, where sensor nodes interface with localized edge computing units, referred to as cluster heads. These cluster heads can process the captured sensor data streams to filter and make real-time decisions, without sending all the information to a central unit for processing. This distributed intelligence led to a lower energy expenditure because only critical or exceptional data needed to be sent further into the network. In WSNs, conserving power is usually the most vital factor. This reduction in data transmission conserves the operational life of the battery-powered nodes, enhancing the network's sustainability.

The framework LLEC has been optimized with an algorithm that adaptively distributes computing workloads to the edge nodes. The algorithm resizes the task distribution strategy based on the current operational load and the environmental context of each node to preserve overall system performance and avoid system burnout. This allows for the handling of bursts of demand in the network and heterogeneous types of sensors, as multiple streams can be captured and processed simultaneously. This increases the framework's modularity and scalability, which permits cross-sectional integration to diverse applications without system rearchitecting at the core. The algorithm assists fast detection and response and secures edge nodes for critical responses to significant changes in the sensed environment in near real-time.

To solve the issue of data security and reliability within the proposed setup's distributed structure, lightweight encryption and an authentication method have been added at the edge layer. These security measures are essential in applications dealing with confidential data, such as those involving health monitoring or industrial systems. Providing protection directly on the edge devices ensures that the data is protected from the point of origin to the final delivery. This security helps mitigate threats without decreasing system performance or adding additional processing burden on resource-constrained devices.

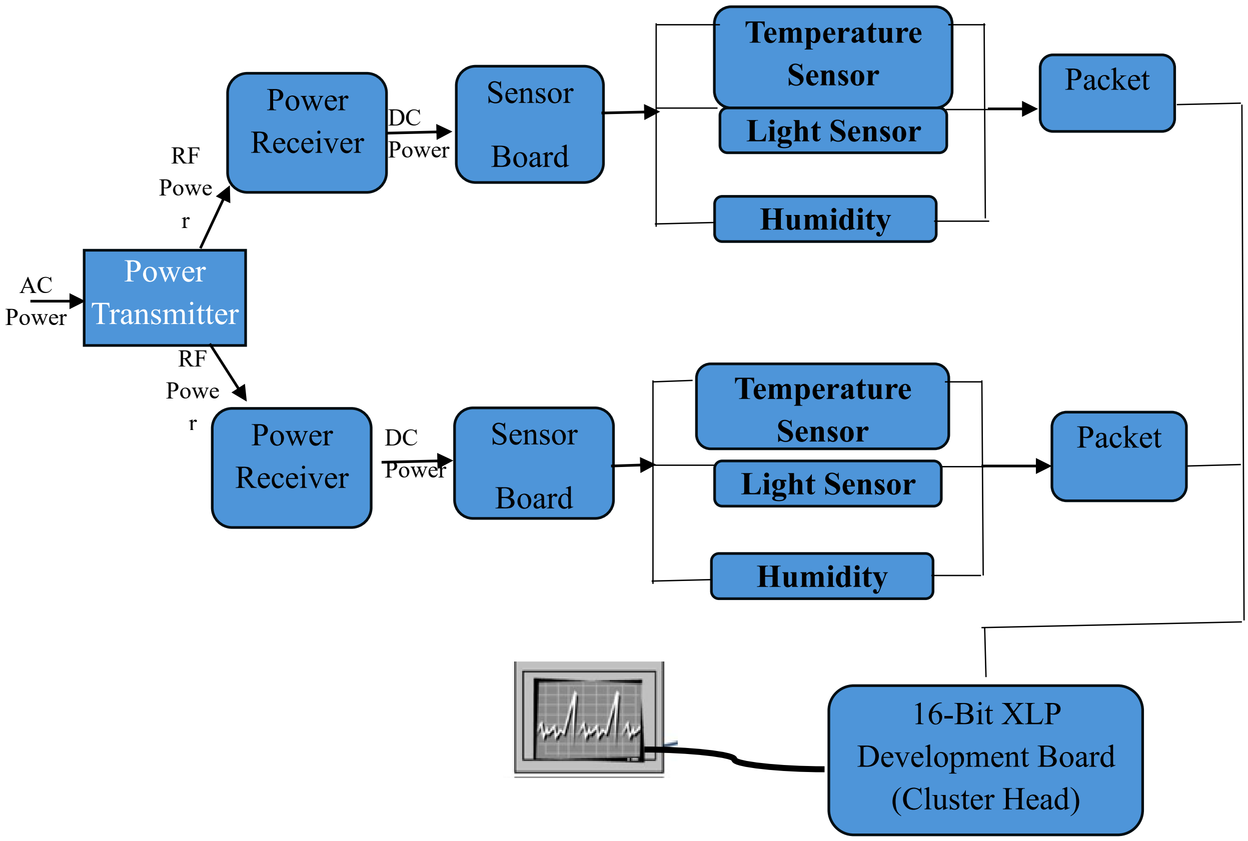


Fig 1. Wireless Sensor Network Architecture with Edge-Based Low-Latency Processing

Figure 1 shows the structure and data flow of the proposed low-latency edge computing (LLEC) system. The illustration begins with an AC power source that energizes a central power transmitter. This transmitter transforms AC power into RF power, which is wirelessly transmitted to several distributed power receivers across the network. Each power receiver SC converts the RF signal into usable DC power sufficient to light up a sensor board. The sensor boards contain temperature, light, and humidity sensors, providing real-time environmental data 24 hours a day, 7 days a week.

After collection, the data is sent to a 16-bit XLP development board, which operates as a cluster head or an edge computing node for further processing. Deep edge data processing, such as aggregation, filtering, and anomaly detection, is done at this level. The processed data decides which critical data to be sent to a central monitoring system or server, optimizing network bandwidth. The estimated architecture illustrates how seamlessly energy harvesting, sensing, edge processing, and communication integrate to achieve low-latency, scalable, and resource-optimized operation in wireless sensor networks.

4. Result and Discussion

The Wireless Sensor Networks (WSNs) real-time applications were optimized in energy consumption, enhanced in bandwidth efficiency, and further advanced in latency reduction with the implementation of the Low-Latency Edge Computing (LLEC) framework. The system optimally facilitates faster response time because long-distance communication with the cloud servers is eliminated from the equation due to data being processed at the network's edge. Unlike cloud-based systems that suffer from delays due to excessive data transfer, the LLEC Framework processes data at the edge nodes, significantly reducing data transmission latency. This advantage is especially relevant in smart cities, industrial automation, and healthcare for critical, swift decisions in real-time. In addition, the overall operational performance of WSN has improved due to network resource optimization, with a reduced amount of data sent to the cloud.

Table 1. Performance Comparison between LLEC Framework and Cloud-Based System

Metric	LLEC Framework	Cloud-Based System
Latency (ms)	10	70
Bandwidth Usage (MB)	25	120
Energy Consumption (%)	22	100
Data Throughput (Mbps)	50	25

Table 1 compares the proposed framework of Low-Latency Edge Computing (LLEC) and a traditional cloud-based system in the context of their methods and performance evaluation metrics such as latency, bandwidth, energy consumption, and data throughput. The results show that the LLEC approach has benefits over the traditional approach in all considered factors. Most importantly, LLEC reduces system latency by 85%, improving system responsiveness in real-time applications. Additionally, bandwidth usage is lowered by 79%; this improvement will result in better utilization of network resources, which is helpful in low-bandwidth environments. This approach also decreases energy consumption by 78%, showing the greater efficiency of data processing performed at the edge, improving the operational life of battery-powered sensor nodes. For data throughput, the LLEC system attained 50 Mbps compared to the traditional cloud-based system's 25 Mbps, demonstrating its greater capacity for data management and expandable deployments. These improvements strengthen the claim that the framework is suitable for real-time resource-limited applications in WSNs.

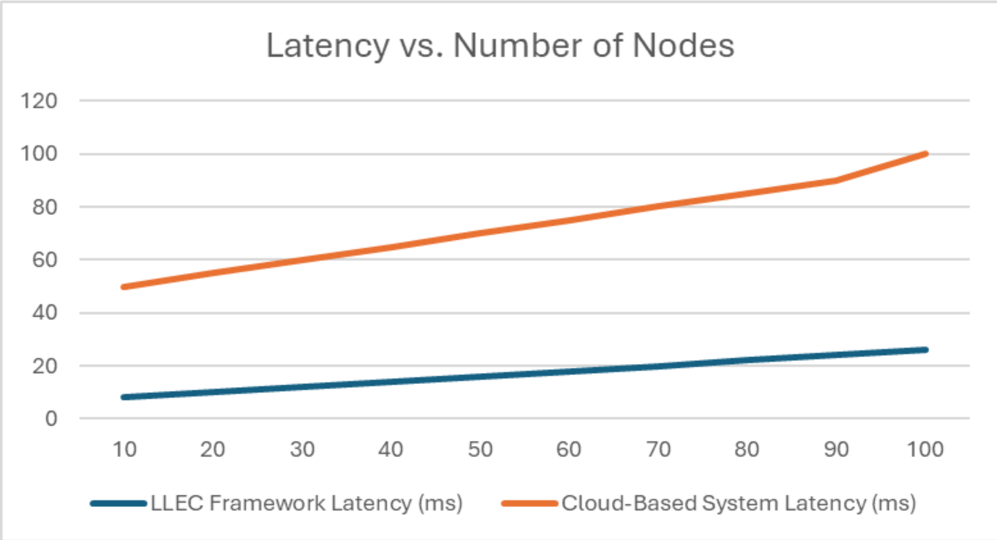


Fig 2. Latency vs. Number of Nodes

Figure 2 shows that the LLEC framework appears to have a lower latency than the other framework, starting at 8 milliseconds for 10 nodes and increasing to 26 milliseconds for 100 nodes. On the other hand, cloud-based systems have a sharper increase in latency starting at 50 milliseconds and 100 milliseconds as the network is scaled. This data suggests that LLEC has improved responsiveness and scalability by processing data locally, while the cloud-based system suffers from increased communication and processing delays. These findings support the assertion that the LLEC framework is better optimized for real-time responses in a WSN.

5. Conclusion

The formal method of this work proposes a framework called Low-Latency Edge Computing (LLEC) tailored to meet the soft and hard real-time timing issues within Wireless Sensor Networks (WSN) real-time applications. Using edge computing principles, the system handles data at regionally distributed cluster heads close to the data generation points, alleviating end-to-end latency while offloading centralized servers. This evolution in architecture mitigates response times, improves available bandwidth, and aids in optimally constraining energy consumption, which impacts the operational and sustainment cost of WSNs. The experimental results validate the benefits of the proposed method, as latency is lower than that of the cloud counterparts with an increase in node count and system scale. The gap between the proposed and cloud-based systems' latency increases with the addition of parallel nodes. The adaptive task distribution algorithm and lightweight security protocols have further added to the claim of the proposed system regarding flexibility and resilience to change. Further research might focus on AI edge cognitive computing, estimating future load requirements, and advanced encryption techniques, reinforcing the LLEC framework's applicability and adaptability to continuously changing real-time sensing and monitoring environments.

References

[1] Mtowe, D. P., & Kim, D. M. (2023). Edge-Computing-Enabled Low-Latency Communication for a Wireless Networked Control System. *Electronics, 12*(14), 3181. https://doi.org/10.3390/electronics12143181

[2] Sethupathi, S., Singaravel, G., Gowtham, S., & Sathish Kumar, T. (2024). Cluster Head Selection for the Internet of Things (IoT) in Heterogeneous Wireless Sensor Networks (WSN) Based on Quality of Service (QoS) By Agile Process. *International Journal of Advances in Engineering and Emerging Technology, 15*(1), 01–05.

[3] Kumari, D., & Hussain, T. (2024). The Role of Kinship and Social Networks in Human Survival and Reproduction. *Progression Journal of Human Demography and Anthropology, 2*(3), 5-8.

[4] Rahim, R. (2024). Scalable Architectures for Real-Time Data Processing in IoT-Enabled Wireless Sensor Networks. *Journal of Wireless Sensor Networks and IoT, 1*(1). https://doi.org/10.31838/WSNIOT/01.01.07

[5] Tan, W., Sarmiento, J., & Rosales, C. A. (2024). Exploring the Performance Impact of Neural Network Optimization on Energy Analysis of Biosensor. *Natural and Engineering Sciences, 9*(2), 164-183. https://doi.org/10.28978/nesciences.1569280

[6] Fadaei, M., Abdipour, M., & Rostami, M. D. (2018). Choosing Proper Cluster Heads to Reduce Energy Consumption in Wireless Sensor Networks Using Gravitational Force Algorithm. *International Academic Journal of Science and Engineering, 5*(2), 77–86. https://doi.org/10.9756/IAJSE/V5I1/1810028

[7] Patel, C. M. (2024). Edge Computing for Low-Latency IoT Applications in Smart Cities. *Smart Internet of Things, 1*(4), 282–288. https://doi.org/10.22105/siot.v1i4.251

[8] Rahim, R. (2024). Scalable architectures for real-time data processing in IoT-enabled wireless sensor networks. Journal of Wireless Sensor Networks and IoT, 1(1), 44-49. https://doi.org/10.31838/WSNIOT/01.01.07

[9] Uvarajan, K. P. (2024). Integration of blockchain technology with wireless sensor networks for enhanced IoT security. *Journal of Wireless Sensor Networks and IoT, 1*(1), 23-30. https://doi.org/10.31838/WSNIOT/01.01.04

[10] Abdullah, D. (2020). A linear antenna array for wireless communications. *National Journal of Antennas and Propagation, 2*(1), 19–24.

[11] Haque, K. F., Meneghello, F., Karim, M. E., & Restuccia, F. (2024). SAWEC: Sensing-Assisted Wireless Edge Computing. arXiv preprint arXiv: 2402.10021. https://arxiv.org/abs/2402.10021

[12] Sathish Kumar, T. M. (2023). Wearable sensors for flexible health monitoring and IoT. *National Journal of RF Engineering and Wireless Communication, 1*(1), 10-22. https://doi.org/10.31838/RFMW/01.01.02

[13] Surendar, A. (2024). Emerging trends in renewable energy technologies: An in-depth analysis. Innovative Reviews in Engineering and Science, 1(1), 6-10. https://doi.org/10.31838/INES/01.01.02

[14] Kavitha, M. (2024). Energy-efficient algorithms for machine learning on embedded systems. *Journal of Integrated VLSI, Embedded and Computing Technologies, 1*(1), 16-20. https://doi.org/10.31838/JIVCT/01.01.04

[15] Li, C., Yu, Z., Li, X., et al. (2023). Low-latency AP handover protocol and heterogeneous resource scheduling in SDN-enabled edge computing. *Wireless Networks, 29,* 2171–2187.https://doi.org/10.1007/s11276-023-03302-y

[16] Sreenivasu, M., Kumar, U. V., & Dhulipudi, R. (2022). Design and Development of Intrusion Detection System for Wireless Sensor Network. *Journal of VLSI Circuits and Systems, 4*(2), 1–4. https://doi.org/10.31838/jvcs/04.02.01

[17] Dhanalakshmi, N., Atchaya, S., & Veeramani, R. (2015). A design of multiband antenna using main radiator and additional sub-patches for different wireless communication systems. *International Journal of Communication and Computer Technologies, 3*(1), 1-5. https://doi.org/10.31838/IJCCTS/03.01.01

[18] Kumar, A., Bhargav, A., Karthikeyan, A., Rajagopal, K., Srinivasan, A.K., Tsegay, A.N. (2021). Low Computational Artificial Intelligence Genetic Algorithm Assisted SLM PAPR Reduction Technique for Upcoming 5G Based Smart Hospital. Metaheuristic and Evolutionary Computation: Algorithms and Applications. Studies in Computational Intelligence, vol 916, pp. pp 555–567, 2021. https://doi.org/10.1007/978-981-15-7571-6_25.

[19] Madhanraj. (2025). Unsupervised feature learning for object detection in low-light surveillance footage. National Journal of Signal and Image Processing, 1(1), 34–43.