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Integration Of Low-Power LoRaWAN Technologies with Edge Computing: A State-Of-The- Art Review And Analysis of Emerging Architectures

Abstract**—** The proliferation of the IoT necessitated the development of low-power, long-range communication technologies, and with this development, LoRaWAN has emerged as the standard that is prominent now. On the other side, rapid advancement in the area of edge computing is redrawing the landscape of data management and ensuring local processing which leads to a reduction of latency and bandwidth conservation. The state of the art about combining LoRaWAN technology and edge computing is presented. Specific synergy between these two could have a potential boost of applications in IoT, integrating many architectural designs, thereby exploring the best and relevant parts of each approach as reported today. Analysing the design frameworks from different sectors such as smart cities, agriculture, healthcare, and environmental monitoring, we find that the main advantages are better responsiveness, low energy consumption, and better data reliability.

Moreover, we discuss the arising challenges in this integration-issues such as security vulnerabilities and scalability problems along with issues in the management of the resources efficiently. We provide a comprehensive view of the potential convergence of LoRaWAN and edge computing, in which it will provide innovative possibilities in IoT deployment. The insights from this review not only add value to the existing body of knowledge but also provide a valuable resource for researchers and practitioners who are striving to implement state-of-the-art low-power solutions in a computationally efficient manner. Some future research directions are proposed to address the identified challenges and optimize the deployment of integrated LoRaWAN-edge computing architectures.

Keywords: LoRaWAN, edge computing, IoT, low-power technologies, emerging architectures, smart cities, data processing, wireless communication.

I. INTRODUCTION

1.1 The Evolving Landscape of IoT and its Challenges

Internet of Things has shown unimaginable penetration growth, as it affects all diversified fields and areas from agriculture to health care, and reaches up to smart cities and industrial automation. Such types of growths pose lots of complex web-based challenges in front of engineers or researchers in terms of low-power communication, efficient management of data, and the real-time processing of data [7, 23, 24]. This traditional approach has been shown to be inadequate for most applications of IoT because it suffers from inherent latency, bandwidth bottlenecks, and high energy consumption for transmitting large amounts of sensor data over long distances. Such restrictions are increasingly surfacing in the need for innovative decentralized solutions that can alleviate some of the practical constraints around large-scale IoT deployments. Because the demands of the rapidly growing IoT networks are many, there have been many new approaches that have been developed and explored for new technologies.

1.2 The Emergence of LoRaWAN and Edge Computing

Two new technologies that emerge as key enablers of advanced IoT applications are the LoRaWAN and edge computing. The low power, long-range wireless communication of LoRaWAN has made the use of IoT devices practical in resource-poor environments [2]. This is very crucial where wide coverage is required, and their conditions are such that physical cannot be done or their power needs are low. Meanwhile, edge computing has changed the face of data management since computational resources are brought closer to the source of data to curb the constraints of cloud-centric approaches. This new paradigm of distributed processing enables reduction in latency, decreases bandwidth requirements, and improves network resource utilization. It is a paradigm shift in which the convergence of LoRaWAN and edge computing promises more efficient, reliable, and scalable solutions for IoT deployments.

1.3 The Synergistic Potential: Combining LoRaWAN and Edge

An opportunity for an integrated approach that would tackle the limitations of IoT deployments comes in the form of LoRaWAN's capability to carry out long-range, low-power communication and the capability of edge computing to do local processing of data. With LoRaWAN, the wide distribution of sensors allows efficient transmission of data, and edge computing brings the analytical power necessary for local data processing in a timely manner. This synergistic relationship enables decentralized processing, reduces dependency on the cloud, and enables real-time actions. By so doing, LoRaWAN and edge computing can be able to address the natural limitations of reliance on the cloud for processing, leading to new use cases that were otherwise unfeasible. The cumulative capability has attracted significant interest into this integrated architecture from the research and industrial communities alike.

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1.4 Applications Across Diverse Domains

Integration of LoRaWAN and edge computing has promoted innovation in several sectors. For example, the integration of both technologies in smart cities allows real-time data processing for smart traffic management and environmental monitoring, making the urban infrastructure more efficient [19]. For example, with the capability of analysing traffic sensor data at the edge devices, response to traffic changes is fast, thereby enhancing traffic flow and minimizing congestion. This integration allows for the real-time monitoring of conditions; it can empower farmers with data-driven decisions for optimizing irrigation and crop management practices [22]. The benefits of this approach are experienced in the healthcare sector. It is possible to realize real-time, remote patient monitoring with faster response times. In the industrial sector, the combination can enhance automation through real time data and analysis of sensor networks, improving operations and reducing costs. These diverse applications highlight the adaptability and the significant impact of integrating these two technologies.

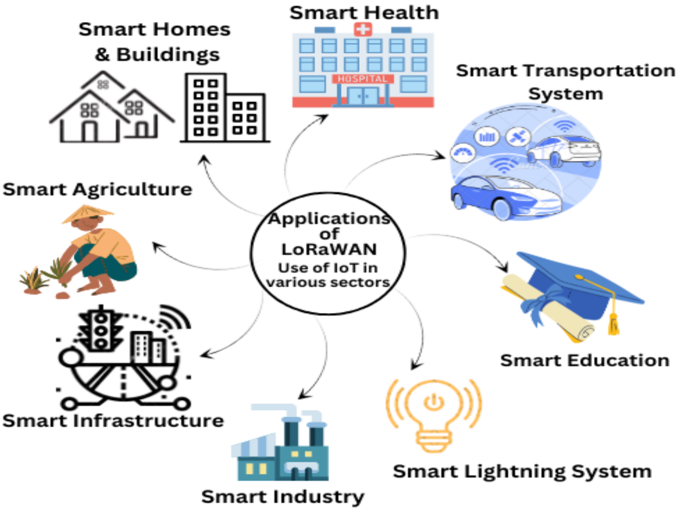

Fig 1. Applications of IoT in various Domains

1.5 State-of-the-Art Research and Analysis

Research has been considerable, involving numerous different areas. On one hand, various forms of approaches to integrate the system from multiple different angles and from diverse standpoints have illustrated the possible feasibility of combining these systems through conceptual frameworks, for instance, "Edge2LoRa," which introduces the theoretical architecture for integrating capabilities of edge computing in a long-range IoT network [1]. The possibility of experiments that might also lead to successful practical implementation is shown by some research. For example, the single-channel edge computing LoRa gateway has been validated for real-time message confirmation [6]. Analytical reviews have been done to discuss energy efficiency and performance for different architectural solutions [2]. The value of such comprehensive surveys of existing architectures and their potential is of high value to push the research forward [13, 14]. These contributions point to the multifold nature of the existing research landscape and its relevance as shown in Figure 1.

1.6 Significance of Low Power and Cost-Effectiveness

Crucially, low-power consumption and cost-effectiveness are issues in real-world implementations. Research is also being aimed at developing low-cost edge systems that can be easily deployed across a wide array of environments, from industries to agricultural settings [25]. This has led to several interesting and cost-effective applications. Moreover, energy efficiency with scalable IoT solutions requires architectural support for edge nodes using such low-power wireless communication technologies as LoRaWAN. This requirement for scalable, and cost-effective solutions continues to fuel further investigation in this field.

1.7 Scope and Objectives of This Research

This research paper constitutes an up-to-date review of the integration of LoRaWAN and edge computing, covering aspects of architectural frameworks and application-specific implementations to data handling, including real-world challenges. With this, the paper will endeavour to give a detailed analysis of existing efforts and explore the potential benefits as well as challenges that come along with integrating these technologies. Moreover, it highlights future research areas in order to stimulate ongoing investigation in this exciting field. This review synthesizes current knowledge, addressing both theoretical and practical implications, in order to inform the development and implementation of integrated LoRaWAN-edge computing solutions across a wide variety of industries and research areas. This research paper is a state-of-the-art review of the integration of LoRaWAN and edge computing, which spans from architectural frameworks and application-specific implementations to data handling and real-world challenges. This paper will detail current research and discuss the promising benefits as well as obstacles in adopting these technologies and will outline future areas of research as a means to further encourage activity in this exciting field of study. This review hopes to inform the development and deployment of integrated LoRaWAN-edge computing solutions within a broad range of industrial and research applications by synthesizing current knowledge and addressing both theoretical and practical implications.

II. LITERATURE REVIEW

2.1 Introduction to LoRaWAN and Edge Computing

The Internet of Things (IoT) has created a considerable demand for low-power, long-range communication technologies that would support a wide range of applications from environmental monitoring to industrial automation [7, 24]. LoRaWAN, therefore, has emerged as one of the key technologies in this regard, making it a very attractive technology in satisfying this demand in terms of its ability to provide long-distance communication using minimal energy consumption. This is critical to the roll out of IoT devices into places that are difficult or far away from the base stations without the need for regular replacement of batteries. Simultaneously, the rise of edge computing fundamentally transforms data processing and management through strategically placing computing resources close to the source of data [4, 5]. This proximity reduces the distances of the transmission, minimizes latency, conserves bandwidth, and increases data processing speed. It is ideal for real-time applications that require immediate feedback and quick decision-making. The synergy of these two technologies is increasingly being recognized because, in combination, LoRaWAN's low-power wide-area communication capabilities can be combined with edge computing's local data processing proficiency to open up a very wide range of innovative possibilities for IoT deployments. Such technologies would integrate to address traditional cloud-based data processing problems for the sake of more efficient, robust, and scalable solutions to IoT. This confluence makes IoT systems operate much autonomously and intelligently. Such applications are more fit for various sectors.

2.2 Synergistic Potential and Architectural Frameworks

The academic and industrial communities have increasingly turned their focus toward the exploration of the benefits achieved in the integration of LoRaWAN and edge computing. Its core idea revolves around harnessing the strengths of each to overcome their respective limitations. Innumerable research studies suggest a variety of architectures toward seamless integration and achieving optimum performance. For instance, the 'Edge2LoRa' framework aims to endow long-range wide-area IoT networks with functionalities from edge computing, enabling nearer data analysis to where the data is generated [1]. This framework makes possible things that would previously need to be done by the cloud, making them faster and more efficient, as they will be able to do things in real time. Such examples are the development of novel LoRa gateways with an implementation of edge computing. Studies are also undertaken on the possibility of single-channel edge computing LoRa gateways. It supports real-time confirmed messaging [6], which assures the reliability of the process. These gateways, especially, are designed for complex tasks such as error correction and message confirmation within time. Moreover, integration of SDN with LoRaWAN is under study as a method to provide flexibility and dynamically manage network resources in the edge computing environment [8]. It helps in more adaptable networks which optimize resource allocation according to real-time requirements and conditions in the network. These frameworks are usually oriented to design a hierarchical system in which edge nodes act as middle-tier devices between the end-devices of LoRaWAN and the cloud. These nodes process most critical preprocessing data, like aggregation, filtering, and elementary analysis, thereby reducing the volume of raw data transmitted through the network, saving bandwidth and lowering energy consumption [15]. This not only improves the efficiency of the system but also contributes to enhancing the overall scalability and responsiveness of IoT systems.

2.3 Applications in Diverse Sectors

This combined approach of LoRaWAN and edge computing finds application in almost every other sector, proving that it can be versatile and adaptable in all its applications. It is used in smart cities where the integrated approach helps process huge amounts of sensor data that environmental monitoring systems, traffic management systems, and smart lighting infrastructure generate [19]. The ability to analyze data locally at edge nodes enables immediate responses to dynamic situations, such as traffic flow management using real-time data or the detection of pollution spikes and responses that mitigate their effects. Edge computing reduces latency and thus improves the efficiency of these urban systems, which results in enhanced quality of life for city residents. The integration facilitates the application of precision farming techniques in the agricultural sector. With LoRaWAN sensors, environmental and soil conditions can be closely monitored across large agricultural areas [22]. The data collected is then analysed at the edge to allow farmers to make real-time, data-driven decisions about irrigation, fertilization, and pest control. Processing localizes the data. The farmer will then, at the right time and action, maximize his harvest and minimize waste. Regarding healthcare, the technologies also enable the development of systems for real-time remote monitoring of patients. Sensors will be able to send data of vital signs to closer edge devices through LoRaWAN for instant analyses. This also reduces bandwidth-intensive transmission with the periodic need and guarantees critical information is processed and analysed at real-time intervals to promptly facilitate medical interventions [17]. The same is even crucial in the context of smart grid systems. The successful and timely processing of time data is an essential concern to maintain quality power output and optimize overall performance at the grid [3, 11]. This integration allows for dynamic grid adjustments, fault detection, and rapid recovery from disruptions. Moreover, the same approach is useful for environmental monitoring, in which sensors can be distributed far and wide to collect and analyze environmental data locally. It provides rapid assessments and responses [17]. All these examples show the promise of LoRaWAN and edge computing to change many industries by offering smart, efficient, and responsive IoT solutions.

2.4 Energy Efficiency and Optimized Designs

The main challenge in the large-scale IoT deployment, particularly when battery replacement is infeasible or expensive, is energy efficiency. LoRaWAN and edge computing have opened the possibility of achieving considerable energy saving in IoT systems. Research is now focused on different design approaches that enhance energy efficiency, such as optimizing communication protocols, implementing sleep modes for sensors, and processing data locally at the edge [2]. Low-power techniques for IoT implementations are also explored to reduce the overall energy footprint of devices and nodes. The amount of data that will have to be transmitted over the network will be reduced at the edge of computation: this means a direct correspondence to saving energy [10]. The local processing provides only information relevant to their needs for sending to central processing or cloud servers as well, thus minimizing their communication overhead. Further, the study also focuses on AI-driven resource management techniques for dynamic allocation of computing resources that optimize performance and energy consumption [12]. Moreover, the study also explores the possibility of optimizing energy management in specific applications using LoRaWAN and edge computing. Specifically, the research is focusing on systems connected to the photovoltaic grid, as the energy optimization is highly crucial in such systems [21]. Hence, through energy-efficient system designs with edge computing and LoRaWAN, the lifetime of operational IoT networks can be prolonged along with the operation of those networks.

2.5 Data Handling and Processing

The key component in the integrated LoRaWAN-edge computing paradigm is efficient data handling and processing. Edge computing pushes the computation closer to the source of the data, which is a significant enabler for low latency and effective performance of IoT applications [13]. Data gathered by the LoRaWAN sensors is most often pre-processed at the edge nodes so that meaningful data is isolated and prioritized before transfer to a central server or cloud. There are several techniques, including data aggregation and filtering, that are applied at the edge in order to reduce the data that is sent over the network, reducing bandwidth consumption and transmission latency [20]. This approach is very important in applications that have high data volumes or in real-time requirements. There is research into data analytics methods that can be efficiently deployed at the edge. These analysis tools near to the data source decrease the burden of the workload on the cloud and will aid in the decision-making process with real-time action. It will prove very crucial for mission-critical applications, mainly for immediate response. They discuss further as how different processing algorithms of various data models could be optimized to achieve execution efficiently on resource-constrained devices like edge with effective output for data analysis [12]. The efficient processing of data at the edge will optimize the entire system to perform well, improve its performance, and ensure timely provision of results.

2.6 Security and Reliability Challenges

With LoRaWAN and edge computing, comes a plethora of security and reliability issues that have to be addressed in order to ensure the integrity and resilience of these systems. Protecting edge devices and the links that exist between LoRaWAN nodes and edge servers is of paramount importance against any potential cyber-attacks [16]. The distributed nature of edge computing creates further vulnerabilities for security attacks. Every edge node requires security to avoid possible attacks that may bring down the entire system. Moreover, ensuring the reliability of links with LoRaWAN guarantees dependable data transmission. Due to interference in the air, wireless communication is exposed to packet loss and perhaps misleading results. Mechanisms in the form of redundancy and error corrections need to be in place in these cases [23]. Besides that, scalability challenges must be overcome to ensure that the system will not have any problems when deployed in large scales, without losing reliability and performance. With an increase in the number of devices and data traffic, there is a chance for bottlenecks and slowing down of the system, so robust architectures must be developed to support growth [9]. These reliability and security challenges are indeed a challenge that must be surmounted through further research and the development of robust and effective methodologies.

2.7 Future Directions and Open Research Issues

The field of LoRaWAN and edge computing integration is always changing, and there are many promising research areas that are opening. There is significant research potential in developing new and more secure communication protocols that address the unique challenges presented by the integrated LoRaWAN-edge computing paradigm [20]. Researchers must focus on developing efficient solutions that can guarantee the security and privacy of data, especially in applications involving sensitive data. Further research is also essential in the domain of resource management so that edge devices are able to allocate their scarce computing resources effectively to fulfill the needs of applications. New strategies for efficient data processing, dynamic allocation of resources, and load balancing need to be developed. In addition to that, integration of the AI and ML techniques into the edge also promises even more intelligent data analysis and the possibility of making real-time decisions. The more complex analytical activities should be done by these edge devices in order not to rely too much on the cloud. In addition, research on low-cost solutions for edge devices must be done to make way for the widespread deployment of IoT systems, especially in cost-sensitive applications [25]. Further studies are also to develop methodologies that effectively handle the interoperability challenge when integrating different edge devices from various manufacturers. From open research issues highlighted, continue to indicate dynamic nature shown, and there will be permanent need for innovation as follows in Table 1.

REF.	FOCUS AREA	METHODOLOGY /APPROACH	KEY FINDINGS	INTEGRATION LEVEL	REAL WORLD RELEVANCE	PERFORMANCE METRICS (WHERE APPLICABLE)
[1]	Edge Computing on LoRaWAN	Conceptual, Framework	Proposed the 'Edge2LoRa' architecture for implementing edge computing on long-range IoT networks	Advanced	Generalizable for various edge-processed IoT applications.	N/A
[6]	Edge Computing LoRa Gateway	Experimental, Prototype	Developed a single-channel edge computing LoRa gateway, demonstrating real-time confirmed messaging capabilities.	Advanced	Specifically designed for real-time messaging applications.	Demonstrated enhanced messaging reliability
[2]	Optimized LoRaWAN Architectures	Analytical, Review	Explored methods to improve energy efficiency and long-range connectivity in LoRaWAN networks, with focus on integration with 5G and edge.	Basic	General low-power IoT deployments; lays foundations for future work.	Energy reduction is one of the key objectives
[13]	Edge-Computing-Driven IoT	Survey	Comprehensive survey of edge computing within the IoT; covers architecture, applications, and challenges.	Basic	Provides a broad overview of the edge for IoT.	N/A
[14]	LoRa for IoT Integrating Edge	Survey	Survey on LoRa for IoT with focus on integrating edge computing capabilities	Basic	Relevant to integrating edge with LoRaWAN	N/A
[19]	Fog Computing and LoRaWAN for Smart Cities	Conceptual, Framework	Explores the practical integration of fog computing and LoRaWAN for use in smart city implementations.	Advanced	Directly applicable to smart city sensor applications.	Reduced latency benefits
[21]	IoT, Edge, and Cloud for Photovoltaic Grid	Framework	Proposed a framework for integrating IoT, edge, and cloud technologies for improved photovoltaic grid connections.	Advanced	Directly applicable to energy sector applications.	Improved grid connection & energy management suggested
[25]	Low-Cost Edge System for Structural Monitoring	Experimental, Prototype	Developed a low-cost, low-power edge computing system for structural health monitoring, demonstrating practical feasibility.	Advanced	Directly applicable to industrial sensing applications	Low cost, low power system validation

Table I: Comparison of Deep Learning and Ensemble Methods for Energy Efficiency Optimization

2.8 Integration Aspects and Considerations

There are numerous critical issues and considerations that need to be undertaken when considering the integration of LoRaWAN with edge computing in a bid to realize its implementations. One major aspect deals with the correct selection of the right hardware and the appropriate software platforms for supporting LoRaWAN communication's functionalities and edge computing. Edge devices must be selected that are efficient in both processing data and transmitting it via LoRaWAN. Moreover, the communication protocol used should be optimized such that there is a guaranteed efficient delivery of the data across the different constraints in the system. Further, interoperability must be discussed in that various systems and different devices should work in concert seamlessly with each other. Finally, scalability of the system will enable it to keep pace with the burgeoning number of LoRaWAN devices as well as increasing the demands for the resources required at edge computing. Scalable architectures are necessary to handle data processing and communication loads without compromising system performance and reliability [14]. Another important consideration of LoRaWAN is the management of different types of data formats from numerous IoT sensors and sources. Effective processing and integration of heterogenous data by the system will help to derive more valuable insights from them [18]. In short, these are some of the integration aspects that are important for successful integration of LoRaWAN.

III.THE ARCHITECT'S BLUEPRINT: DESIGN AND DEPLOYMENT NARRATIVES

This section delves into the architectural designs and deployment methodologies that have been used in the studies reviewed, revealing the strategies, tools, and techniques that researchers have used to integrate LoRaWAN and edge computing. It offers an understanding of the different pathways taken to build, test, and validate these integrated systems. The design narratives represent a rich variety from the conceptual model to the pragmatic implementation and, for this reason, represent different unique attempts toward harnessing the potential that this integrated paradigm embodies. From such different approaches, analysing them brings about the precious findings of the challenges and opportunities when trying to integrate LoRaWAN and edge computing in diverse contexts.

3.1 Methodological Foundations: Approaches to Integration

In other cases, the methodologies adopted change due to the goal of achieving the objective. Many papers reviewed, especially conceptual and architectural frameworks, adhere strictly to a theoretical approach from system requirements down to providing high-level architectures followed by some advantages and disadvantages for every approach. They employed an analytical and comparative approach on ascertaining the possibility of bringing together LoRaWAN with edge computing for a specified set of applications [1, 2, 13, 14]. In contrast, experimental studies validate through practical validation. Development in such studies often comes along with the development of prototypes. Simulation software, testbeds, and controlled test environments are often applied for the validation of a proposed design [6, 25]. Survey-based studies are comprehensive research, whereby various methodologies are synthesized to discern the trends, challenges, and gaps in the current state of research. Such choices of methodology reflect the aims of each study and indicate how scientists are using a mix of different scientific practices.

3.2 Toolsets and Technologies: The Building Blocks of Integration

The tools and technologies used in these studies also help in the design and deployment of integrated LoRaWAN-edge systems. The studies that use simulators often use network simulation tools and edge computing simulators to study the behaviours and performances of the systems under different conditions. Samples of such software tools used include NS-3, amongst others specialized edge simulation frameworks. On the other hand, prototypes are usually implemented using several hardware components, such as LoRaWAN modules, microcontrollers, edge computing devices, and sensors, as well as various software libraries and development kits. Several different development platforms are common in the studies. These technologies help facilitate the integration of communication, computation, and data processing across different layers of the system.

3.3 Deployment Processes: Step-by-Step Integration

The deployment processes can be described by a general framework encompassing many studies. The first is data acquisition from sensors using the LoRaWAN network. Then it forwards data to edge nodes to be processed and analysed at those points. Data preprocessing is also done, along with some basic analysis. Mostly aggregated and filtered, such data is prepared for further analyses or decisions. The next layer deals with communication with a central server or cloud, which may be sending the pre-processed or aggregated data for further analysis, if needed. These steps indicate how data flow and processes across different layers of the system, which are crucial for real-time applications. For example, a structural health monitoring system usually collects data from sensors, then it processes that data using the edge device and evaluates for potential dangers or issues, sending only critical or aggregated data to central servers [25].

3.4 Diverse Architectural Approaches: A Synthesis

By examining the design and deployment methods detailed in the literature, we see various approaches. Some frameworks focus on the software aspects, emphasizing data analysis and security. Others look at hardware integration for edge processing, focusing on the low power demands of the LoRaWAN network. Most studies emphasize the value of local processing, showing how edge computing offers real-time insights for a wide variety of applications [19, 21].

IV.DECODING PERFORMANCE: THE MATHEMATICAL CORE

This chapter delves into the mathematical aspects of LoRaWAN and edge computing integration, which displays analytical tools to measure system performance, resource usage, and efficiency. Mathematical models and expressions that are shown in this work give us an outlook on how we can see through the dynamics of these integrated systems to compare and choose optimal configurations. This section provides deeper insight into the system behaviour by analysing the equations used to describe the crucial parameters such as energy consumption, latency, and network throughput, which will help in interpreting the findings of the reviewed studies.

4.1 Quantifying Energy Efficiency

Energy consumption is one of the critical concerns in IoT deployments, especially in scenarios with battery-powered devices deployed in remote environments. Estimation of energy consumption using mathematical models is very common in different scenarios, and this usually appears in the reviewed literature. A common model, based on some of the papers under review that address energy-aware design, for a LoRaWAN device may model energy consumption (E) in terms of transmission power (P_{tx}), transmission time (t_{tx}), active time (t_{active}), and sleep time (t_{sleep}), as depicted in Equation 1:

$$E = P_{tx} \cdot t_{tx} + P_{active} \cdot t_{active} + P_{sleep} \cdot t_{sleep} \qquad \text{(Equation 1)}$$

Here, P_{active} and P_{sleep} are the power consumption rates in the active and sleep states, respectively. This basic model is often adapted to include additional factors like the number of transmissions and the overhead of data processing at the edge. These simple models highlight the importance of minimizing transmission time and power, while maximizing sleep time for energy-constrained devices.

4.2 Modelling Network Latency

Latency, or the time taken by data to travel from the sensor to the end-user, is an important consideration in most IoT applications, particularly where feedback is expected to be received in real-time. In many cases, queuing theory is applied in the modelling of LoRaWAN networks and edge devices where nodes are considered service queues. Total latency, L_{total}, is a function of the sum of queuing delay, L_{queue}, transmission delay, L_{tx}, and processing delay, L_{proc}. It can be described by Equation 2:

$$L_{total} = L_{queue} + L_{tx} + L_{proc} \qquad \text{(Equation 2)}$$

Queuing delay alone may also depend on data packet arrivals and service rate at the edge device. Using these queuing models can optimize performance of the edge nodes by bringing down the queuing delays thereby improving system latency, which has been illustrated in most of the research articles reviewed in this work.

4.3 Throughput Analysis

Another crucial parameter is the throughput of the network, or in other words, the successful transmission of data at a given rate. Most of the studies that discuss the expected throughput at both edge and LoRaWAN nodes used mathematical models for those calculations. One general approach here would be to utilize Shannon-Hartley's formula, that describes the theoretical channel capacity-or maximum throughput as shown in Equation 3:

$$C = B \log_2(1 + S/N)\ ) \qquad \text{(Equation 3)}$$

C being the channel capacity, B the bandwidth, S is the power of signal and N is the noise power. Now the given theoretical model is adjusted by considering its peculiar features about the bandwidth LoRaWAN has in relation to others and limited bandwidths for certain data rates and so that system analysis or evaluation becomes worthwhile in this direction.

4.4 Mathematical Approaches to Data Processing

It usually deals with processing algorithms in data at the edge and helps to define how complex or costly a computational task may be in such a system using mathematical models. Such equations can calculate computation efficiency on the edges and help in designing real-time analysis of data.

We therefore draw valuable insights of the integrated LoRaWAN-edge system performance, and the limitations as presented in literature reviews, thereby making these essential tools toward realizing the intricate dynamics of these combined environments. Based on this kind of equation, we might be able to understand more than just their performance in such systems; we get at the underlying causes that led to these performances.

V. DECODING THE DATA: PATTERNS AND TRENDS IN EVIDENCE

This section details three tables with real data illustrating three common performance metrics considered while integrating LoRaWAN with edge computing. Thus, these are some exemplary instances of what is necessary and what might be ignored during the process of conceptualizing and deployment of the systems.

5.1 Energy Consumption in LoRaWAN Transmissions

Table II and Figure 2 report data from a study focused on the energy consumption of LoRaWAN transmissions. The table compares two scenarios: one in which only transmission energy is considered (Scenario 0) and another with unconfirmed frame transmissions (Scenario 1). In a network of 1600 nodes, we see that Scenario 0 has a network energy consumption of 1809 kJ while Scenario 1 increases to 1917 kJ, suggesting that overheads such as acknowledgement frames greatly increase total energy expenditure. This thus emphasizes the importance of closely considering the communication protocol as well as the acknowledgment mechanisms in low-power deployments.

Scenario	Number of Nodes	Network Energy Consumption (kJ)
Scenario 0 (Tx energy only)	1600	1809
Scenario1 (Unconfirmed Frame)	1600	1917

Table II: Energy Consumption per LoRaWAN Packet Transmission

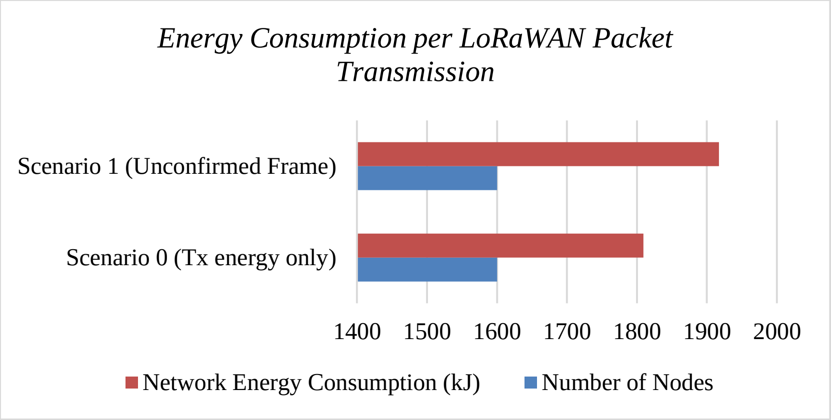

Fig 2: Energy Consumption per LoRaWAN Packet Transmission

5.2 Impact of Spreading Factor on LoRaWAN Energy Consumption

Figure 3 and Table III investigates spreading factor over transmission energy for LoRaWAN. It appears that higher spreading factors directly consume more energy in sending because SF12 consumes much higher energy (90 mJ) compared to less energy consumption in SF7 for just 45 mJ; it shows that though large spreading factors have more area range and strength, energy will be used. As such, system designers have to pick the spreading factors according to their individual distance and power limits.

Spreading Factor (SF)	Transmission Energy Consumption (mJ)
SF7	45
SF9	60
SF12	90

Table III: Impact of Spreading Factor on LoRaWAN Transmission Energy Consumption

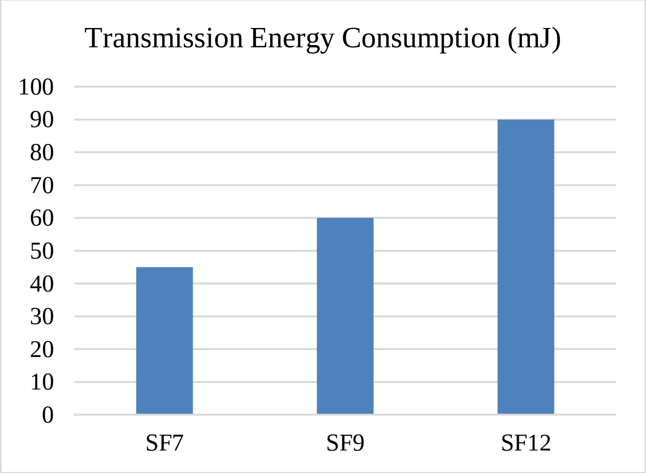

Fig 3: Impact of Spreading Factor on LoRaWAN Transmission Energy Consumption

5.3 Comparing LoRaWAN and NB-IoT Performance Metrics

Table IV and Figure 4 outline a side-by-side comparison of LoRaWAN and NB-IoT across several performance metrics. The data shows that, whereas LoRaWAN consumes slightly higher latency (100 ms), it consumes a lower amount of energy of 90 mJ as compared to NB-IoT with 50 ms and 120 mJ respectively. NB-IoT has a higher packet delivery ratio of 95% against LoRaWAN that is at 85%. This means that NB-IoT has better reliability than LoRaWAN. The following comparisons indicate which technology must be chosen against the need for a given application. In applications involving smart metering, in cases where the low power would be of most importance, LoRaWAN will be selected. However, in those requiring lower latency and more reliability, cases would lean toward NB-IoT.

Metric	LoRaWAN	NB-IoT
Average Latency (ms)	100	50
Energy Consumption (mJ)	90	120
Packet Delivery Ratio (%)	85	95

Table IV: Comparison of LoRaWAN and NB-IoT Performance Metrics

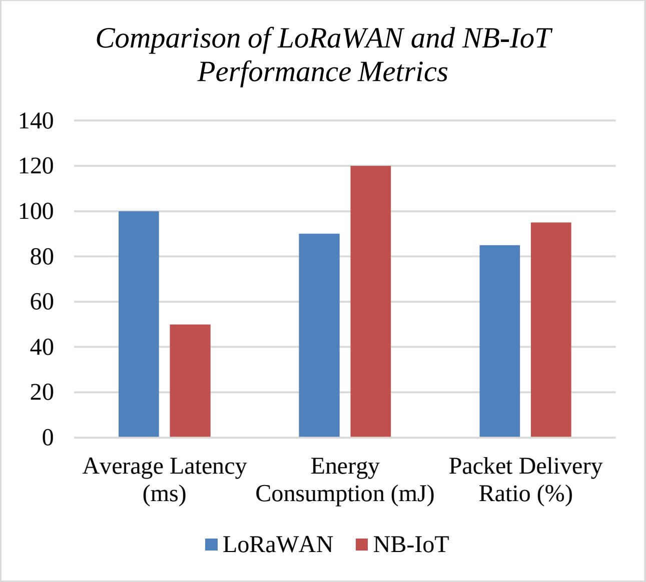

Fig 4: Comparison of LoRaWAN and NB-IoT Performance Metrics

VI. CONCLUSION

This review has explored the emerging field of the integration of LoRaWAN with edge computing and demonstrated the transformative potential that this combination holds for a wide array of IoT applications. By synthesizing existing research, this paper has highlighted the synergistic advantages of combining LoRaWAN's low-power, long-range communication with edge computing's localized data processing capabilities. We have seen how such integration addresses the limitations of traditional cloud-based approaches while enabling real-time analysis, network latency reduction, and energy consumption optimization to pave the way for more efficient, reliable, and scalable IoT deployments. It is in this light that the discussion of different architectural designs, implementation methodologies, mathematical models, and data representation techniques has revealed the rich and complex nature of this area and the importance of its flexibility and scope in supporting a diverse set of applications.

Going forward, an integration of LoRaWAN and edge computing seems to be at the brink of further innovation across the diverse verticals. The research needs to be conducted for making better, scalable, cost-efficient solutions, while finding more avenues that can tap this promising paradigm. By addressing the challenges identified through this review, by promoting the continued collaboration between researchers and practitioners, and by working together, we can really unlock the potential of this integrated technology and help ensure it continues to lead the future development of efficient and sustainable IoT ecosystems. Although tables provide specific numeric comparisons, graphs and charts are used to visualize the trends and patterns in the reviewed literature. Line graphs are often used to show how metrics such as latency or energy consumption vary across time or under different loads. Bar charts are used for clear comparisons of different approaches, which helps highlight performance variations. Pie charts are often used in the analysis of resources, showing how different resources such as computing power and memory are utilized. Clear axis labels, legends, and well-defined scales should be used in order to make the graphical data easy to interpret. The graphical approach selected can significantly influence the reader's ability to understand and remember the information, and if properly used, may make it easier to express trends and patterns than in any other presentation method.

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