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Scalability and Performance Analysis of LoRaWAN Networks for IoT Implementation: Comprehensive Review and Research Agenda

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Abstract **– The surge in IoT devices has created the need for a scalable and high-performance network infrastructure capable of handling massive data flows and diverse application requirements. Among the various wireless technologies available, with long-range communication capabilities, low power consumption, and cost-effectiveness, the Low-Power Wide-Area Network (LPWAN) has emerged as a highly popular choice for numerous applications. This literature review aims to provide a comprehensive overview of recent developments in scalability and performance analysis of LoRaWAN networks for IoT implementation by reviewing existing research and identifying key challenges and opportunities for the research agenda. In the research on LoRaWAN performance in IoT, five characteristics have been proven and become factors for using LoRaWAN in IoT: low energy power usage, wide coverage, low cost, stable data transmission speed, and system reliability. However, not many have discussed its security. Based on the literature review, LoRaWAN does have some characteristics that make it suitable for large-scale IoT applications. This review will contribute to advancing knowledge in this field, enabling the development of scalable and high-performance IoT systems to meet the demands of the growing IoT ecosystem.**

Keywords: IoT, LoRaWAN, Wireless Network, Technology.

I. INTRODUCTION

In this increasingly connected world, millions and even billions of connected devices have been introduced into various sectors, such as healthcare [1], agriculture [2]–[5], and the environment [6]–[8]. This rapid growth triggers an increased need for network infrastructure supporting extensive IoT device connectivity.

One of the networking technologies that has emerged as a promising solution for IoT implementation is the Low-Power Wide-Area Network (LPWAN), with one of its prominent implementations being the Long Range Wide Area Network (LoRaWAN). LoRaWAN offers cost-effectiveness, long-range connectivity, and low power consumption, attractive factors for many IoT applications. [9]

Many previous studies have used LoRaWAN technology for IoT implementation. In research [2], a precision irrigation tool for fresh market tomato production in a plasticulture system was developed and evaluated using a LoRaWAN-based IoT system. Then research [10] introduced a Flood Monitoring and Warning System that utilizes LoRaWAN to ensure extensive network connectivity, minimize power consumption, and utilize low data transmission rates.

In research [11], An IoT-based prototype was created to enable efficient energy management in smart homes, utilizing LoRaWAN and Sigfox technologies. The study highlighted the crucial role of LoRaWAN, a low-power wide-area network technology, in delivering cost-effective and energy-efficient devices.

However, while LoRaWAN shows great potential, some challenges must be overcome. The scalability and performance of LoRaWAN networks pose significant challenges in the context of the exponential increase in connected devices. A comprehensive analysis of LoRaWAN's capacity to handle large device populations, maintain reliable connectivity, and facilitate efficient data transmission is essential to address the demands of extensive data flows and diverse application requirements.

Furthermore, evaluating the performance characteristics of LoRaWAN networks, including throughput, latency, and packet loss, is crucial. Understanding the factors that influence network performance is equally important. Therefore, a comprehensive review is required to explore LoRaWAN as a transformative technology for IoT, known for its long-range connectivity and low power consumption.

This literature review aims to provide a comprehensive analysis of the scalability and performance aspects of LoRaWAN networks within the context of IoT implementations. By surveying and incorporating existing research and academic contributions, this review will explore various dimensions of scalability, including network capacity, device density, scalability limitations, and resource management techniques. In addition, it will also investigate performance metrics such as throughput, latency, and packet loss, analyzing the factors that affect network performance.

By examining existing research and identifying key challenges and opportunities, this review will contribute to advancing knowledge in this field, enabling the development of scalable and high-performance IoT systems to meet the demands of the growing IoT ecosystem.

II. BASIC OF THEORY

IoT (Internet of Things) refers to an old Machine-to-Machine (M2M) usage. M2M enables automated information exchange between systems without human intervention with wired or wireless networking technologies.[9] Many protocols are used in IoT, such as 2G, 3G, 4G, 5G, Bluetooth, NFC, Zigbee, WiFi, and others. These protocols are usually classified based on bandwidth and range, as shown in Figure 1.

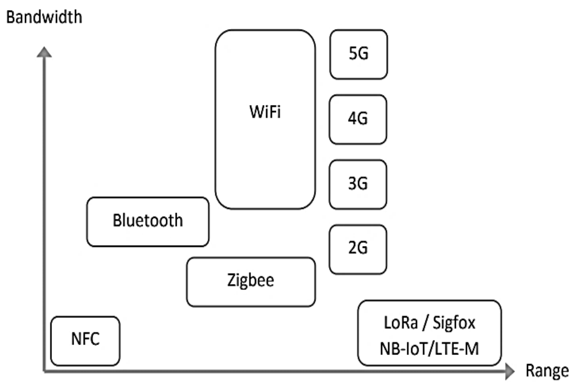

Figure 1. Protocols Used in IoT

This graph does not represent the power consumption generated by these protocols. LoRaWAN and Sigfox are protocols with low power requirements and have a very long range. They are some of the generally called Low Power Wide Area Networks (LPWANs). This research focuses on LoRaWAN.

LoRaWAN, an extension of the LoRa protocol, provides the ability to connect devices to a server to provide data to end users securely. LoRa is the modulation type for LoRa devices or an end device to a gateway. Figure 2 shows the overall architecture of LoRaWAN. [9]

LoRaWAN end device transmits data, and then the user receives the data transmitted over the network. The IoT platform and user connection are not part of the LoRaWAN architecture core because it is a web service. [9]

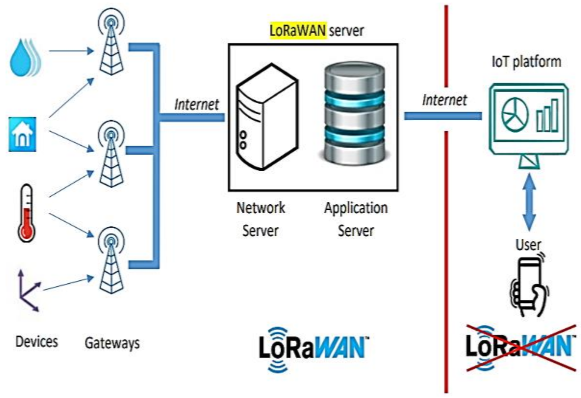

Figure 2. The overall architecture of a LoRaWAN network

LoRaWAN end devices are low power consumption, small size, and low-cost IoT embedded systems. To reach the gateway, they are equipped with LoRa radio transceivers. All gateways in the coverage area receive and process device messages from LoRaWAN end devices: [9]

The LoRaWAN gateway in Figure 3 listens to all channels and spreading factors simultaneously. The gateway sends the contents over the Internet to the pre-configured Network Server at the gateway as soon as a LoRa frame is received. [9]

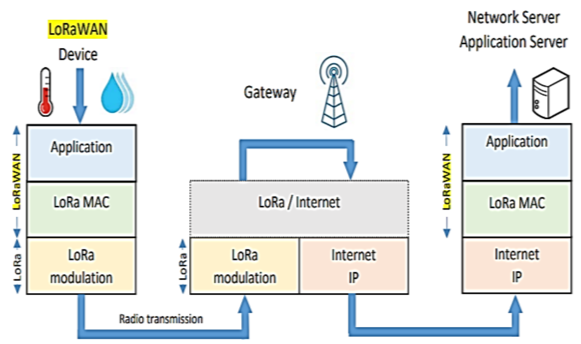

Figure 3. The LoRaWAN gateway

On the one hand, LoRa modulation is received by the gateway through the antenna. On the other hand, the gateway connects to the Internet through possible backhauls: WiFi, 3G, 4G, 5G, Ethernet, and LTE-M. A unique identifier (64-bit EUI) makes each LoRaWAN gateway different. The unique ID helps the Network Server to register and activate the gateway.

Network Server receives the gateway's messages and eliminates duplicate packets. The Network Server authenticates the message using Network Session Key, a 128-bit AES key. Then, the encrypted message will be received by the Application Server. The Application Server uses Application Session Key for the encryption and decryption operations. [9]

The LoRaWAN standard is intended for applications with very low power consumption. Generally, LoRaWAN devices have a battery life of several years. Several parameters affect the consumption of a LoRa system, including the

Spreading Factor, data payload, collisions during delivery, retransmission, request acknowledgment of sent frames, duty cycle, power used in standby mode between transmissions, and the transceiver power.

III. METHOD AND DESIGN

This study used a systematic literature review (SLR) methodology. SLR involves a rigorous process of determining, evaluating, and analyzing existing research to obtain conclusive insights and address specific research inquiries.[12]. The systematic literature review (SLR) methodology is executed systematically, adhering to predefined stages and protocols. These stringent guidelines ensure that the literature review process remains unbiased and minimizes subjective interpretations by researchers [13].

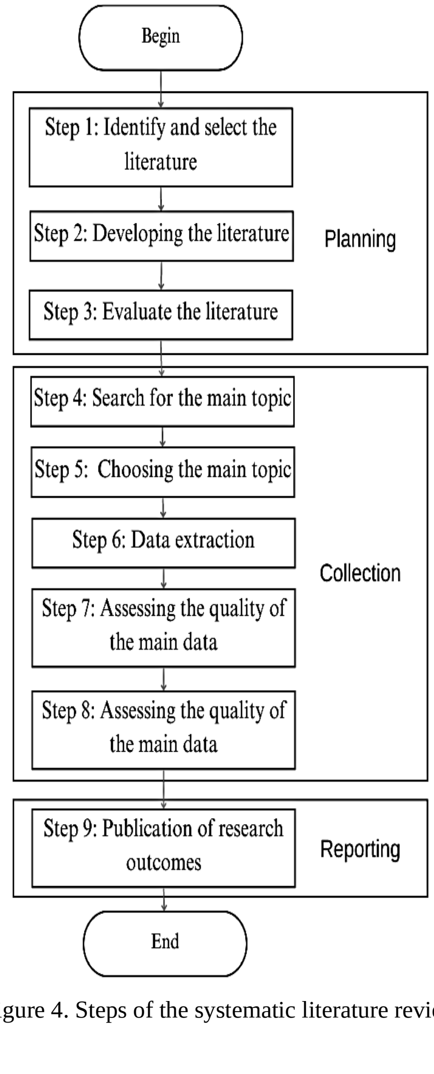

Figure 4. Steps of the systematic literature review

Data sources were collected through literature searches of indexed reputable international journals. The data population of this study is a journal that focuses on using LoRaWAN in IoT. There were 25 articles from reputable international journals selected as the literature to be reviewed. The SLR stage consists of 3 main parts: Planning, Conducting, and Reporting. These stages can be seen in Figure 4.

The first step was to identify and fulfill the requirements of a systematic literature review focusing on LoRaWAN technology performance in IoT. The next stage followed the SLR protocol to reduce the possibility of bias in the research. The process involves several key steps. The research question is initially formulated, followed by a search strategy. The study selection process is then carried out, utilizing predefined inclusion and exclusion criteria. Next, the quality of the selected studies is assessed, and relevant data is extracted and synthesized. Finally, the findings are reported, involving the composition of a study report based on the reviewed literature using the established protocol. Additionally, a discussion is compiled, and conclusions are drawn from the gathered information.

A. Research Question

These research questions ensured that the SLR remained focused on following the objectives. Research questions were compiled using the PICOC guide [12], which includes the criteria of Population (P), Intervention (I), Comparison (C), Outcome (O), and Context (C). Table 1 displays the PICOC structure of the research question (RQ) on the Systematic Literature Review of LoRaWAN network scalability and performance for IoT implementation.

Table 1. Summary of PICOC

Criteria	Description
Population (P)	LoRaWAN network for IoT implementation
Intervention (I)	Scalability and performance analysis
Comparison (C)	None
Outcome (O)	Understanding the scalability and performance of LoRaWAN networks
Context (C)	IoT implementation using the LoRaWAN network

The research questions (RQ) formulated in this study are listed in Table 2.

Table 2 Research Questions on the Literature Review

ID	Research Question	Motivation
RQ 1	What are the most significant journals on LoRaWAN performance for IoT?	Identify the most significant journals that discuss the scalability and performance of LoRaWAN networks for IoT implementation.
RQ 2	Who are the most influential and active researchers on LoRaWAN performance in IoT?	Identify the most active and influential researchers on LoRaWAN network scalability and performance for IoT implementations.
RQ 3	What is the reliability of LoRaWAN networks in IoT applications?	Knowing the extent to which LoRaWAN networks are reliable in supporting connectivity and data delivery in an IoT environment.
RQ 4	How does the LoRaWAN network perform in terms of coverage and signal strength?	Understand how much the LoRaWAN network can cover a wide geographical area and provide strong signals to support IoT applications.
RQ 5	Is the LoRaWAN network energy efficient?	Evaluate the level of energy usage efficiency in the LoRaWAN network to optimize the endurance of connected IoT devices.
RQ 6	How does the LoRaWAN network perform in terms of throughput and latency?	Measure the data transmission speed and delay in the LoRaWAN network to determine the extent of the network's ability to transfer data efficiently in IoT applications.
RQ 7	How is data security and privacy guaranteed in LoRaWAN connections in IoT applications?	Data security and privacy are important aspects of using LoRaWAN in IoT applications. Understanding data protection and privacy measures will help in implementing a secure solution.

The main questions in this systematic literature review focus on research questions RQ 3 - RQ 7. These questions help direct the research focus and better understand the scalability and performance of LoRaWAN networks for IoT implementations. Meanwhile, the research questions in RQ1-RQ2 will assist the researcher in evaluating the context of the main study and provide information regarding the summary and synopsis of the research field related to LoRaWAN performance in IoT.

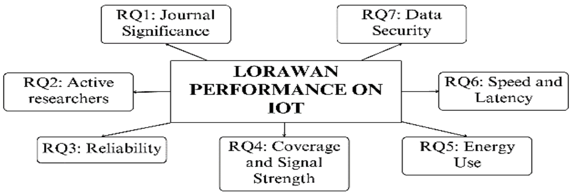

Figure 5. SLR mind map of LoRaWAN performance in IoT

This research's main objective is to understand and analyze the performance of LoRaWAN networks in the context of IoT applications. As such, this research is geared towards providing insights into the reliability, range, energy efficiency, data delivery speed, and factors that affect the performance of LoRaWAN networks in supporting IoT applications. The mind map of this systematic literature review can be seen in Figure 5.

B. Search Strategy

The fourth step in systematic literature review involves a search process consisting of several activities. These steps encompass choosing a digital library, formulating a search string, searching, filtering the search string, and retrieving a list of essential research from the digital library. This process ensures that a comprehensive search can be conducted effectively. Before starting the search, a suitable data selection was conducted to find highly relevant articles. The database used in the digital search is Semantic Scholar (https://www.semanticscholar.org/).

The keyword search in this systematic literature review followed these steps: Determine search terms derived from the PICOC framework, focusing on population and intervention; identify search terms that align with the research question; identify search terms within the title, abstract, and keywords, Identify synonyms, antonyms, and alternative spellings associated with the search terms, Carry out the search filter, such as AND and OR. Example: (IoT AND LoRaWAN). The purpose of this keyword search is to get as many articles as possible that are relevant to the topic under review.

C. Study Selection

In this process, criteria included and excluded were used to select the primary research described in Table 3.

Table 3. Inclusion and Exclusion Criteria in SLR

Inclusion	Exclusion
Research articles in the field of IoT that use LoRaWAN technology	Articles only focus on nontechnical aspects such as social or business in IoT implementation.
Included research articles are preferably Scopus-indexed journal articles.	Research that only focuses on theoretical or conceptual aspects without any real nplementation of LoRaWAN etworks for IoT applications.
For duplicate publications of the same study, only the ost complete and recent will be included	Research that is not relevant to the scalability and performance of LoRaWAN networks in IoT implementations.

Mendeley is used as a reference manager to manage search results and store literature. The study selection process consists of two stages of exclusion based on their title and abstract, then based on a thorough examination of their full text.

D. Data Extraction

The data extraction step involved retrieving information from the collected articles and systematically entering it into a data extraction summary table. The main study was extracted by collecting data that would be used as answers to the research question (RQ). The summary data extraction was identified based on the research question and the analysis conducted by the researcher, as shown in Table 4 below.

Table 4. Data Extraction

Property	Research Question
Identification and publication	RQ1, RQ2
Reliability	RQ3
Coverage	RQ4
Energy use	RQ5
Throughput and latency	RQ6
Security	RQ7

E. Study Quality Assessment and Data Synthesis

This step was used as a guide in data synthesis to determine the strength of conclusions and avoid bias. Data synthesis aimed to collect evidence for answering the research questions from the selected studies. The strategy used in this data synthesis was the narrative method. The data was organized consistently according to the research questions. Visualizations such as bar and pie charts, curves, and tables were used to represent LoRaWAN performance in IoT.

IV. Results and Discussion

A. Significant Journal Publications

In this systematic literature review, 25 journals studied using LoRaWAN in IoT. Most studies occurred in the last five years, between 2019-2023, and the most in 2020. Figure 6 displays the distribution of researchers' interest in discussing and studying LoRaWAN performance in IoT. Figure 6 also shows that the research field of LoRaWAN performance in IoT is still relevant in the current context.

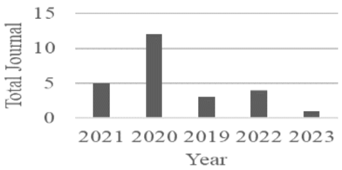

Figure 6. Distribution of LoRaWAN performance studies on IoT

B. Most Active and Influential Researchers

From the selected literature, researchers discussing LoRaWAN performance in IoT have actively examined the problems, risks, and constraints associated with LoRaWAN performance in IoT. From the selected data, it was found that S. R. Jino Ramson, Waheb A. Jabbar, Antonio Valente, and Salviano Soares are some of the researchers who have used LoRaWAN technology in IoT the most.

C. Research Topic

LoRaWAN performance in IoT is a significant research topic in telecommunication technology studies. Some selected research on LoRaWAN in IoT revealed that the things analyzed in LoRaWAN performance focus on five topics: Identifying LoRaWAN performance problems and solutions in IoT, discovering the risks and efficiency of LoRaWAN deployment in IoT, classifying the use of LoRaWAN in IoT in various fields, optimizing the performance of LoRaWAN usage on IoT, and analyzing literature that uses LoRaWAN technology in IoT.

Research [2], [14], [15] discusses the development of LoRa and LoRaWAN-based smart irrigation systems. The results [14] demonstrated the accuracy of radio planning tools for optimizing the network's overall performance regarding coverage, cost, and energy consumption. Research [15] results indicate that the LoRa air interface applies the toughest scalability limitations, particularly concerning the number of sensors transmitting data from the farm to the gateway. Some latency was found in the IoT platform but did not significantly impact the solution's overall performance.

In research [11], It was found that LoRaWAN has an important role in providing energy-efficient devices at low cost. Research [5], [16], [17] successfully developed low-cost sensor nodes that can communicate remotely and power-efficiently over LoRaWAN IoT networks. LoRaWAN has been used for developing a new system [4], [10], [18], [19] to ensure strong network connectivity, minimize power usage, and employ low data transmission rates.

Article [20] showed high flexibility and great potential to be applied in smart agriculture. Research [21] specifically focuses on exploring the potential of LoRa/LoRaWAN technology as a solution for WUSN applications in agriculture. Extensive research and simulations have confirmed the capabilities and scalability of LoRaWAN in WUSN applications.

Research [22] showed that the implemented system could communicate data continuously without losing data. LoRaWAN offers lower cost and better coverage than WiFi or Bluetooth. That advantage is essential for applications in areas with limited cellular network coverage.

Article [23] proves the reliability of the communication channel up to 8.33 km offshore distance. Research [24] empowers mussel farmers along the river by providing well-informed, precise, and prompt insights that enhance their capacity to effectively address unfavorable environmental occurrences, such as floods and heat waves.

In the study [25], The system demonstrated successful functionality in laboratory and operational tests in the field, including signal propagation checks and water leak detection. Research [1] proves that LoRaWAN allows efficient and energy-efficient communication between connected devices and has wide coverage in the mine.

Research [6], [8] presents an environmental monitoring system using the LoRaWAN network. The study of [7] proved the reliability and scalability of this network in testing in a wide environment. In the study of [3], The edge-computing gateway offers significant cost, latency, and power consumption advantages to monitor the plant growth environment.

Research [26] concluded that LoRaWAN is well-suited for providing sensor coverage on a city scale where connectivity is an issue. In the article [27], [28], the system can transmit real-time air quality information over the Internet.

D. Characteristics of using LoRaWAN in IoT

The LoRaWAN characteristics discussed and proven in the research on LoRaWAN performance, as seen in Figure 8, include five characteristics of LoRaWAN usage factors in research on IoT.

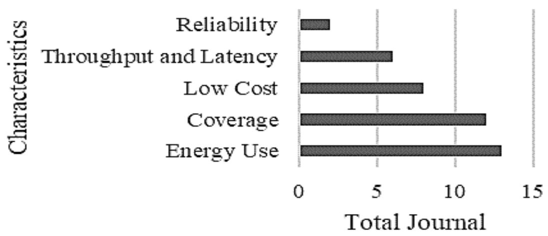

Figure 7. Characteristics of LoRaWAN in IoT Research

E. Research Agenda

The research agenda for LoRaWAN in IoT focuses on enhancing its performance in waste management, water leakage detection, environmental monitoring, and agriculture. Some sensors normally require wirelessly transporting large amounts of data (e.g., vibration sensors, cameras). With the advent of AI/ML capabilities on edge (on end devices), such use cases became possible even when using LoRaWAN connectivity.

The development of deep learning algorithms can be explored to analyze the geolocation coordinates of waste bins and create optimized truck routes to optimize waste collection. Artificial intelligence techniques, including machine learning, can also be investigated for early radiation detection in waste management, enabling timely mitigation measures.

Additionally, integrating artificial intelligence into IoT nodes aims to detect water leakages using neural network-based models and optimize water consumption through predictive models, facilitating smart irrigation and water conservation. Machine learning algorithms and statistical models can be utilized to analyze environmental data, producing accurate flood predictions that enhance the effectiveness of disaster management.

The research agenda extends to medical prognosis systems, leveraging AI to analyze patient data and provide personalized medical prognoses. Forecasting future environmental conditions and predicting air quality indexes using machine learning models contribute to proactive environmental planning.

Furthermore, AI and machine learning techniques are applied to prevent plant diseases, optimize fish farming processes, and enhance agricultural productivity.

Comparisons with NB-IoT technology are pursued to investigate the performance and cost-effectiveness of LoRaWAN. Potential future research could focus on investigating approaches to expand the communication range. This approach might encompass the exploration of advanced network planning techniques, the optimization of gateway placement, and the implementation of mesh networks. Additionally, researchers may incorporate alternative communication technologies, such as cellular IoT or satellite communication, into the system to improve its robustness and expand its coverage area.

The agenda also includes in-depth research on the effects of burying LoRaWAN devices at different depths underground, optimizing signal propagation and communication performance. By addressing these research areas, the aim is to advance the performance of LoRaWAN in IoT, improving waste management, water conservation, environmental monitoring, and agricultural practices, thereby contributing to sustainable and efficient resource utilization.

V. CONCLUSION

Twenty-five research articles on the performance of LoRaWAN in IoT were chosen following the defined inclusion and exclusion criteria. This literature review, also called a Systematic Literature Review (SLR), entails identifying, evaluating, and interpreting all accessible research evidence to address a predefined research question. Research on LoRaWAN performance in IoT has focused on several research areas, namely: the level of reliability of LoRaWAN networks in IoT applications, coverage and signal strength, efficiency in energy use, throughput and latency, and data security. LoRaWAN technology is used in various research and applications in agriculture, environment, air quality monitoring, energy management, and natural disaster monitoring. In research on LoRaWAN performance in IoT, five characteristics have been proven and become a factor in using LoRaWAN in IoT: low energy power usage, wide coverage, low cost, stable data transmission speed, and system reliability. However, not many have discussed its security, which can be a future research topic for other researchers. Based on the literature review, LoRaWAN has several characteristics that make it suitable for large-scale IoT applications.

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