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Optimising Connectivity and Energy: The Future of LoRaWAN Routing Protocols for Mobile IoT Applications

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Abstract: The proliferation of Internet of Things (IoT) applications has significantly increased the demand for communication protocols that are both resilient and energy-efficient. Among these, Low Power Wide Area Network (LPWAN) technologies - specifically Long-Range Wide Area Network (LoRaWAN) - offer long-distance wireless connectivity for IoT devices, characterized by their extended transmission range and minimal energy consumption. However, the mobility of IoT devices introduces challenges in optimizing energy efficiency. This study provides a comprehensive review of energy-efficient routing algorithms for LoRaWAN in mobile IoT applications. A systematic approach is employed, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, to identify, evaluate, and synthesize pertinent literature, offering an in-depth exploration of existing methodologies, their advantages and limitations, and potential avenues for future research. Key topics examined include AI-enhanced adaptive data rate (ADR) methods, coding schemes based on the Chinese Remainder Theorem (CRT), and processes utilizing Variable Order Hidden Markov Models (VHMM). These approaches have demonstrated improvements in packet delivery ratios (PDRs), latency reduction, and energy efficiency within mobile IoT contexts. Despite notable advancements, significant opportunities remain for enhancing scalability, developing hybrid solutions, applying these methodologies in real-world contexts, and implementing robust security protocols. This paper contributes valuable insights into the current landscape of energy-aware routing protocols for LoRaWAN in mobile IoT applications and outlines critical areas for future research aimed at achieving sustainable and efficient IoT networks.

Keywords: Energy-aware routing protocols; LoRaWAN; Mobile IoT; Review; Routing protocol.

1. INTRODUCTION

The Internet of Things (IoT) has emerged as a transformative paradigm, facilitating the interconnection of a diverse array of devices and systems by means of the internet [1]. This network of interconnected devices facilitates the collection, exchange, and analysis of data, driving innovations across various sectors, including healthcare, agriculture, transportation, and smart cities [2-5]. By incorporating mobile devices, mobile IoT expands the capabilities of traditional IoT, enabling more mobility and the interchange of data in real-time [6]. The ability to move or change position is of utmost importance for applications such as tracking assets, monitoring the environment, and managing logistics in an intelligent manner [7].

Long-Range Wide Area Network (LoRaWAN) is a prominent technology within the field of Low Power Wide Area Networks (LPWANs). It is specifically developed to provide long-distance communication while minimizing power usage [8]. According to [9], LoRaWAN is a service that runs on an open standard, which makes it highly adaptable and scalable for a wide variety of IoT applications. The architecture of the system enables a star-of-stars topology, in which gateways act as intermediaries for transmitting messages between end-devices and a central network server [10]. This structure facilitates the efficient transmission of data over long distances, up to several kilometers, even in challenging environments, and provides extensive coverage [2]. The significance of LoRaWAN resides in its capacity to provide a sustainable solution for IoT deployments that necessitate extended battery life and extensive coverage [8]. The low power consumption of IoT devices allows them to function for extended periods without requiring regular battery replacements, which makes them well-suited for remote and inaccessible locations [9]. In addition, the extensive communication range of LoRaWAN decreases the expenses related to setting up multiple gateways, thereby enabling cost-efficient IoT solutions [10].

The importance of LoRaWAN and energy-efficient IoT solutions is emphasized by current trends and data. The increasing interest in IoT technologies is a result of their widespread acceptance and dependence in numerous industries. Moreover, industry research and market analysts predict significant expansion in the IoT business, emphasizing the necessity for effective and adaptable communication protocols such as LoRaWAN. Statista's analysis predicts that the global number of IoT linked devices will surpass 32.1 billion by 2030, highlighting the extensive integration of IoT technology into daily life [11]. According to [12], the IoT has the potential to provide an economic impact ranging from $5.5 trillion to $12.6 trillion per year by 2030. This suggests that there is a significant opportunity for creating value using IoT technologies [12]. The IoT has emerged as a transformative paradigm, facilitating the interconnection of a diverse array of devices and systems by means of the internet [1]. This network of interconnected devices facilitates the collection, exchange, and analysis of data, driving innovations across various sectors, including healthcare, agriculture, transportation, and smart cities [2-5]. By incorporating mobile devices, mobile IoT expands the capabilities of traditional IoT, enabling more mobility and the interchange of data in real-time [6]. The ability to move or change position is of utmost importance for applications such as tracking assets, monitoring the environment, and managing logistics in an intelligent manner [7]. Google Trends data shows a consistent rise in the level of interest in the word "IoT" over the last five years as shown in Figure 1.

In order to acquire a more complete understanding of the problems and improvements in energy-efficient communication protocols for mobile IoT applications, it is of the utmost importance to perform a thorough analysis of the existing literature [13]. Maintaining energy efficiency in mobile IoT systems is a particular problem due to their dynamic nature, which is typified by frequent changes in network topology and device mobility [14]. This study seeks to address this deficiency by conducting a comprehensive assessment and synthesis of existing research on energy-conscious routing methods for LoRaWAN in mobile IoT applications [15]. By engaging in this process, it offers significant knowledge about current solutions, recognizes persistent difficulties, and proposes avenues for future investigation [16].

This study is guided by the following research questions: What challenges and limitations are faced when using LoRaWAN in mobile IoT applications? What is the existing energy-aware routing protocols for LoRaWAN in mobile IoT applications, and how do they address the challenges of energy efficiency? What are the key challenges and limitations associated with these protocols? What alternative approaches exist for achieving energy efficiency in mobile IoT? What future research directions are suggested by the current literature? By addressing these research questions, this paper aims to contribute to the ongoing discourse on optimizing energy consumption in IoT networks, thereby supporting the sustainable and efficient deployment of IoT technologies.

1.1. Terminology and Key Concepts

To facilitate the understanding of technical concepts discussed in this review, Table 1 presents the key terminology and acronyms used throughout this paper. These definitions provide a foundation for the detailed discussion of LoRaWAN routing protocols and mobile IoT applications that follow.

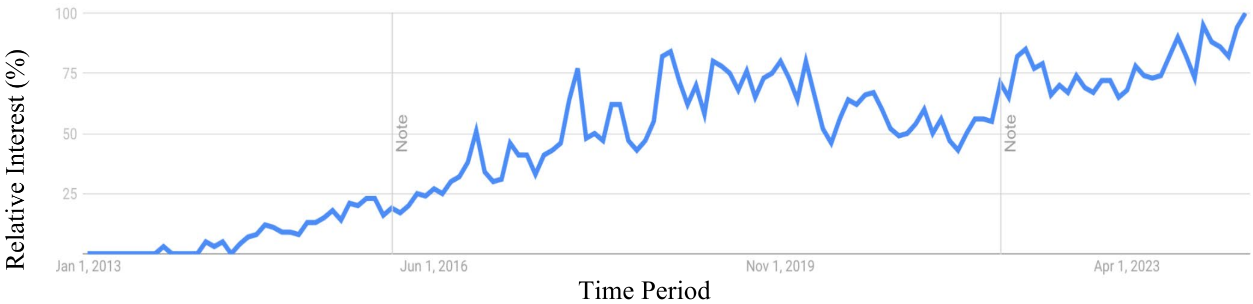

Figure 1. Google trends data in the term of "IoT".

Table 1. Key Terminology and acronyms.

Acronym	Term	Definition
ACK	Acknowledgment	Control message confirming successful packet reception
ADR	Adaptive Data Rate	Mechanism that optimizes data rates, transmit power, and frequency channels according to network conditions
AI-ERA	Artificial Intelligence-Empowered Resource Allocation	Framework using deep neural networks to assign spreading factors for uplink transmissions
CRT	Chinese Remainder Theorem	Mathematical concept used in coding schemes for transmitting redundant data fragments
CSS	Chirp Spread Spectrum	Radio modulation technique used in LoRa for reliable long-range communication
DaRe	Data Recovery Framework	System combining convolutional and fountain code-based application layer coding
DNN	Deep Neural Network	Machine learning model used for optimizing network parameters
E-ADR	Enhanced ADR	Technique that dynamically adjusts transmission parameters based on mobile device position
ECC	Elliptic Curve Cryptography	Cryptographic algorithm used in secure roaming protocols

ED	End Device	Sensor or actuator device in a LoRaWAN network that collects/generates data
FANET	Flying Ad Hoc Network	Network architecture for aerial IoT applications using mobile nodes
GPS	Global Positioning System	Satellite-based navigation system used for device localization
GSM	Global System for Mobile Communications	Standard for cellular communications
GW	Gateway	Intermediary device that relays messages between end devices and network server
HBEE	Hierarchy-Based Energy-Efficient Routing	Protocol incorporating concurrent transmission and multi-path strategies
IIoT	Industrial Internet of Things	IoT applications in industrial settings
IoT	Internet of Things	Network of interconnected devices that collect and exchange data
ISM	Industrial, Scientific, and Medical	Radio bands reserved for industrial, scientific, and medical purposes
LGRP	LoRaWAN Geographic Routing Protocol	Routing protocol using neighbor tables and multi-criteria metrics
LoRa	Long Range	Physical layer wireless radio modulation technology
LoRaWAN	Long Range Wide Area Network	Network protocol built on top of LoRa technology
LPADA	Low-Power AES Data Encryption Architecture	Energy-efficient encryption system for secure communications
LPWAN	Low Power Wide Area Network	Wireless telecommunication network designed for long range communications at low bit rate
MAC	Medium Access Control	Protocol layer managing device access to shared communication medium
MEMS	Micro-Electro-Mechanical Systems	Technology used in inertial sensors
ML	Machine Learning	Artificial intelligence techniques for network optimization
NB-IoT	Narrowband Internet of Things	Cellular-based low power wide area network technology
NRH	Next-Ring-Hop	Routing technique in variable-hop protocols
NS	Network Server	Central server that manages the LoRaWAN network
PDR	Packet Delivery Ratio	Ratio of successfully delivered packets to total transmitted packets
PLR	Packet Loss Rate	Percentage of packets that fail to reach their destination
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses	Methodology guidelines for systematic reviews
QoS	Quality of Service	Measure of network performance and reliability
RF	Radio Frequency	Electromagnetic waves used for wireless communication
SF	Spreading Factor	Parameter determining trade-off between range and data rate
SNR	Signal-to-Noise Ratio	Measure of signal quality relative to background noise
UAV	Unmanned Aerial Vehicle	Aircraft without human pilot aboard used in mobile IoT applications
VH	Variable-Hop	Routing methodology incorporating multiple hop strategies
VHMM	Variable Order Hidden Markov Model	Mathematical model used for predicting node trajectories
WSMST	Weight Superposable Minimum Spanning Tree	Algorithm for identifying optimal relay nodes

1.2. Comparison with Existing Reviews

Although several extensive studies of LoRaWAN technology are present in the literature, our study provides unique additions that differentiate it from prior research. By doing an organized assessment in accordance with Systematic Reviews and Meta-Analyses (PRISMA) criteria [17], our research offers a thorough analysis of energy-efficient routing algorithms specifically designed for mobile IoT applications, a domain that has garnered insufficient focused attention in the current literature.

Studies examining cross-layer optimization approaches and protocol developments were conducted by [18, 19], however their focus on mobile IoT applications was tangential. In 2024, the study examined the incorporation of artificial intelligence and machine learning for the optimization of LoRaWAN, emphasizing methodologies such as deep learning, reinforcement learning, and clustering to improve network efficiency. Although these studies are significant, they did not directly tackle the distinct issues of mobile IoT contexts.

The 2023 landscape of LoRaWAN evaluations exhibits a variety of focal points. Research by [16, 21] examined scaling challenges and performance enhancement in particular domains, whereas investigations by [22, 23] explored the characteristics of LoRaWAN technology in automated systems, with an emphasis on smart cities, industrial automation, and agricultural. Significant contributions were made by [24] through investigating machine learning techniques to improve LoRaWAN performance, however its focus on mobile IoT applications was marginal. Furthermore, valuable insights into security vulnerabilities and systematic mitigation measures were provided by [25], while it did not specifically address energy efficiency considerations.

Three significant reviews emerged in 2022, each with distinct focal points. A comprehensive review of LPWANs was presented by [27], emphasizing LoRa/LoRaWAN systems and current cloud-based methodologies for data management. The architecture and performance optimization of LoRaWAN was analyzed by [28], whereas examination of diverse routing protocols and network architectures, especially hierarchical algorithms, was conducted by [29]. Significant contributions were made by [13] through examining communication protocols with a focus on energy efficiency, whereas [30] concentrated on physical layer attacks and their respective responses.

Our review differentiates itself from existing studies in numerous significant respects. While works such as [16, 21] focused on scaling challenges and performance enhancement in particular sectors, our research offers an extensive examination of energy-efficient routing algorithms tailored for mobile IoT environments. In contrast to [38], which examined the problems of LoRaWAN technology in ultra-dense network environments without especially focusing on mobile IoT or energy efficiency, our study directly addresses these critical elements.

The analysis of energy efficiency in LoRaWAN has been conducted differently in several reviews. Research conducted by [24] examined machine learning methodologies for enhancing energy usage and investigations by [29] analyzed energy efficiencies among routing algorithms, while our research offers a comprehensive investigation of energy-efficient routing protocols tailored for mobile IoT applications. This expands on the research of [13, 32], providing a more focused examination for mobile contexts.

Moreover, our methodical methodology, adhering to PRISMA principles, guarantees a rigorous sound analysis that may be replicated by future researchers. This differentiates our study from assessments such as [22], which concentrated on testing procedures without explicitly addressing mobile IoT applications or energy efficiency. Our methodology also enhances security-centric evaluations such as [25, 26, 31] by investigating the implementation of energy-efficient routing protocols that uphold security and dependability in mobile IoT environments.

Our review's comprehensive nature is particularly important as it synthesizes current research trends, difficulties, and future directions in energy-efficient routing for mobile IoT applications utilizing LoRaWAN. This comprehensive viewpoint offers academic researchers and industry professionals practical insights creating and executing energy-efficient solutions in mobile IoT implementations. Table 2 delineates these principal distinctions, emphasizing how our review's concentrated methodology on energy-efficient routing in mobile IoT applications addresses a significant void in the current literature, while augmenting and enhancing the noteworthy contributions of prior evaluations in the domain.

Table 2. Comparison between existing LoRaWAN reviews.

Reference	Focus area	Methodology	Mobile IoT coverage	Energy efficiency analysis
Our Review	Energy-efficient routing algorithms specifically for mobile IoT applications	Systematic review adhering to PRISMA guidelines for rigorous analysis	Comprehensive analysis of mobile IoT applications, addressing dynamic environments	In-depth exploration of energy-efficient routing protocols and their impact on mobile IoT
[18] (2024)	Advanced cross-layer optimization techniques for LoRaWAN in IoT applications	Categorization of cross-layer approaches, performance analysis, and bibliometric analysis	Discusses the impact of cross-layer optimization on LoRaWAN efficiency, indirectly covering mobile IoT	Emphasizes energy utilization efficiency in LoRaWAN, addressing distance coverage challenges
[19] (2024)	Review of LoRaWAN protocols in IoT, focusing on challenges, innovations, and future directions	Comprehensive review of LoRaWAN's architecture, technical features, and recent innovations to address challenges	Highlights LoRaWAN's long-range communication capabilities, suitable for large-scale IoT deployments	Discusses energy constraints and proposes solutions like adaptive data rates and energy optimization schemes to enhance efficiency
[20] (2024)	Integration of AI and ML in optimizing LoRaWAN for energy efficiency and performance	Systematic literature review using PRISMA model, analysis of ML and AI techniques like DL, RL, and clustering for optimization	Discusses LoRaWAN's application in large-scale IoT, including urban and industrial environments	Focuses on reducing energy consumption through ML techniques like K-means clustering, SVR, and DNN to enhance battery life and network efficiency
[16] (2023)	Specifically addresses the scalability issues of LoRaWAN in massive IoT deployments, highlighting the	Systematic literature review approach, classifying and analyzing studies related to scalable	Focuses on LoRaWAN's potential for supporting massive IoT applications, indirectly addressing mobile IoT coverage	Examines energy efficiency in the context of LoRaWAN's scalability, discussing solutions to improve energy utilization in dense network environments

	challenges and potential solutions	LoRaWAN deployment	through scalability solutions	
[21] (2023)	Specific focus on LoRaWAN technology, its architecture, and performance optimization, particularly in sectors like agriculture, health, and environmental monitoring	Systematic literature review approach, classifying and analyzing studies related to scalable LoRaWAN deployment	Focuses on LoRaWAN's potential for supporting massive IoT applications, indirectly addressing mobile IoT coverage through scalability solutions	Examines energy efficiency in the context of LoRaWAN's scalability, discussing solutions to improve energy utilization in dense network environments
[22] (2023)	Testing and evaluation methodologies in LoRa and LoRaWAN-based networks in IoT	Classification and unified view of test parameters and evaluation methodologies	Not specifically addressed	Not specifically addressed
[23] (2023)	Investigation of LoRaWAN technology features and applications in automatic systems, focusing on smart cities, industrial automation, and agriculture	Comprehensive review, empirical analysis, and case studies to evaluate real-world performance	Highlights LoRaWAN's long-range communication capability, suitable for wide coverage in urban and rural settings	Emphasizes LoRaWAN's low power consumption, enabling extended operation of IoT devices without frequent battery replacements
[24] (2023)	Enhancing LoRaWAN performance using machine learning (ML) techniques	Survey of ML methods, including supervised and reinforcement learning, for resource management and optimization	Discusses ML applications for improving network capacity and reliability, indirectly supporting mobile IoT coverage	Focuses on optimizing energy consumption through ML-driven resource management and SF allocation
[25] (2023)	Survey of LoRaWAN security vulnerabilities, attacks, and systematic mitigation strategies	Proposes a novel methodology for creating evolvable surveys to analyze critical security concepts over time	Focuses on LoRaWAN's application in urban environments, industrial settings, and critical infrastructures	Not specifically addressed; the focus is on security rather than energy efficiency
[26] (2022)	Specific focus on LoRaWAN security issues and key management models	Analysis of cryptographic techniques and security models for key management	Not specifically addressed	Discussion on reducing battery consumption through asynchronous communication models
[27] (2022)	In-depth analysis of LPWANs with a focus on LoRa/LoRaWAN systems and their potential	Comprehensive study including recent cloud-based and open-source approaches for data management	Not specifically addressed	Analysis of energy-efficient and cost-effective technologies in LPWANs
[28] (2022)	Specific focus on LoRaWAN technology, its architecture, and performance optimization	Classification of studies into categories such as power consumption and network scalability	Discussion on LoRaWAN's long-range communication and its potential for IoT applications	Examination of LoRaWAN's low energy consumption and strategies for improving power efficiency
[29] (2022)	Examining various routing protocols and network architectures in LoRaWAN, particularly	Comparative study of hierarchical algorithms, considering criteria and metrics such as	Discusses the impact of environmental constraints like obstacles and interferences on	Compare energy-efficiencies between routing algorithms

	hierarchical algorithms, to enhance network performance and energy efficiency	environmental constraints, to ensure long network lifetime and balanced energy consumption	network performance, indirectly addressing mobile IoT coverage	
[13] (2022)	Investigation of LoRaWAN communication protocols with an emphasis on energy efficiency	Comprehensive literature review and categorization of protocols into multi-access, routing, and energy-efficient protocols	Discusses the challenges of achieving extensive coverage in dense networks and urban areas	Focuses on optimizing energy consumption through protocol design, resource allocation, and dynamic state transitions
[30] (2022)	Review of physical layer-based attacks on LoRaWAN and corresponding countermeasures	Analysis of various attack types and countermeasures, including replay and jamming detection, and secret key agreement methods	Not specifically addressed	Discusses energy consumption impacts of attacks like worm-hole and jamming, which can force higher SF settings and increase energy use
[31] (2021)	Security vulnerabilities and enhancements in LoRaWAN, including replay attacks, key management, and secure communication	Various methodologies including experimental validation, simulation models, and systematic reviews	Limited focus on mobile IoT coverage, primarily addressing security aspects of stationary IoT networks	Discuss energy attacks and their impact on power consumption, with some studies focusing on energy efficiency improvements
[32] (2021)	Optimization of Adaptive Data Rate (ADR) schemes in LoRaWAN for improved energy efficiency and throughput	Review of constrained optimization techniques, including computational complexity analysis and comparison of existing ADR schemes	Focuses on optimizing transmission parameters like bandwidth, spreading factors, and transmission power to enhance coverage and capacity	Emphasizes minimizing energy consumption through efficient ADR algorithms, with specific attention to energy usage per end device
[33] (2020)	The focus is on the viability of confirmed traffic in LoRaWAN, addressing challenges like duty cycle restrictions, ACKs, and network congestion	Various methodologies including surveys, simulations, and experimental validations to assess LoRaWAN's performance and scalability	Limited discussion on mobile IoT coverage, with more emphasis on stationary network performance and scalability	Examine energy consumption in the context of confirmed traffic and propose solutions like aggregated ACKs to improve energy efficiency
[3] (2020)	Review and classification of multi-hop communication in LoRaWAN mesh networks	Comparative analysis and classification of multi-hop proposals, considering technical characteristics and network topologies	Discusses multi-hop mechanisms to extend coverage, using intermediate nodes for message forwarding	Proposes energy-efficient multi-hop communication solutions that improve energy consumption
[34] (2020)	Security vulnerabilities, attacks, and mitigation techniques in LoRaWAN	Review and analysis of security issues, including key management and cryptography, with proposed mitigation strategies	Discusses LoRaWAN's application in IoT, highlighting its use in mobile network operators and IoT domains	Addresses energy efficiency through solutions like Low-Power AES Data Encryption Architecture (LPADA) to reduce power consumption
[35] (2020)	Performance analysis of LoRaWAN in industrial scenarios, focusing on	Evaluation of LoRaWAN's robustness in industrial	Highlights LoRaWAN's capability to create proprietary networks,	Emphasizes LoRaWAN's high energy efficiency, making it appealing for monitoring use cases in IIoT

	interference, signal attenuation, and reliability	environments with frequent packet generation and controlled latency requirements	offering full control over infrastructure, suitable for IIoT applications	
[36] (2020)	Systematic review of LoRaWAN applications across various domains such as smart cities, smart grids, and health	Systematic review of 71 application cases, focusing on deployment challenges and network protocol characteristics	Highlights LoRaWAN's wide area coverage suitable for IoT applications in diverse environments	Emphasizes LoRa's low energy consumption, making it a viable option for IoT scenarios
[37] (2020)	Routing protocols in LoRaWAN, focusing on tree topologies and flooding methods	Survey of existing routing algorithms, experimental settings analysis, and evaluation of packet delivery ratio (PDR)	Discuss scalability and performance in realistic settings with hardware nodes, highlighting challenges in large networks	Highlights the need for energy-saving mechanisms like sleeping and parent rotation to enhance network lifetime
[38] (2020)	Review of LoRaWAN technology and its challenges in ultra-dense network scenarios	Literature review of LoRaWAN protocol advancements and evaluation of its application in ultra-dense networks	Not specifically addressed	Not specifically addressed
[39] (2019)	Overview of LoRaWAN architecture, protocol, and technologies	Survey and analysis of LoRaWAN features and state-of-the-art studies	Discussion on LoRaWAN's long-range communication and coverage potential	Examination of LoRaWAN's low energy consumption and potential for solar energy use

2. REVIEW METHODOLOGY

Our research examines energy-aware routing protocols in LoRaWAN mobile IoT applications through a systematic and structured approach. To ensure comprehensive coverage, we followed the Preferred Reporting Items for PRISMA framework, which provides clear guidelines for conducting thorough literature reviews. We began by searching four major academic databases: IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar. Our search focused on papers published between 2019 and 2024, using specific keyword combinations that linked energy efficiency, routing protocols, and LoRaWAN in mobile applications. This recent timeframe ensures the analysis captures current technological developments while maintaining historical context.

The review process involved three main filtering stages. Our initial search identified 545 papers, from which we first removed 123 duplicates. The remaining 422 papers underwent basic eligibility screening, where we checked for English language, full text availability, and peer review status. Finally, we conducted a detailed assessment of each paper's relevance to our research questions, resulting in a final selection of 92 papers for in-depth analysis. Figure 2 presents the PRISMA flow diagram that illustrates this systematic selection process, showing the number of papers considered and eliminated at each stage of the review. The diagram clearly demonstrates our rigorous approach to paper selection and helps ensure the reproducibility of our methodology.

For each selected paper, we examined several key aspects: the main objectives, methodology, findings, and performance metrics. We paid particular attention to energy efficiency approaches, routing protocol designs, and mobile application considerations. To organize this information systematically, we created comparison matrices that helped identify patterns in successful approaches and gaps in current research.

The evaluation of selected papers followed a comprehensive set of criteria to ensure the quality and relevance of our analysis. First, we examined each paper's direct relevance to energy-aware routing in LoRaWAN, ensuring that the research specifically addressed our core focus area. Second, we assessed the paper's coverage of mobile IoT applications, as mobility presents unique challenges in routing protocol design. Third, we evaluated the quality of research methodology employed in each study, looking for robust experimental designs and clear analytical approaches. Fourth, we carefully considered the clarity and completeness of results and findings, ensuring that conclusions were well-supported by evidence. Finally, we examined each paper's treatment of practical implementation considerations, as real-world applicability is crucial for advancing the field.

This structured approach revealed important trends in the field, highlighted areas needing further research, and identified promising future directions. Throughout our analysis, we maintained a focus on practical applications and real-world implementation challenges, ensuring our findings would be valuable for both researchers and practitioners. This methodology enabled us to provide a comprehensive overview of current developments while identifying areas where further research could make significant contributions to the field.

3. DATA EXTRACTION AND SYNTHESIS

In this section, we detail the process of data extraction and synthesis utilised in this study. The data extraction phase involved meticulously summarising critical information from each selected study. This included outlining the study objectives, the methodologies employed, the key findings, the limitations identified, and the proposed future work. The synthesis process aimed to consolidate this information to provide a comprehensive overview of the various approaches to energy-aware routing in LoRaWAN within the context of mobile IoT applications.

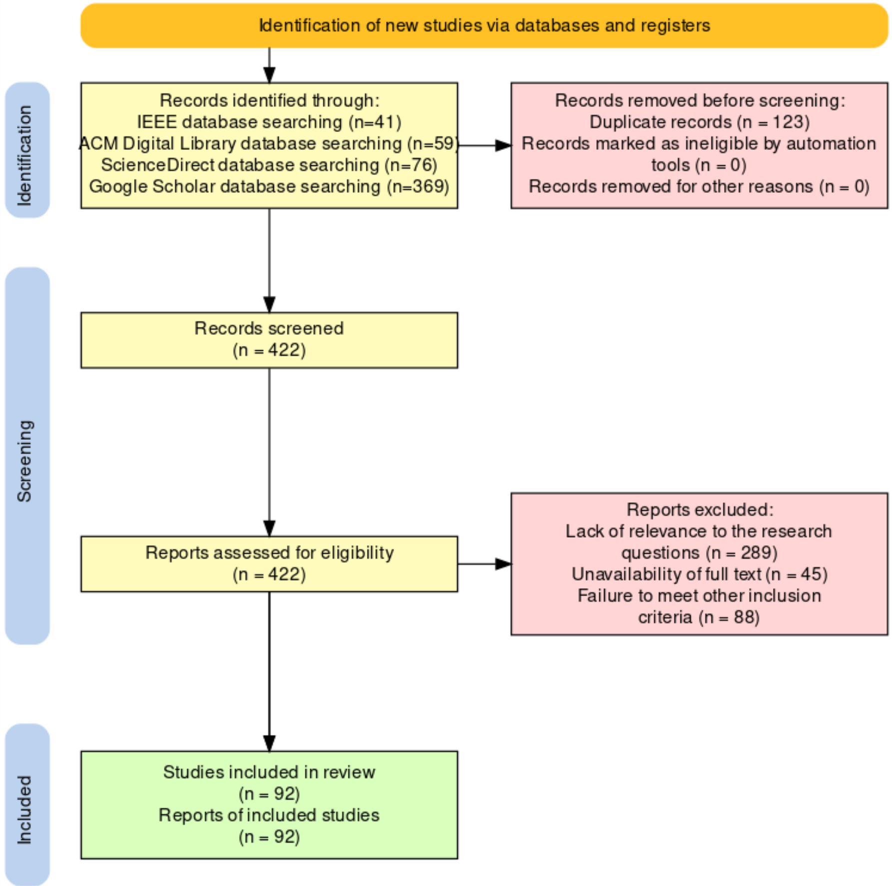

Figure 2. PRISMA flow diagram.

3.1. LoRaWAN Protocol in Mobile IoT Applications

LoRaWAN, a cloud-based MAC layer networking protocol created and maintained by the LoRa Alliance, is thoroughly described in the reviewed literature [28]. This protocol functions inside the unlicensed ISM bands and is specifically engineered for wireless connections of battery-operated items to the Internet. It caters to crucial IoT needs such as two-way communication, end-to-end security, mobility, and localization [13]. LoRaWAN is renowned for its capacity to facilitate long-distance communication connections, rendering it well-suited for a wide range of IoT applications, including industrial sensor communications, smart cities, smart buildings, and remote environmental monitoring. Having this feature is crucial for providing dependable communication across vast distances, which is a notable benefit for implementing IoT solutions in extensive or remote locations [6]. The LoRaWAN architecture consists of three primary device types: ED, Gateways (GW), and Network Servers (NS). EDs produce uplink traffic to send to GW or receive downlink traffic from the NS. GW decodes LoRa communication and relay it between the NS and the ED, with the ability to monitor many channels at the same time and manage a large number of ED. The NS serves as the central backend, gathering data from all ED and handling it on an application server [28]. Figure 3 provides a visual representation of the LoRaWAN architecture, detailing the communication flow between end devices, gateways, and the network server.

LoRaWAN categorises communication classes into three categories to accommodate various application requirements. Class A provides rudimentary bidirectional communication, with each transmission from the device followed by two brief intervals for receiving messages from the network. Class B introduces scheduled receive slots to increase the frequency of downlink communication. On the other hand, Class C offers constantly open receive windows, which are suited for applications that require real-time communication but consume more energy [40]. Figure 4 provides a visual representation of the different LoRaWAN classes.

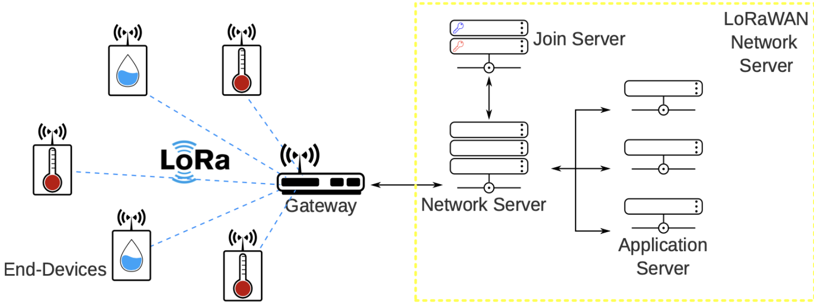

Figure 3. LoRaWAN architecture [3].

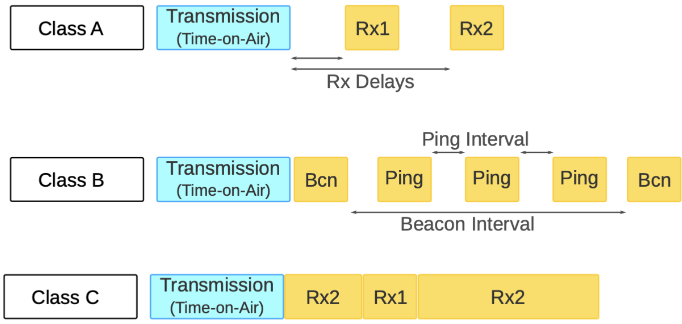

Figure 4. LoRaWAN classes [3].

The literature also highlighted LoRaWAN's advantages over competing LPWAN technologies. LoRaWAN offers significant benefits due to its open standard and versatile nature. LoRaWAN is designed as an open standard network protocol, enabling the establishment of private networks without relying on third-party infrastructure. The flexibility of this technology provides a notable benefit compared to proprietary technologies such as SigFox and cellular-based LPWANs. These proprietary technologies generally necessitate subscription fees and are under the control of mobile carriers [41]. In addition, LoRaWAN operates in unlicensed ISM bands, which means there is no need to obtain expensive spectrum licences. This makes it a more cost-effective option compared to licenced technologies such as NB-IoT and LTE-M, which require ongoing subscription fees and are subject to the conditions set by mobile operators [28]. LoRaWAN offers significant benefits in terms of its extensive range and wide coverage capabilities. LoRaWAN offers a wide range and great coverage, making it well-suited for applications in rural and isolated areas. It is capable of attaining communication distances of up to 10 km in urban environments and even greater distances in rural regions, which is on par with or superior to other LPWAN technologies [28, 42]. The vast coverage provided by LoRaWAN is enhanced by its low power consumption, allowing IoT devices to have long-lasting battery life. This is especially beneficial for situations where devices are placed in remote locations, and it is not feasible to change the batteries [13, 41]. Scalability is another LoRaWAN benefit. The protocol has the capability to accommodate a substantial quantity of ED per gateway, which enhances its scalability for extensive IoT installations. Having the ability to link thousands of devices is a crucial benefit for applications like smart cities and industrial IoT [10]. In addition, LoRaWAN has inherent security measures, including AES-128 encryption, to guarantee the secure transmission of data. The security level provided is similar to that of cellular-based LPWANs, which gives it a notable advantage over certain other technologies that operate in unlicensed frequency bands [43]. The Adaptive Data Rate (ADR) mechanism of LoRaWAN optimizes data rates, transmission power, and frequency according to network conditions, thereby improving energy efficiency and network performance. This property is especially advantageous in dynamic contexts characterized by fluctuating network conditions [16]. Moreover, the utilization of Chirp Spread Spectrum (CSS) modulation in LoRaWAN offers exceptional resistance to interference, multipath, and Doppler effects. LoRaWAN is a reliable option for locations that experience significant amounts of interference [44].

Several studies have conducted comparisons between LoRaWAN and other LPWAN technologies such as SigFox, NB-IoT, and LTE-M in the context of mobile IoT. These studies have focused on different elements such as coverage, energy efficiency, cost, and scalability. The unique characteristics of LoRaWAN, including its wide communication range, little battery consumption, capacity to handle huge data volumes, flexibility in data rates, compatibility with mobile devices, and robust security measures, make it an excellent choice for mobile IoT applications. The characteristics of LoRaWAN enable reliable, efficient, and secure communication in diverse and dynamic environments, underscoring its suitability for a wide range of IoT applications. Table 3 presents a summary of the comparison between LoRaWAN and other LPWAN technologies within the Mobile IoT environment.

Table 3. Comparison between LoRaWAN and other LPWAN.

Metric	LoRaWAN	SigFox	NB-IoT	LTE-M
Coverage Range [40][45]	1-20 km	10-40 km	Up to 10 km	Up to 5 km
Frequency Band [16][40]	Unlicensed ISM bands	Unlicensed ISM bands	Licensed LTE frequency bands	Licensed LTE frequency bands
Battery Life [4][16]	About 10 years	About 10 years	About 10 years	About 10 years
Energy Efficiency [24][28][40][45]	High, due to low-power consumption and sleep modes	High, but less flexible than LoRaWAN	Moderate, higher energy consumption due to complex modulation	Moderate, higher energy consumption due to complex modulation
Deployment Cost [16][46]	Low, due to unlicensed spectrum and private network options	Low, due to unlicensed spectrum	High, due to licensed spectrum and operator fees	High, due to licensed spectrum and operator fees
Scalability [40][45][47]	High, but can face congestion issues in dense deployments	Moderate, limited by fixed data rates	High, supports massive IoT deployments	High, supports massive IoT deployments
Data Rate [48][49]	Low, suitable for small data packets	Very low, suitable for small data packets	Moderate, supports higher data rates	High, supports higher data rates
Quality of Service (QoS) [2][47]	Moderate, suitable for delay-tolerant applications	Low, limited QoS provisions	High, better QoS provisions	High, better QoS provisions
Mobility Support [24][48]	Moderate, with recent enhancements for roaming	Low, primarily designed for static applications	High, integrated with cellular networks	High, integrated with cellular networks
Security [4][16]	Moderate, with ongoing improvements	Moderate, with basic security features	High, due to cellular network security protocols	High, due to cellular network security protocols

3.2. LoRaWAN in Mobile IoT

The LoRaWAN technology has emerged as a promising solution for mobile IoT applications, providing a distinctive set of benefits that are particularly well-suited to the requirements of mobile scenarios. One of its main advantages is its capacity to offer long-range communication capabilities. Research studies by [50, 51] reported that the technology is good for city-scale IoT applications since it supports communication over 2–5 km in urban areas and up to 15 km in suburban settings. This broad coverage facilitates a variety of applications, with demonstrations by [50] showing how the communication range was utilised for applications that necessitate the maximum distance between Unmanned Aerial Vehicle (UAV) nodes. However, it gets harder to maintain dependable connectivity as mobile devices travel through various locations. Studies conducted by [51] indicate that changes in the microenvironment and urban landscape have a significant impact on LoRa link performance, resulting in dynamic link behaviour. Devices may experience frame loss rates of up to 70% as they distance themselves from GW due to this variability [10]. Research findings in [52] further exacerbate these issues by highlighting the absence of effective retransmission schemes in the basic configuration, notably in dynamic environments.

Another significant benefit of LoRaWAN is its ultra-low energy consumption design, which renders it an optimal choice for battery-operated devices in a variety of mobile IoT scenarios [52]. This feature is very important for making IoT devices last longer, especially in situations where replacing batteries often is hard to do or costs a lot of money. Unfortunately, the current ADR methods can make LoRaWAN less energy-efficient when used in mobile settings. In dynamic situations, these methods might generate excessive energy consumption due to recurrent packet retransmissions [52]. Although the traditional ADR method works well in static circumstances, it is slow to adjust to the dynamic conditions of mobile apps, which leads to resource consumption and performance degradation [52, 53].

Another notable benefit of LoRaWAN is its scalability, which allows it to support a high number of ED in dense IoT environments [52]. For large-scale IoT deployments in many fields, this trait along with LoRaWAN's long-range capabilities makes it a good choice. Nonetheless, there are particular challenges in controlling this scalability in mobile situations. Managing a large number of mobile devices makes it more difficult to coordinate roaming between home and visiting networks [43]. In addition, a major problem in mobile IoT applications with high device density is maintaining consistent Quality of Service (QoS) while minimising energy consumption [54].

The adaptability of LoRaWAN in terms of parameters such as bandwidth, transmission capacity, and spreading factor (SF) is a significant advantage. This flexibility allows for a balance between data rate, coverage, and energy use, meeting the needs of a wide range of IoT uses [54]. Recent improvements, such as the VHMM-based E-ADR mechanism, anticipate making changes in real time based on changes in signal quality [54]. Nevertheless, the implementation of adaptive mechanisms that are effective in mobile environments continues to be a challenge. Research findings by [54] indicate that conventional

ADR methodologies encounter communication inefficiencies as a result of the presence of unknown or random mobility patterns. Due to mobility, it is difficult to achieve fine-grained measurements, resulting in a trade-off between measurement granularity and adaptability [51]. Furthermore, achieving the least delay and packet loss criteria is a challenge for applications that demand real-time data transmission, such as intelligent transportation systems (ITS) or bicycle accident detection [55, 56].

LoRaWAN has the advantage of minimal deployment costs, making it an appealing option for large-scale IoT installations [24]. The development of affordable gateway prototypes employing this technology has further enhanced LoRa technology's accessibility and promise for prolonged computational runtime in many applications [1]. In mobile scenarios, however, the requirement for secure and resilient deployments introduces further complications. Security risks, including vulnerabilities to surveillance, replay, and impersonation attacks from the plain text transmission of session information, must be mitigated [43]. Moreover, managing data from various automotive IoT devices presents difficulties in ensuring accurate data representation in the context of vehicle mobility as well as privacy issues [1].

In summary, long-range communication, energy efficiency, scalability, flexibility in parameter change, and cost-effectiveness are just a few of the many benefits that LoRaWAN offers for mobile IoT applications. These advantages are, however, outweighed by the considerable difficulties in managing device density, responding quickly to changes in signal quality, keeping dependable connections in dynamic environments, protecting security and privacy, and satisfying the real-time needs of specific applications. Addressing these difficulties is critical to unlocking LoRaWAN's full potential in mobile IoT applications. Building on the strengths of LoRaWAN while reducing its weaknesses in mobile IoT deployments should be the main focus of future research and development. This will include making adaptive mechanisms better, security protocols better, and performance better in a variety of mobile settings.

3.3. Related Works on LoRaWAN in Mobile IoT

3.3.1 Improving Adaptive Data Rate (ADR) Algorithms

The standard ADR methods in LoRaWAN work well in static situations but face significant challenges when devices are moving. These issues primarily arise from rapidly changing channel conditions as devices move, resulting in poor SF assignments, increased packet loss, and wasteful energy consumption. Various studies have suggested innovative solutions to resolve these challenges, though each approach presents its own set of advantages and limitations.

Recent advancements in machine learning applications for LoRaWAN have demonstrated promising results in addressing these mobility-related challenges. The AI-ERA (Artificial Intelligence-Empowered Resource Allocation) framework, introduced by [52], represents a significant step forward in addressing high packet loss due to incorrect SF assignments in dynamic environments. This framework employs a deep neural network (DNN) model to assign efficient SFs for uplink transmissions proactively, aiming to predict and adapt to changing conditions faster than traditional methods. When implemented through NS-3 simulation, AI-ERA demonstrated remarkable improvements, achieving a 32% increase in Packet Success Ratio (PSR) in static scenarios and 28% in mobility scenarios compared to conventional ADR methods. However, critical examination reveals that this improvement comes at the cost of increased computational complexity, potentially limiting its applicability in resource-constrained devices. The framework's reliance on deep neural networks, while effective in controlled environments, may face challenges in highly dynamic mobile scenarios where training data rapidly becomes obsolete.

Addressing similar challenges through a different approach, [54] introduced the Enhanced ADR (E-ADR) technique. This mechanism was developed to address the high packet loss rates (PLR) that occur when mobile nodes encounter rapidly changing radio channel conditions. E-ADR dynamically adjusts transmission parameters based on mobile device position and trajectory, incorporating a counter for uplink transmission failures to improve radio coverage. Testing in a testbed setting utilizing Waspmote SX1272 devices demonstrated improved network performance through reduced energy consumption and packet loss. However, the approach shows limitations in urban environments with complex RF characteristics, and its performance notably decreases in areas with high multipath interference. Enhancement on the Waspmote SX1272 platform in a smart farm scenario achieved 87% accuracy in forecasting node trajectories, resulting in substantial improvements in packet loss and energy efficiency [57]. The comparative analysis between VHMM-based E-ADR and previous approaches demonstrates its superior adaptation to mobility patterns, though critical analysis reveals that this accuracy significantly decreases in dense urban environments, and the energy cost of maintaining the predictive model must be carefully balanced against the energy savings it provides.

The evolution from traditional ADR methods through AI-ERA to VHMM-based solutions represents a progressive improvement in handling mobile LoRaWAN scenarios, with each iteration addressing limitations of previous approaches whilst introducing new considerations for practical implementation. These advancements demonstrate the potential of machine learning in addressing complex mobile IoT challenges, though common challenges persist across all approaches when deployed in demanding urban environments.

3.3.2 Energy Efficiency and Data Transmission

Mobile IoT applications present unique challenges in balancing energy efficiency and data quality. Key concerns include high frame loss rates caused by fluctuating distances between mobile nodes and gateways, increased energy consumption from repeated retransmissions, and the necessity for effective data retrieval without compromising battery life. Recent research has produced several innovative approaches to address these challenges, each offering distinct advantages and trade-offs.

The DaRe (Data Recovery) framework, proposed by [10], represents a significant advancement in addressing energy-efficient data recovery in basic LoRaWAN deployments. This is particularly crucial given that frame loss rates can reach up to 70% as devices move away from gateways. DaRe's innovative approach combines convolutional and fountain code-based application layer coding, implementing an encoder in the LoRaWAN end-device and a decoder on the application server. Quantitative analysis demonstrates impressive results: a 99% data recovery ratio with a code rate of 1/2, along with a 21% improvement in data recovery while reducing energy usage by up to 42% for small data units. However, critical examination reveals performance variations under different conditions. While DaRe excels in ideal channel conditions, its effectiveness diminishes significantly in environments with high multipath interference - a common characteristic of urban IoT deployments. The framework's energy overhead for maintaining redundant data paths, though not fully addressed in the original analysis, represents a crucial consideration for real-world implementations.

In contrast, the CRT-LoRa framework proposed by [53] takes a different approach, focusing on packet loss reduction through a coding technique based on the Chinese Remainder Theorem (CRT). This methodology specifically targets three key challenges: rapid changes in node distance from the sink, inefficiencies of traditional ADR methods in mobile scenarios, and latency requirements in data transmission. The framework's implementation of CRT-based coding for transmitting redundant fragments showed superior performance in OMNeT++ simulations, particularly in PLR reduction and latency improvement. However, detailed analysis reveals specific limitations: performance degradation occurs when node density increases, and efficiency notably decreases at mobile speeds exceeding 30 km/h. These limitations, though not thoroughly addressed in the original study, highlight important considerations for deployment scenarios.

The comparative analysis of these implementations reveals several key insights about improving both energy efficiency and data integrity in mobile LoRaWAN deployments. While DaRe excels in energy efficiency and high recovery rates under optimal conditions, CRT-LoRa offers better performance in scenarios with varying node distances but struggles with high-speed mobility. Both approaches demonstrate that improved coding algorithms and data recovery mechanisms can significantly enhance network performance, though each faces similar challenges: performance degradation in dense urban environments, computational overhead concerns, and the need for more comprehensive real-world testing. Future developments should focus on addressing these common limitations while maintaining the achieved improvements in energy efficiency and reliability, particularly in scenarios involving high node density and rapid mobility.

The implementation experiences from these studies suggest that a hybrid approach, combining the strengths of multiple methodologies, might offer the most promising path forward. Such an approach could potentially address the current limitations while maintaining the demonstrated benefits in energy efficiency and data integrity.

3.3.3 Mobility and Routing Protocols

High mobility in LoRaWAN networks creates new obstacles, particularly in vehicle and aerial applications. The primary challenges are continuously changing network topologies, the need for real-time data transfer with minimal delay, and ensuring dependable connectivity in metropolitan locations with signal blockages. Recent research has produced several innovative solutions, each addressing different aspects of these challenges.

The LoRaWAN-based Geographic Routing Protocol (LGRP) developed by [56] represents a significant advancement in addressing vehicular network challenges. By combining LoRaWAN and 802.11p technologies, LGRP achieved remarkable performance metrics: a 41% improvement in Packet Delivery Ratio (PDR), a 98% reduction in average end-to-end delay, and a 5% reduction in energy usage compared to existing protocols. These improvements were validated through comprehensive NS-3 simulations using realistic urban scenarios generated by OpenStreetMap and SUMO. However, critical analysis reveals that LGRP's performance can degrade in areas with high building density, where signal blockage becomes more prevalent.

A contrasting approach is seen in [50]'s hybrid architecture integrating LoRaWAN and Wi-Fi for Flying Ad Hoc Networks (FANETs). This solution specifically addresses the unique challenges of aerial IoT applications, where maintaining stable connections despite three-dimensional mobility is crucial. Through NS-3 simulations and real-world UAV testing, the architecture demonstrated superior performance in both communication range and energy efficiency compared to standard LoRaWAN deployments. The key innovation lies in its adaptive network selection mechanism, though performance can be affected by weather conditions and high-altitude interference.

Study in [1] introduced an innovative solution utilizing parked automobiles as temporary roadside gateways, addressing urban vehicular communication challenges. The solution's unique approach to packet retransmission management resulted in improved packet success rates and reduced bandwidth usage. Quantitative analysis showed significant improvements in overall packet throughput compared to traditional roadside unit deployment. However, the effectiveness of this approach varies with parking density and urban parking patterns.

The comparative analysis of these methods exposes a number of noteworthy insights. Vehicle-centric technologies, like Low Ground Relay Protocol (LGRP) and stationary automotive gateways, demonstrate enhanced efficacy in congested metropolitan environments. Hybrid structures provide remarkable adaptability to various movement patterns. Significant enhancements in energy efficiency are realised when intelligent routing decisions are integrated into the system. These improvements indicate a transition from single-protocol solutions to more complicated hybrid systems, which are more adept at tackling the intricacies of mobile IoT applications. Nonetheless, numerous problems persist across all methodologies. This encompasses performance deterioration in areas with inadequate infrastructure, heightened protocol overhead in high-mobility contexts, and the persistent requirement to reconcile routing complexity with energy efficiency.

These improvements highlight the transition from single-protocol solutions to more sophisticated hybrid systems, which are more adept at addressing the complex requirements of mobile IoT applications. Nevertheless, specific problems persist across all methodologies. This encompasses the problem of performance decline in areas with insufficient infrastructure, the heightened protocol overhead in high-mobility settings, and the ongoing necessity to balance routing complexity with energy efficiency.

3.3.4 Security and Roaming

As mobile IoT devices frequently transition between networks, ensuring secure and efficient roaming becomes paramount. The challenges associated with this process extend beyond basic connectivity, encompassing the need for security in untrusted visiting networks, energy-efficient authentication mechanisms, and the reduction of roaming-related overhead.

The SEC-ROAM technique, presented by [43], represents a significant progression in secure roaming solutions. The principal innovation is in reducing connectivity with the home Network Server (hNS) while ensuring strong security via an ED Verification Mechanism. Quantitative study revealed that SEC-ROAM significantly decreases roaming verification time relative to conventional methods, reduces energy consumption through optimised authentication operations, and improves security through an ECC-based Diffie-Hellman key exchange.

However, a detailed evaluation reveals certain trade-offs. While SEC-ROAM effectively reduces communication overhead, it imposes additional computational demands on end devices. Performance analysis through simulation indicated that the mechanism’s efficiency is influenced by network density and the frequency of roaming. In high-mobility scenarios, where devices frequently switch networks, the cumulative energy cost of repeated authentication processes becomes significant. The researchers' analysis discovered multiple essential elements affecting roaming performance. Authentication latency was seen to rise with increased distance from the home network, whereas energy usage fluctuated significantly based on the frequency of roaming. Moreover, reconciling security overhead with the resource constraints of devices presents a significant barrier, while the effectiveness of network handover is largely contingent upon the density and distribution of gateways.

These findings suggest that while SEC-ROAM offers a robust framework for secure roaming, achieving optimal performance necessitates careful consideration of deployment contexts and mobility patterns. Future enhancements should focus on adaptive security mechanisms tailored to device mobility patterns and the trust levels of specific networks.

3.3.5 Simulation and Testing Frameworks

Several comprehensive studies have focused on developing simulation and testing frameworks to support mobile LoRaWAN research and development. These tools play a crucial role in evaluating and optimising network performance under diverse mobility scenarios, particularly addressing challenges such as dynamic signal propagation, device localisation, and adaptive network topologies.

The development of comprehensive simulation tools has emerged as a response to the limitations of existing frameworks in adequately modelling the intricate interactions between mobile IoT devices and their dynamic environments. A notable advancement in this field was the introduction of the DingNet simulator, which addressed the requirement for comprehensive modelling and assessment of self-adaptive solutions for IoT systems based on mote mobility [58]. This simulator has proven particularly valuable for evaluating motes' reliability, energy consumption, and adaptability to changing environmental circumstances, especially when testing adaptive algorithms and protocols designed to enhance LoRaWAN performance in mobile environments.

Significant methodological advancements have been made in assessing LoRaWAN performance within mobile contexts, particularly addressing the challenges of reliably measuring LoRa link-level coverage and localisation. Recent research has demonstrated the effectiveness of adaptive geography scaling and deep learning algorithms for estimating predicted signal power [51]. A comprehensive evaluation of these methods involved deploying a mobile LoRaWAN system with two gateways and six end nodes across a 6x6 km^2 region. The findings revealed that each gateway achieved coverage of 11.3 km^2 with a median localisation error of approximately 400 m. Notably, the research established that minimal improvements in signal-to-noise ratio (SNR) could significantly enhance coverage, highlighting the potential for optimising mobile LoRaWAN networks through meticulous signal quality management.

The establishment of robust modelling and testing frameworks represents a critical milestone in advancing research into mobile LoRaWAN applications. These frameworks provide realistic and comprehensive methods for evaluating network performance under various mobility scenarios, enabling researchers and developers to identify and address potential challenges before real-world deployment. This capability for accurate simulation and testing of mobile scenarios has proven instrumental in developing more resilient and efficient mobile LoRaWAN networks.

In conclusion, the literature on LoRaWAN in Mobile IoT demonstrates a comprehensive approach to addressing mobility-related challenges. The field has witnessed significant advancements through various research initiatives, encompassing improvements in ADR algorithms through AI and predictive models, development of energy-efficient data recovery mechanisms, creation of novel routing protocols for high-mobility scenarios, and enhancement of secure roaming capabilities. The development of thorough testing and simulation frameworks has further accelerated this progress, enabling researchers to validate and refine their concepts in realistic mobile environments. As mobile IoT continues to evolve, these research directions will increasingly influence the trajectory of LoRaWAN technology and its applications in dynamic, mobile contexts. Table 4 presents a comprehensive summary of these developments in LoRaWAN technology, detailing the focus areas, addressed challenges, key solutions, performance improvements, validation methods, and technological significance.

Table 4. LoRaWAN technology summary.

Citation	Focus area	Challenges addressed	Key solutions	Performance improvements	Testing/ validation	Technological significance
[24]	AI-enhanced ADR	Improving ADR in mobile scenarios	AI and predictive modelling for ADR optimization	Enhanced packet success rate (PSR)	General review of AI impact	Improving ADR responsiveness to mobility
[52]	AI-ERA Framework	High packet loss, SF inefficiencies	DNN for efficient SF assignment	Improved PSR by 32% in static, 28% in mobility	NS-3 simulations	Reducing retransmissions & energy waste
[54]	Enhanced ADR (E-ADR)	High PLR in mobile contexts	Position-based dynamic transmission	Reduced packet loss and energy consumption	Testbed with Waspmote SX1272 devices	Optimising coverage and energy in mobility
[57]	VHMM-based E-ADR	Unpredictable mobile trajectories	Variable order Hidden Markov Model (VHMM)	87% trajectory prediction accuracy	Waspmote SX1272 in smart farm setup	Accurate SF adjustment to prevent loss
[10]	Data Recovery Framework (DaRe)	Energy-efficient data recovery	Convolutional & fountain code-based coding	99% data recovery with 1/2 code rate	Real-world application server & devices	Reliable data recovery in poor connectivity
[53]	Chinese Remainder Theorem (CRT-LoRa)	Packet loss in mobile transmission	Chinese Remainder Theorem-based coding	Reduced packet loss and latency	OMNeT++ simulations	Efficient coding for dynamic data transfer
[56]	Geographic Routing Protocol (LGRP)	Topological changes in vehicle networks	LoRaWAN-802.11p multi-criteria routing	41% PDR improvement, 98% reduction in delay	NS-3 urban simulation	Enhancing vehicle network communication
[50]	Hybrid LoRaWAN-WiFi Architecture	Communication in aerial IoT	Hybrid FANET architecture with Wi-Fi	Enhanced PDR and energy efficiency	NS-3 simulations & real UAV testing	Stable aerial communication in FANETs
[22]	Secure Roaming Protocol (SEC-ROAM)	Secure and efficient roaming in mobile networks	ECC-based Diffie-Hellman for secure roaming	Lower roaming verification latency & cost	Simulation for roaming efficiency	Secure roaming with minimal energy use
[58]	DingNet Simulator	Comprehensive simulation for mobile LoRaWAN	Adaptive simulation framework	Improved reliability & energy evaluation	Simulation tool development	Realistic testing environment for research
[51]	Deep Learning-based Coverage Estimation	Accurate PDR and localisation measurements	DeepLoRa for signal power estimation	Extended gateway coverage to 11.3 km²	Mobile LoRaWAN field tests	Coverage and signal quality optimization

3.4. Energy-Aware Routing Protocols for LoRaWAN

Energy-efficient routing algorithms in LoRaWAN represent critical strategies specifically developed to optimize network node energy consumption while maintaining effective data transfer and network performance. These protocols play a vital role in network operations, particularly considering that numerous IoT devices operate on battery power and are often deployed in remote or challenging locations. The fundamental objective of energy-aware routing is to optimize the utilization of limited energy resources, thereby extending the network's operational lifespan.

Clustering-based approaches have emerged as significant developments in energy-efficient routing strategies. One notable advancement involves a layering methodology that optimizes uplink multi-hop communication and reduces energy consumption through systematic node organization [59]. While this approach demonstrates superior energy efficiency compared to flat network topologies, certain overhead challenges associated with cluster formation and maintenance warrant consideration, particularly in mobile IoT environments.

The evolution of clustering concepts led to more sophisticated routing protocols, including the Variable-Hop (VH) routing methodology. This advanced approach incorporates direct-hop (DH), next-ring-hop (NRH), and variable-hop routing techniques to enhance uplink multi-hop communication efficiency. Empirical evidence suggests significant improvements in network longevity through reduced energy burden on peripheral nodes [60]. However, the implementation requires more sophisticated network management systems to effectively handle dynamic hop distances.

Real-time data transfer requirements in mobile IoT applications have driven the development of innovative protocols. A notable advancement in this domain is the Multi-Hop Real-Time LoRa Protocol, which implements a two-hop relay mechanism combined with real-time slot scheduling to optimize transmission power [61]. This solution has demonstrated particularly impressive reliability and packet delivery rates in mobile IoT scenarios, despite potential challenges with high-traffic situations.

Advanced algorithmic approaches to routing optimization have also emerged, exemplified by the development of MLora, which utilizes the Weight Superposable Minimum Spanning Tree (WSMST) algorithm. This sophisticated approach identifies optimal relay nodes by analyzing energy consumption patterns and connection quality metrics [62]. While enhancing reliability and coverage, considerations regarding overhead management in high-traffic scenarios remain particularly relevant for mobile IoT implementations.

Recent innovations have focused on latency reduction through smart hop management strategies. The Smart-Hop protocol represents a significant advancement in this area, utilising high-precision clock synchronization to minimize energy consumption while optimizing data transmission efficiency [63]. Contemporary research has also produced the Hierarchy-Based Energy-Efficient Routing (HBEE) protocol, incorporating concurrent transmission and multi-path strategies to ensure balanced energy utilization across network nodes [41].

Geographic routing solutions have demonstrated particular promise in addressing mobile IoT challenges. The LoRaWAN Geographic Routing Protocol (LGRP) exemplifies this approach, utilizing comprehensive neighbor tables and multi-criteria routing metrics to optimize path selection [56]. Despite potential environmental and mobility-related challenges in neighbor detection, this methodology has shown significant improvements in packet delivery ratios and energy efficiency within mobile IoT contexts.

In conclusion, while these protocols present diverse approaches to energy-aware routing in LoRaWAN, their applicability and performance in mobile IoT applications vary considerably. Particularly noteworthy are the demonstrated successes of the Multi-Hop Real-Time LoRa Protocol and LGRP in mobile environments. However, further investigation remains essential to comprehensively evaluate protocol efficacy across diverse mobile IoT applications and address challenges related to overhead management and adaptation to rapidly changing network conditions. Table 5 provides a detailed comparative analysis of these energy-aware routing protocols, highlighting their distinctive characteristics and advantages for specific IoT implementations.

Table 5. Comparison between energy-aware routing protocols for LoRaWAN.

Protocol	Description	Energy Efficiency	Comparison	Performance in Mobile IoT
Clustering-Based Layering Approach [59]	Uses clustering to organise nodes into layers, optimising uplink multi-hop communication to reduce energy consumption.	Reduces the overall energy consumption and extends the network's operational life.	Generally, more energy-efficient than flat network topologies but may introduce overhead due to cluster formation and maintenance.	Not Stated
Variable-Hop (VH) routing [60]	Uses clustering to organise nodes into layers, optimising uplink multi-hop communication and using DH, NRH and VH routing	VH outperforms DH routing by reducing the energy burden on nodes farthest from the gateway, thereby enhancing network lifetime.	VH is more energy-efficient than DH routing but requires more sophisticated network management to handle variable hop distances.	Not Stated
Multi-Hop Real-Time LoRa Protocol [61]	Improves real-time data transmission using a two-hop relay mechanism.	Reduces the transmission power using real-time slot scheduling	Improves reliability but may struggle with high traffic due to increased overhead and potential delay	High reliability and high packet delivery rates
MLora [62]	Utilised WSMST algorithm to select optimal relay nodes based on their energy consumption and link quality	Balancing energy consumption by evaluating the gain-to-cost ratios of potential relay candidates	Extend coverage, improves reliability but potentially increased overhead in high traffic	Potentially increased overhead in high traffic
Smart-Hop [63]	Provides low-latency communication by selectively replacing	Reduces energy consumption via	Data extraction time decreased and reduce	Not Stated

	high SF links with chains of lower SF links	high-precision clock synchronisation	packet collision via coordinated protocol	
Hierarchy-Based Energy-Efficient Routing (HBEE) [41]	Utilise concurrent transmission, implicit routing exploration method and multi-path and multi-channel strategy	Reduce packet collision and balanced energy consumption among all ENs	EN can be assigned to a network layer within a short time without packet collision and minimise radio overhead	Not Stated
LoRaWAN-based Geographic Routing Protocol (LGRP) [56]	Using global neighbour table and multi-criteria routing metric to select optimal path to destination	Minimise energy consumption by optimising routing path during data transmission	Improves PDR and robust routing path but relies on neighbour discovery which can be affected by environmental factor and mobility	PDR improved, average end-to-end delay is enhanced, and energy consumption is reduced

3.5. Real-world Applications on LoRaWAN in Mobile IoT

In emergency and safety applications, the implementation of LoRaWAN has exhibited substantial progress in mobile solutions. One of the most important innovations in this industry is the LOCATE system [64], which offers mobile emergency management capabilities that are uniquely intended for regions that have limited access to standard cellular service. The system makes it possible for alert messages to be distributed in several hops and across large distances, which guarantees that vital information reaches rescue crews quickly. Additionally, the technology has been effectively modified for communication in disaster areas without the need of GPS or GSM [64], demonstrating its efficacy in mobile emergency response situations with up to 15 km of coverage in difficult-to-reach areas. LoRaWAN has made it possible for real-time crash detection and alerting for cyclists in urban settings, making it a particularly notable mobile application in cyclist safety systems [55]. By integrating MEMS inertial sensors into bicycles and helmets as part of its distributed motion sensing elements, this system may cover entire urban areas through a single gateway while preserving energy efficiency through adaptive transmission techniques.

Within the context of urban environments, LoRaWAN has demonstrated a particularly promising potential for use in mobile applications for smart city operations. Intelligent transport systems that use the LGRP protocol have successfully integrated the technology, allowing for traffic control and real-time vehicle tracking [46]. This implementation reduces power consumption by 5% compared to existing protocols, while simultaneously achieving substantial improvements in packet delivery and end-to-end latency. In addition, hybrid systems that incorporate mobile components have been created for smart garbage collection [56]. These systems allow mobile collection units to be tracked and coordinated in an effective manner using the LoRaWAN network. These systems operate sustainably in urban environments with minimal power consumption, utilizing sleep modes and solar power to improve energy efficiency.

LoRaWAN has been instrumental in facilitating a number of mobile-oriented deployments within the field of network integration. One notable example of this is the use of mobile underwater components for dynamic data collecting in underwater monitoring systems [65], which allow data to be transferred from underwater sensors to terrestrial networks under difficult underwater conditions. Additionally, geofencing systems [66] have shown notable mobility, efficiently tracking and monitoring moving assets with the help of static infrastructure. It has been demonstrated that these systems are more energy-efficient and scalable than alternatives that are based on cellular technology. They also provide coverage over a vast region without the need for internet connectivity.

LoRaWAN has been effectively implemented in industrial environments for applications that involve the monitoring of mobile workforces. This is especially noticeable in shipbuilding settings [46], where the technology allows for the real-time tracking of mobile personnel while keeping an eye on poisonous gas levels. This combines environmental sensing and personal safety monitoring in a dynamic industrial scenario. This device is designed to operate for over six months without the need for battery replacement. It showcases remarkable energy economy in complex industrial settings where conventional communication methods might be hindered.

Table 6. Comprehensive analysis of mobile LoRaWAN applications across different sectors.

Category	Mobile applications [Reference]	Key features	Technical benefits	Implementation challenges	Target use cases
Emergency Response Systems	LOCATE system [64]	Real-time emergency tracking	Functions without cellular connectivity	Signal reliability in emergencies	Emergency services
	Disaster area communication [64]	Non-GPS dependent location	Long-range communication (up to 7.6 km)	Battery life management	Disaster response teams

	Cyclist safety systems [55]	Automatic crash detection	Low power consumption	Accuracy of location tracking	Cyclist safety monitoring
		Wide area coverage	Real-time alerting capabilities	Network coverage in remote areas	Remote area operations
Urban Mobile Infrastructure	Intelligent transportation [46]	Real-time vehicle tracking	Enhanced network coverage	Urban signal interference	Public transportation
	Mobile waste collection [67]	Route optimization	Improved packet delivery	Moving node connectivity	Waste management fleets
		Mobile asset monitoring	Reduced end-to-end delay	Real-time data processing	Urban logistics
		Dynamic data collection	5% power consumption reduction	Network handover management	Mobile asset tracking
Mobile Network Integration	Mobile underwater elements [65]	Dynamic tracking capability	Seamless data transmission	Underwater signal propagation	Marine monitoring
	Mobile geofencing [66]	Underwater communication	Wide area coverage	Movement tracking accuracy	Asset tracking
		Geographic boundary monitoring	Flexible boundary definition	Power management	Fleet management
		Real-time location updates	Reliable tracking capability	Data synchronization	Boundary surveillance
Industrial Mobile Solutions	Worker safety tracking [46]	Real-time worker tracking	6-month battery life	Industrial interference	Industrial safety
		Toxic gas monitoring	Comprehensive coverage	Worker privacy concerns	Worker protection
		Mobile safety alerts	Real-time hazard detection	Complex environmental navigation	Hazard monitoring
		Dynamic risk assessment	Immediate alert system	Alert reliability	Emergency response

This in-depth analysis of mobile LoRaWAN applications in Table 6 reveals the distinctive features of the technology in terms of its ability to support moving elements and dynamic monitoring scenarios. These implementations have demonstrated LoRaWAN's ability to sustain dependable connections with mobile nodes in low-power environments, rendering it particularly well-suited for applications that necessitate real-time tracking and monitoring of individuals or assets that are in motion.

4. DISCUSSION

Several studies have shown that LoRaWAN has potential in the mobile IoT application space, which has been the topic of extensive research into its suitability for such applications. LoRaWAN is a promising choice for a range of mobile IoT applications due to its scalability, low power consumption, and long-range communication capabilities [52, 53]. However, when used in mobile situations, technology confronts some limitations. A number of potential uses for LoRaWAN have been highlighted in recent research [52, 55], including asset tracking, logistics, and accident detection. For industrial applications that need real-time data transfer, its capacity to support low-power, long-range communication is very advantageous [53]. However, devices suffer high frame loss rates and increased latency as they move away from GW, and the technology has trouble sustaining consistent connectivity [10, 54]. We can therefore draw the conclusion that while LoRaWAN has shown promise in mobile IoT applications, more research and development is still needed to fully understand how it performs in extremely dynamic mobile situations. While some mobile situations have demonstrated the effectiveness of the technology, there are still issues with maintaining consistent performance across a variety of mobile applications.

According to the research, there is conflicting evidence about how well existing energy-aware routing algorithms work with LoRaWAN in mobile IoT applications. Some protocols have been built or tested expressly for mobile use cases, whereas others have largely focused on static deployments. In mobile IoT contexts, protocols like Multi-Hop Real-Time LoRa [61] and LGRP [56] have proven to be very reliable and improved packet delivery rates. The specific constraints of mobile environments, like dynamic network topologies and the requirement for real-time data transfer, can be effectively addressed by these protocols. However, several energy-efficient LoRaWAN routing protocols, such as the Clustering-Based Layering Approach [59] and VH routing [60], have not specifically indicated their performance in mobile IoT scenarios. While these protocols have improved energy efficiency in static deployments, their performance in mobile situations has to be thoroughly examined. Adapting and testing these protocols in mobile contexts could provide useful information about their robustness and scalability in dynamic environments by evaluating their performance across diverse mobility patterns, examining their adaptation to fluctuating network conditions, and quantifying their energy efficiency in mobile environments.

Several options for improving LoRaWAN's energy-aware capabilities appear to be viable. One way to further decrease energy usage is to combine energy-aware routing protocols with other technologies or approaches. The use of energy-aware routing protocols and machine learning techniques, for instance, has the potential to improve the adaptation of these protocols to dynamic mobile contexts. Research in [52] introduces AI-ERA framework that shows how DNN can be used to assign optimal SFs proactively, which improves mobile scenarios' energy efficiency. Integrating ADR methods with energy-aware routing is another promising advancement. In their proposal, [54] demonstrates how predictive models can be utilised to adapt transmission parameters in response to fluctuating signal quality. This could result in substantial decreases in energy consumption and packet loss in mobile IoT applications.

Additionally, exploring hybrid designs that integrate LoRaWAN with other communication technologies, such as Wi-Fi or cellular networks, may also provide energy-saving benefits [50]. In a study conducted by [50], a hybrid design was suggested for FANETs, which showed that it outperformed standard LoRaWAN configurations in terms of communication range and energy efficiency.

Overall, LoRaWAN is a promising technology for mobile IoT applications, but there is still a lot of space for refinement and research. One area that needs special attention is the creation and modification of energy-aware routing protocols for use in mobile environments. The integration of advanced technologies such as machine learning, predictive modelling, and energy harvesting opens new possibilities for improving LoRaWAN's energy-aware capabilities in mobile IoT applications. Table 7 summarises the main issues addressed in papers within our review database. This overview highlights the evolution of research focus and the persistent challenges in the field over time.

Table 7. Summary of research issues addressed in energy-aware routing protocols for LoRaWAN in mobile IoT (2019-2024).

Issue	2019	2020	2021	2022	2023	2024
Adaptive data rate (ADR) optimization	[54]	[59]	[6] [57] [68] [64] [69]	[4] [7] [8] [10] [13] [16] [28] [63] [70 - 73]	[24] [52] [53] [74]	[43] [66] [75] [76]
Energy-Efficient data transmission	[9] [40] [54] [55] [58] [77 - 80]	[1] [3] [59] [60] [65] [81 - 84]	[5] [6] [14] [44] [49] [57] [68] [69] [85 - 90]	[4] [7] [8] [10] [13] [16] [28] [41] [42] [51] [62] [63] [46] [70 - 73] [91 - 98]	[2] [24] [47] [50] [52] [53] [56] [67] [74] [99 - 104]	[15] [43] [45] [48] [66] [75] [76] [105 - 111]
LoRaWAN performance	[9] [40] [54] [55] [77] [78] [79] [80]	[1] [3] [59] [60] [65] [81 - 84]	[6] [14] [44] [49] [57] [68] [69] [85 - 90]	[4] [7] [8] [10] [13] [16] [28] [41] [42] [51] [61] [62] [63] [70 - 73] [91] [92] [93] [95] [97] [107]	[24] [47] [50] [52] [53] [56] [74] [99 - 101] [103] [104]	[15] [43] [45] [48] [66] [75] [76] [105] [107 - 111]
LPWAN comparison	[40] [78]	[59] [81 - 84]	[14] [44] [49] [69] [90]	[4] [7] [10] [13] [16] [28] [70] [72] [92] [95] [107]	[24] [47] [50] [99- 101]	[45] [48] [76] [105] [107] [108]
Mobility and mobile IoT applications	[54] [55] [58] [79]	[1]	[5] [6] [14] [57] [64] [68] [87] [112]	[46] [51] [61] [72] [94] [97]	[2] [50] [52] [53] [56]	[43] [48] [113]
Routing protocols	[9] [79]	[3] [59] [60]	[14] [44] [64] [88] [112]	[8] [13] [16] [41] [61] [62] [63] [71] [91] [93]	[50] [56] [103]	[66] [76]
Security and roaming		[3] [81]	[5] [14] [88]	[4] [28] [46] [92]	[47] [102]	[15] [43] [66] [76] [106] [109]
Simulation	[9] [58] [80]	[1] [59] [60]	[5] [6] [14] [57]	[7] [8] [13] [28]	[47] [52] [56]	[45] [66] [76]

and testing frameworks		[65] [81]	[68] [87]	[41] [63] [93]	[74] [103] [104]	[110]
Static IoT applications	[9] [78]	[3] [59] [60] [65] [81 - 84]	[44] [49] [69] [85] [86] [88] [89] [90] [114]	[4] [7] [8] [10] [13] [16] [28] [41] [42] [46] [62] [63] [70 - 73] [91 - 98]	[47] [52] [67] [74] [99 - 104]	[15] [45] [48] [66] [75] [76] [105 - 111] [115]

The preceding summary provides a comprehensive temporal mapping of research priorities, illustrating the field's maturation and calling attention to emerging areas of investigation. This analysis is particularly beneficial for comprehending the trajectory of technological advancement and identifying prospective areas for future research. The chronological arrangement of research topics reveals a distinct trend, beginning with the development of core protocols and progressing to increasingly complex implementations.

During the initial phase, the primary focus of the researchers was on the development of fundamental protocols and simulation experiments. In 2019, study in [58] made basic simulation frameworks, while [9] focused on basic data transfer processes in heterogeneous networks. In these basic studies, the building blocks for later advances were laid. This foundational work sets the stage for more advanced developments in the field.

As discipline evolved, research goals experienced substantial changes. An increasing emphasis was placed throughout the middle period on energy efficiency as well as the optimization of routing. Research in [52] made a noteworthy contribution to adaptive data rate optimization by introducing artificial intelligence-enhanced resource allocation. Also, during this period, the development of hierarchy-based energy-efficient routing protocols by [41] exemplified the emergence of more sophisticated approaches to energy-aware routing. The development of more complicated solutions reflected the growing understanding of the difficulties that are inherent in the deployment of mobile Internet of Things devices.

Building on these advances, researchers began focusing on practical applications and implementation challenges. In recent years, study has become more and more focused on how to implement ideas and connect different systems. In 2023, [74] introduced advanced adaptive data-rate techniques for smart city applications, while [75] illustrated energy-efficient implementations in agricultural environments. This move towards practical uses is expected as technology advances and is more widely used in many industries.

The incorporation of artificial intelligence techniques has emerged as a particularly promising path in routing protocols. Study in [52] demonstrated a 32% increase in packet success ratio through their work on AI-enhanced resource allocation. The research continued by [57] where they able to forecast trajectory with 87% accuracy using VHMM-based approaches. These enhancements demonstrate how machine learning can be used to solve challenging optimization problems in mobile IoT settings.

While performance and efficiency improvements were significant, researchers also recognized the critical importance of security in IoT deployments. Recent studies have shown that security issues are becoming increasingly prominent, which is reflective of the growing knowledge of the cybersecurity challenges that are associated with Internet of Things deployments. [66]'s creation of scalable security frameworks and [43]'s work on secure roaming protocols shows how the field has evolved towards more thorough security integration. This emphasis on security complements current efforts towards improving energy efficiency and performance.

The practical application of these theoretical advances has shown promising results in real-world scenarios. Recent investigations have demonstrated a particularly promising approach to addressing practical deployment issues. Both [107, 108] have made major contributions to the monitoring of water quality and the management of agricultural land, respectively. These applications demonstrate the adaptability of LoRaWAN technology while emphasising the significance of application-specific optimisation tactics.

Despite these advances, several critical areas still require further investigation. Although there is a lot of information about how things work in the short term, there hasn't been any research on how things work in the long run in actual deployments. Also, there is a lack of research on the integration of LoRaWAN with complementary technologies, which presents a potential area for future investigation. It also becomes clear that there is a significant need for the establishment of uniform performance indicators and testing frameworks.

These findings point toward several promising directions for future research. In addition to documenting the development of the area, the temporal analysis shown in Table 7 offers insightful information for future study paths. Moving from simple protocols to complex systems with AI features shows how far the field has come and points out areas that need more research. This thorough grasp of research patterns will help to guide future advances in LoRaWAN mobile IoT applications. With the sector constantly changing, research will most likely focus on integrating new technologies and solving real-world implementation problems. Technological progress and emerging research objectives highlight real-world deployment restrictions and potential. This understanding lays the groundwork for more efficient, secure, and practical mobile IoT systems.

5. LIMITATIONS AND RESEARCH GAPS

This comprehensive study on energy-aware routing methods for LoRaWAN in mobile IoT applications, while providing useful insights, reveals several significant research gaps and limitations that warrant further investigation. These limitations can be examined across methodological, technical, and application domains.

A primary methodological limitation stems from the field's significant dependence on simulated environments and controlled testbeds for protocol assessment. As pointed out by [58], simulations may overlook crucial nuances and challenges present in real-world deployments. The results from these controlled studies may not fully capture the complexities of operating self-adaptive systems or the uncertainties inherent in real mobile IoT deployments. This gap between simulated and real-world performance represents a critical area for future research. The absence of long-term performance data emerges as another significant research gap. While current studies provide valuable insights into immediate system behavior, further research is needed to determine the efficacy of adaptive procedures in long-term, real-world, dynamic settings [52]. This limitation particularly affects our understanding of system sustainability and long-term reliability in diverse operating conditions.

Current research exhibits notable technical gaps, particularly in security integration. As highlighted by [43], while security considerations in mobile LoRaWAN installations are crucial, many existing protocols have not given them sufficient attention. This creates a significant research opportunity at the intersection of security and energy-efficient routing protocols. Similarly, critical considerations such as scalability and interoperability with existing infrastructure remain underexplored in current research.

A fundamental limitation arises from the context-specific nature of existing studies. For instance, [1] acknowledge that their research focused solely on one city's on-street parking lots, potentially limiting its applicability to the broader spectrum of mobile IoT applications. This specificity in research contexts creates a gap in our understanding of how these solutions might perform across different mobile IoT environments and use cases. The study's primary focus on energy economy and packet delivery performance, while important, reveals gaps in addressing other critical aspects of mobile IoT applications. This narrow focus suggests opportunities for more holistic approaches that consider multiple performance metrics simultaneously. Future research could bridge these gaps by developing comprehensive frameworks that balance energy efficiency with other crucial system requirements.

These identified gaps and limitations point toward several promising research directions: the development of more realistic testing environments, long-term performance studies in real-world conditions, integrated security solutions, and broader application-focused investigations. Addressing these gaps will be crucial for advancing the field toward more practical and widely applicable solutions.

6. FUTURE WORKS

These constraints, together with the existing level of knowledge, highlight a number of interesting avenues for further investigation. Future research should prioritise rigorous real-world testing of energy-aware routing methods for LoRaWAN in various mobile IoT scenarios. According to [58], conducting such large-scale field deployments would provide more accurate performance metrics and reveal obstacles that might not be apparent in virtual settings. The usefulness and efficiency of these protocols in real-world mobile IoT installations could be greatly enlightened by this kind of testing.

Another important area for future research is the creation of a standardized evaluation framework for mobile IoT protocols. This framework should include a consistent set of performance measurements and evaluation procedures. Such a framework would allow for more precise comparisons of methods, taking into account factors like energy efficiency, latency, PDR, and flexibility to changing network conditions [51]. This standardization would significantly improve our capacity for evaluating and contrasting the efficacy of various protocols across a wide range of mobile IoT applications.

Future research should also focus on studying the effectiveness and flexibility of energy-aware routing strategies in dynamic mobility contexts over the long run. Such research would shed light on the protocols' long-term performance and possible degradation, as pointed out by [68], giving a more complete picture of their sustainability in mobile IoT applications. Integrating robust security features into energy-aware routing protocols without significantly reducing their energy efficiency is a crucial direction for future research. For mobile IoT devices with limited resources, it is crucial to create safe routing algorithms and lightweight encryption approaches [43]. This integration would solve emerging security issues in IoT installations while maintaining the protocols' energy efficiency.

Mobile LoRaWAN deployments could benefit from more comprehensive energy-aware solutions if researchers investigated cross-layer optimization methods that take into account interactions across the physical, MAC, and network levels. As indicated by [57], such an approach could result in more comprehensive and efficient protocols that take advantage of synergies across network layers. Another promising area for further study is the use of machine learning methods to mobile IoT settings, namely in the areas of predictive routing and adaptive parameter adjustment. More research in this area, expanding on the findings of [52], could greatly improve the efficiency and effectiveness of LoRaWAN protocols in continuously shifting mobile settings.

Research into hybrid network architectures that integrate LoRaWAN with other wireless technologies could help address some of LoRaWAN's problems in mobile scenarios. Studies conducted by [50] suggest that in order to provide better and more adaptable solutions for mobile IoT applications, researchers should look into ways to make handoffs smooth and how to allocate resources optimally in hybrid networks. Lastly, a good area to focus on future studies is on how to include energy harvesting technologies into LoRaWAN devices and how this could impact the development of energy-aware routing protocols. Research findings by [56] indicate that this method may provide new opportunities for sustainable operations in the long run by radically altering energy management tactics in mobile IoT deployments. Addressing these areas can greatly enhance future research in energy-aware routing protocols for LoRaWAN in mobile IoT applications, making them more resilient, efficient, and adaptive. The full potential of LoRaWAN technology in the demanding and ever-changing conditions of mobile IoT deployments can only be achieved with this combined effort.

7. CONCLUSIONS

This comprehensive analysis has explored the current state of energy-aware routing protocols for LoRaWAN in mobile IoT applications, identifying notable advancements as well as existing challenges. The inherent low power consumption and extensive communication range of LoRaWAN position it as a compelling solution for mobile IoT deployments. Recent developments in PDRs, latency reduction, and energy efficiency have been achieved through innovative protocols such as the AI-ERA framework, the CRT-LoRa framework, and the VHMM-based E-ADR mechanism. Despite these advancements, significant challenges remain, particularly in managing energy consumption and ensuring reliable communication in highly dynamic environments. The integration of advanced technologies presents an exciting avenue for enhancing the capabilities of LoRaWAN in mobile IoT contexts. Potential improvements include incorporating energy harvesting techniques, cross-layer optimization, and machine intelligence to optimise performance.

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The authors declare no potential conflicts of interest with respect to the research and publication of this article.

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