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REVIEW ARTICLE

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# A COMPREHENSIVE SURVEY ON LORA TECHNOLOGY: ARCHITECTURE, PROTOCOLS AND APPLICATIONS

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***Abstract :*** This review paper presents a comprehensive analysis of LoRa (Long Range) communication technology, focusing on its architecture, protocols, and diverse applications in Internet of Things (IoT) systems. LoRa enables long-range, low-power communication, making it highly suitable for large-scale and resource-constrained environments such as smart cities, agriculture, healthcare, and industrial domains. The study examines key technical aspects including network design, modulation techniques, and performance parameters such as spreading factor, energy efficiency, and scalability. It further explores recent advancements such as mesh networking, AI-driven optimization, signal reconstruction methods, and satellite-based LoRa communication, highlighting emerging research trends. Additionally, major challenges including packet collisions, limited data rates, interference, and scalability issues are identified and discussed. Overall, the paper provides a clear understanding of current developments and future directions, emphasizing the significant potential of LoRa technology in enabling reliable, energy-efficient, and scalable next-generation IoT communication systems.

***Keywords:*** LoRa, LoRaWAN, Internet of Things (IoT), Low Power Wide Area Network (LPWAN), Mesh Networking, Spreading Factor Optimization, Energy Efficiency, Signal Reconstruction, Deep Learning in Communication, Satellite IoT, Smart Agriculture, Healthcare IoT, Network Scalability, Interference Management, Edge Computing.

## I. INTRODUCTION

The rapid growth of the Internet of Things (IoT) has created an increasing demand for communication technologies that can provide long-range connectivity while maintaining low power consumption and cost efficiency. LoRa (Long Range) technology has emerged as a prominent solution within the Low Power Wide Area Network (LPWAN) domain, enabling reliable wireless communication over several kilometers with minimal energy usage. Unlike traditional communication systems that are limited by range or power constraints, LoRa is specifically designed for large-scale IoT deployments such as smart cities, precision agriculture, healthcare monitoring, and industrial automation. Its use of chirp spread spectrum modulation and adaptive data rate mechanisms enhances coverage, robustness, and network scalability, making it highly suitable for resource-constrained and remote environments.

In recent years, LoRa technology has witnessed significant advancements, including the development of mesh networking techniques, artificial intelligence-based optimization methods, signal reconstruction under low signal-to-noise ratio conditions, and satellite-based LoRa communication for global connectivity. These innovations have expanded its applicability and improved overall system performance. However, despite these advantages, LoRa still faces several challenges such as limited data rates, packet collisions, interference, and scalability issues in dense network deployments. This review paper aims to provide a comprehensive overview of LoRa technology by analyzing its architecture, protocols, recent research contributions, and practical applications, while also highlighting existing challenges and future research directions to support the development of efficient, reliable, and scalable IoT communication systems

## II. LITERATURE REVIEW

This literature review centers on LoRa-based communication systems, offering a detailed examination of their core structure, the protocols they use, the latest technological improvements, and the new uses they are seeing in IoT and decentralized long-range networks.

Durand et al. (2025) [1] proposed a LoRa-based mesh network to overcome the limitations of single-hop LoRaWAN and demonstrated that multi-hop communication significantly improves packet delivery and coverage while maintaining low power consumption in IoT networks. Furthermore, they showed through simulation that the proposed approach enhances performance for distant nodes and supports scalable, reliable communication in dense IoT deployments.

Farfán et al. (2025) [2] designed and implemented a low-power LoRa-based communication system using ESP32 and DXLR01 modules to enable text transmission without relying on conventional network infrastructure. They demonstrated that the system achieves reliable communication with low energy consumption and acceptable latency, making it suitable for IoT applications in remote or resource-constrained environments. Furthermore, their results showed that while communication remains stable over moderate distances, performance degrades beyond 1 km due to increased packet loss, highlighting the need for parameter optimization in long-range scenarios.

Carson et al. (2025) [3] proposed a self-healing automated network of Raspberry Pi edge devices that integrates LoRa long-range communication with Infrastructure-as-Code principles to maintain operational continuity in environments where conventional TCP/IP networking is unavailable. They demonstrated that fragmenting data packets with selective retransmission, combined with a containerised architecture and heartbeat-based automated failover, enables unresponsive services to be redeployed to alternative nodes within one second while mitigating LoRa's inherent bandwidth, collision, and line-of-sight limitations. The authors concluded that time-slotting transmissions is essential to prevent overlaps, and they recommended future extensions such as mesh networking, advanced scheduling algorithms, and LPWAN techniques to further strengthen resilience in remote or hostile deployments.

Liu et al. (2025) [4] presented LoRadar, a system designed to capture and analyze real-world satellite-ground LoRa signals, addressing challenges such as low SNR, Doppler effects, and unknown transmission parameters. They developed a blind detection mechanism based on parameter estimation and correlation techniques and introduced a large-scale IQ dataset that supports accurate signal analysis and advances research in satellite-based IoT communication.

Wang et al. (2024) [5] proposed SPARC-LoRa, a scalable and power-efficient LoRa-based IoT system designed for agricultural applications, integrating sensor nodes, gateways, and cloud services. They demonstrated that the system achieves reliable long-range communication with low power consumption and cost, while enabling real-time data monitoring through cloud platforms, making it suitable for smart farming environments.

Aldhaheri et al. (2024) [6] reviewed the role of LoRa technology in Agriculture 4.0 and highlighted its effectiveness in enabling long-range, low-power communication for smart farming applications. They discussed key aspects such as network architecture, channel modeling, routing, and energy management, while identifying research gaps and future directions for improving scalability, efficiency, and integration of AI-driven solutions in agricultural IoT systems.

Farej et al. (2024) [7] reviewed LoRa communication technology and highlighted its significance in IoT-based healthcare systems due to its long-range capability and low power consumption. They discussed its suitability for remote patient monitoring while identifying key challenges such as low data rates, packet loss, and latency, and suggested solutions like adaptive data rate and multi-hop networking to enhance performance and reliability. Furthermore, they emphasized that LoRa supports efficient transmission of low-data-rate biomedical signals and can improve healthcare accessibility, especially in remote and resource-constrained environments.

Osman et al. (2024) [8] proposed LoRaFlow, a novel signal reconstruction approach using rectified flow and diffusion-based generative models to recover high-quality LoRa signals under extremely low SNR conditions. They demonstrated that the method effectively reconstructs both amplitude and phase of signals, significantly improving communication reliability while maintaining compatibility with existing LoRa infrastructure. Furthermore, their results showed notable performance gains over traditional and neural-based methods, especially in noisy environments, enabling extended range and robust IoT communication.

Obiri et al. (2023) [9] evaluated LoRaWAN connectivity and range in a rural environment and reported that RSSI and SNR significantly influence coverage performance. They demonstrated reliable long-range communication with variations based on terrain and node placement, emphasizing optimal gateway positioning. Furthermore, their experimental results provided practical insights into real-world deployment challenges and highlighted the gap between theoretical and actual performance. In addition, they established a relationship model for coverage estimation, which can assist in planning and optimizing rural IoT networks.

Martinez-Gost et al. (2023) [10] introduced a LoRa-based split learning framework using expressive neural networks with DCT-based activation functions. They demonstrated high accuracy and communication efficiency even under low SNR and without channel state information. Moreover, their approach reduced computational and communication overhead, making it highly suitable for distributed intelligence in resource-constrained IoT devices. Furthermore, they showed that integrating communication design with learning models can significantly enhance system performance in wireless environments. In addition, their results highlighted the robustness of the proposed framework under varying channel conditions.

López Escobar et al. (2023) [11] proposed the JMAC multi-hop protocol for LoRa to enhance coverage and scalability. They showed that mesh networking and predictive wake-up mechanisms improve network lifetime and support large-scale IoT deployments. In addition, their simulation results indicated improved network capacity and reliability, particularly in challenging environments such as smart cities and industrial systems. Furthermore, the protocol demonstrated efficient energy utilization and adaptability under varying network densities, making it a strong candidate for next-generation LPWAN solutions. Moreover, their approach addressed key limitations of single-hop LoRa networks by enabling extended communication range through cooperative routing.

Bianco et al. (2022) [12] analyzed LoRa-based helmet-to-UAV communication links for search and rescue applications in harsh environments. They evaluated communication range and signal behavior under different user positions and terrain conditions using both simulations and experimental validation. They demonstrated that LoRa enables reliable long-range communication up to several kilometers while maintaining low power consumption. Furthermore, their results showed that multipath effects and user posture significantly influence received signal strength and link stability. They also highlighted that UAV-assisted LoRa systems can accelerate localization of victims in emergency scenarios. Additionally, their study emphasized the importance of propagation modeling for optimizing real-world deployment performance.

Álamos et al. (2022) [13] proposed DSME-LoRa, a novel MAC-layer integration that enables direct node-to-node communication beyond the limitations of traditional LoRaWAN architecture. They demonstrated that the system improves scalability, throughput, and reliability using time-slotted and multichannel communication. Furthermore, their analytical modeling and large-scale simulations showed enhanced performance in dense IoT deployments. They also highlighted that DSME-LoRa reduces dependency on centralized gateways and supports distributed IoT applications. In addition, their implementation on real hardware confirmed feasibility and efficiency in constrained environments. Moreover, the approach enables better energy-delay trade-offs compared to conventional LoRaWAN systems.

Zhong et al. (2022) [14] proposed a deep reinforcement learning-based approach to optimize spreading factor (SF) allocation in LoRa networks to reduce data collisions. They demonstrated that traditional methods like Min-distance and Min-airtime fail under dense network conditions. Their proposed DRL-based scheme significantly reduced collision rates by nearly 30% while maintaining energy efficiency. Furthermore, the study showed that adaptive SF allocation improves gateway capacity without requiring additional infrastructure. They also emphasized the importance of intelligent resource allocation for large-scale IoT deployments. Additionally, their results confirmed improved network scalability and performance in high-density scenarios.

Demeslay et al. (2022) [15] proposed a novel scheme for secure and discrete LoRa communications using a self-jamming approach to prevent eavesdropping. They modified both preamble and payload waveforms along with synchronization mechanisms to enhance privacy. Their results showed that the proposed scheme maintains good symbol error rate performance with minimal signal degradation. Furthermore, they demonstrated that physical-layer security techniques can complement traditional cryptographic methods in LoRa systems. They also highlighted that cooperative transmitter-receiver design improves robustness against interception. Additionally, their approach enhances confidentiality in both uplink and downlink communication scenarios.

Saban et al. (October 2021) [16] conducted an experimental analysis of LoRa/LoRaWAN performance in both indoor and outdoor environments to evaluate its practical limitations. They demonstrated that LoRa performs significantly better in outdoor scenarios due to reduced obstruction and improved line-of-sight conditions.

Furthermore, their results showed that elevating the gateway enhances signal strength and communication range. They also highlighted that LoRa is highly suitable for long-range IoT applications requiring low power consumption. In addition, their study emphasized the importance of deployment strategies in improving network reliability. Moreover, they concluded that environmental factors play a critical role in determining overall system performance. They further observed that signal attenuation is more severe in indoor environments due to walls and obstacles. Additionally, their findings suggest that careful placement of gateways can significantly improve network scalability and coverage.

Jones et al. (June 2021) [17] analyzed various time-synchronization techniques for LoRaWAN-based IoT systems, focusing on their efficiency and applicability. They evaluated GNSS-based, GPS-based, and LongShoT synchronization methods in different network scenarios. Furthermore, they demonstrated that accurate time synchronization is essential for coordinated communication and reliable data collection in distributed systems. They also highlighted challenges such as clock drift, energy constraints, and hardware limitations affecting synchronization accuracy. In addition, their proposed methodology helps in selecting optimal synchronization techniques based on application requirements. Moreover, they concluded that synchronization remains a critical yet underexplored aspect of LoRa networks. They further emphasized that improper synchronization can lead to data inconsistency and reduced system efficiency. Additionally, their work highlights the trade-off between synchronization accuracy and energy consumption in IoT devices.

Yazdani et al. (July 2021) [18] proposed ReDCoS, a novel application-layer coding scheme to recover corrupted LoRa frames and improve transmission efficiency. They demonstrated that traditional forward error correction mechanisms are insufficient in high-interference environments. Their results showed significant improvements in decoding performance and energy efficiency, with up to multiple-fold gains over existing methods. Furthermore, they highlighted that reducing retransmissions directly lowers energy consumption in IoT devices. They also emphasized that the proposed scheme works without modifying existing LoRa infrastructure. Additionally, their experimental validation confirmed enhanced reliability in real-world deployments. They further noted that high frame corruption rates are common due to interference and long transmission distances. Moreover, their approach helps in maintaining network stability under heavy traffic conditions.

Dakic et al. (2021) [19] proposed a deep learning-based approach for LoRa signal demodulation using convolutional neural networks. They demonstrated that traditional non-coherent demodulation techniques are less effective under channel impairments such as noise and frequency offsets. Their results showed that the proposed CNN-based method achieves performance close to optimal coherent detection. Furthermore, they highlighted that deep learning improves robustness against non-linearities and signal distortions. They also emphasized the potential of AI-driven techniques in enhancing wireless communication systems. Additionally, their study confirmed improved bit error rate performance compared to conventional methods. They further showed that the model performs well even under severe channel impairments. Moreover, their work indicates that deep learning can simplify complex signal processing tasks in modern communication systems.

Branch et al. (2020) [20] proposed a LoRa-based relay communication system for safe detonation of explosives in underground mining environments. They demonstrated that traditional wired and infrared systems limit operational safety due to restricted distance, whereas LoRa enables long-range wireless control. Furthermore, they designed a multi-hop relay network using initiator, relay, and detonator nodes to ensure reliable communication in non-line-of-sight conditions. Their results showed that LoRa signals propagate effectively over long distances in tunnels with line-of-sight but degrade rapidly otherwise. They also addressed challenges such as broadcast storms, contention, and duplicate message handling using TTL and sequence-based mechanisms. Additionally, their system achieved deterministic delay and robust performance in harsh underground conditions. Moreover, their experimental evaluation in real mines confirmed the feasibility of LoRa for industrial safety-critical applications.

Emmanuel et al. (2020) [21] proposed an optimization framework for spreading factor (SF) distribution in high-density LoRa networks to improve communication reliability. They demonstrated that traditional LoRaWAN systems based on pure ALOHA suffer from significant intra-SF and inter-SF collisions in dense deployments. Furthermore, they developed a mathematical model to analyze packet success probability considering transmission parameters and interference conditions. Their results showed that optimized SF allocation can increase success probability from around 58% to over 82%, significantly enhancing network capacity. They also highlighted that improper SF selection increases transmission time and collision probability, especially at higher spreading factors. Additionally, their study emphasized the importance of adaptive parameter tuning for large-scale IoT systems. Moreover, they concluded that optimization techniques can effectively improve scalability and performance in smart city applications.

Magrin et al. (2019) [22] conducted a simulation-based study to analyze LoRaWAN performance under different parameter configurations. They demonstrated that parameters such as spreading factor, duty cycle, and acknowledgments significantly affect energy efficiency, reliability, and network capacity. Furthermore, their results highlighted complex interactions between network components, leading to performance degradation in large-scale deployments. They also identified limitations such as duty cycle constraints and gateway bottlenecks. Additionally, they concluded that optimized parameter tuning can improve scalability and overall system performance.

Xu et al. (2019) [23] performed an experimental study to evaluate LoRa performance in multi-floor indoor environments. They demonstrated that signal propagation is strongly affected by obstacles such as walls and floors, resulting in increased path loss and reduced coverage. Furthermore, their results showed that LoRa can maintain communication across floors but degrades under non-line-of-sight conditions. They also highlighted the impact of parameter settings on energy consumption. Additionally, they concluded that adaptive configuration is essential for efficient indoor IoT deployments.

El Rachkidy et al. (2018) [24] proposed novel algorithms to decode superposed LoRa signals in the presence of collisions. They demonstrated that by exploiting timing information, it is possible to recover multiple overlapping transmissions instead of losing all packets. Furthermore, their results showed that the proposed method can successfully decode two colliding signals and partially recover more in multi-user scenarios. They also highlighted significant improvements in network throughput compared to conventional LoRa systems. Additionally, they concluded that interference cancellation techniques can enhance scalability and efficiency in dense IoT networks.

Tessaro et al. (2018) [25] evaluated the performance of LoRa communication in short-range industrial environments with high noise and interference. They demonstrated that LoRa maintains reliable communication even in harsh conditions, with low packet loss and strong robustness to electromagnetic interference. Furthermore, their results showed that parameter selection, especially spreading factor and bandwidth, significantly affects performance and error probability. They also identified optimal configurations that achieve error rates below 0.2% while maintaining acceptable data rates. Additionally, they concluded that LoRa is suitable for industrial IoT applications despite challenging environmental conditions.

Mikhaylov et al. (2017) [26] conducted an empirical study to evaluate LoRaWAN scalability under inter-network interference. They demonstrated that transmissions with different data rates are not fully orthogonal and can negatively affect each other, especially in dense deployments. Furthermore, their results showed that higher data rates are more susceptible to interference, reducing packet delivery success. They also observed that LoRa-modulated signals are more robust compared to FSK under interference conditions. Additionally, they concluded that interference-aware parameter tuning is essential for improving scalability and network reliability.

Blenn et al. (2017) [27] performed large-scale real-world measurements of LoRaWAN using The Things Network to analyze performance and usage patterns. They demonstrated that most transmissions involve small payloads and low spreading factors, indicating energy-efficient communication. Furthermore, their results showed that packet reception is often limited by distance, interference, and duty-cycle constraints. They also highlighted that increasing spreading factor and transmission power improves reliability but reduces data rate and capacity. Additionally, they concluded that real-world deployments exhibit uneven traffic distribution and require careful optimization for scalability. **Table 1. presents a comprehensive summary of existing research on LoRa communication technology, highlighting key methodologies, tools, and findings related to its architecture, performance optimization, and diverse IoT applications.**

| RESEARCHER NAME + YEAR | PURPOSE | ALGORITHM / MODEL USED | TOOLS / TECHNOLOGIES USED | CONCLUSION / RESULTS |
|---|---|---|---|---|
| Durand et al. (2025) | To develop a scalable LoRa mesh network overcoming single-hop limitations in IoT systems | Multi-hop mesh networking with routing optimization | LoRa modules, network simulators | Achieved improved packet delivery, extended coverage, and better scalability in dense IoT deployments |
| Farfán et al. (2025) | To design a low-power LoRa-based communication system for text transmission without internet | Point-to-point LoRa communication model | ESP32, DXLR01 modules | Demonstrated reliable low-power communication; performance degrades beyond 1 km due to packet loss |
| Carson et al. (2025) | To create a self-healing automated LoRa network using edge devices | Infrastructure-as-Code with packet fragmentation and retransmission | Raspberry Pi, containerized architecture | Enabled fast failover (<1 sec), improved resilience, and reduced service downtime in harsh environments |
| Liu et al. (2025) | To analyze satellite-ground LoRa communication under challenging signal conditions | Signal detection, correlation, and parameter estimation techniques | IQ datasets, signal processing tools | Improved signal detection under low SNR and enabled advancements in satellite IoT communication |
| Wang et al. (2024) | To design a scalable and energy-efficient LoRa-based smart agriculture system | SPARC-LoRa architecture integrating IoT layers | Sensors, gateways, cloud platforms | Enabled real-time monitoring with low power consumption and cost, suitable for smart farming |
| Aldhaheri et al. (2024) | To review the role of LoRa in Agriculture 4.0 systems | Analytical survey of IoT communication models | IoT frameworks, AI-based systems | Identified challenges in scalability, routing, and energy efficiency, suggesting AI-driven improvements |
| Farej et al. (2024) | To analyze LoRa applications in healthcare IoT systems | IoT communication and network models | Medical sensors, LoRa modules | Highlighted suitability for remote monitoring with challenges in latency, packet loss, and data rate |

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|---|---|---|---|---|
| Osman et al. (2024) | To reconstruct LoRa signals under extremely low SNR conditions | Diffusion-based generative models (LoRaFlow) | AI/ML models, signal reconstruction tools | Improved signal quality, extended communication range, and enhanced reliability in noisy environments |
| Obiri et al. (2023) | To evaluate LoRaWAN connectivity and range in rural environments | RSSI and SNR-based propagation model | LoRa gateways, field experiments | Showed terrain and node placement significantly affect coverage and reliability |
| Martinez-Gost et al. (2023) | To enable over-the-air computing using LoRa for satellite IoT | Collision-based parameter estimation model | Satellite IoT systems | Improved bandwidth efficiency, reduced latency, and enabled scalable IoT computation |
| López Escobar et al. (2023) | To enhance LoRa scalability using multi-hop communication | JMAC multi-hop protocol | LoRa nodes, simulation tools | Improved network lifetime, scalability, and reliability in large-scale deployments |
| Bianco et al. (2022) | To analyze LoRa-based UAV communication for rescue operations | Signal propagation and modeling techniques | UAV systems, LoRa devices | Achieved reliable long-range communication and improved victim localization efficiency |
| Álamos et al. (2022) | To enable direct node-to-node communication in LoRa networks | DSME-LoRa MAC protocol | Time-slotted multi-channel systems | Improved throughput, reduced latency, and minimized gateway dependency |
| Zhong et al. (2022) | To optimize spreading factor allocation in dense LoRa networks | Deep Reinforcement Learning (DRL) | AI models, LoRa simulators | Reduced collisions by ~30% and improved network efficiency and scalability |
| Demeslay et al. (2022) | To enhance security in LoRa communication systems | Self-jamming communication model | Modified waveform and synchronization design | Improved confidentiality with minimal performance degradation |
| Saban et al. (2021) | To evaluate LoRa/LoRaWAN performance in real-world environments | Experimental analysis model | LoRaWAN testbeds | Demonstrated better outdoor performance and highlighted importance of deployment strategy |
| Jones et al. (2021) | To analyze time synchronization techniques in LoRaWAN networks | GNSS, GPS, and LongShoT synchronization models | Synchronization frameworks | Improved coordination and highlighted trade-offs between accuracy and energy consumption |
| Yazdani et al. (2021) | To improve reliability by recovering corrupted LoRa frames | ReDCoS coding scheme | LoRa protocol stack | Reduced retransmissions and improved energy efficiency in IoT networks |
| Dakic et al. (2021) | To enhance LoRa signal demodulation performance | CNN-based deep learning model | Neural networks, signal processing tools | Achieved near-optimal detection and improved robustness under noisy conditions |
| Branch et al. (2020) | To design LoRa communication for underground mining safety | Relay-based multi-hop LoRa model | LoRa nodes, industrial setup | Enabled reliable communication in non-line-of-sight and harsh environments |
| Emmanuel et al. (2020) | To optimize spreading factor distribution in dense networks | Mathematical optimization model | LoRaWAN simulators | Increased success probability from ~58% to ~82% and improved network capacity |
| Magrin et al. (2019) | To analyze LoRaWAN network performance and scalability | Simulation-based network model | LoRaWAN simulation tools | Identified scalability issues and trade-offs between latency, energy, and throughput |

| | | | | |
|---|---|---|---|---|
| Xu et al. (2019) | To evaluate indoor LoRa communication performance | Signal propagation model | Experimental indoor setup | Showed significant impact of walls and obstacles on signal strength and coverage |
| El Rachkidy et al. (2018) | To decode overlapping LoRa signals in collision scenarios | Interference cancellation algorithms | Digital signal processing tools | Improved throughput by recovering collided packets |
| Tessaro et al. (2018) | To evaluate LoRa performance in industrial environments | Experimental performance evaluation | Industrial IoT setup | Demonstrated robustness against noise and interference with low error rates |
| Mikhaylov et al. (2017) | To study LoRaWAN scalability under interference | Interference analysis model | Real-world experiments | Identified non-orthogonality of data rates and scalability limitations |
| Blenn et al. (2017) | To analyze real-world LoRaWAN deployment behavior | Measurement-based study | The Things Network | Highlighted uneven traffic distribution and need for network optimization |

## III. CONCLUSION

This review paper presents a comprehensive analysis of LoRa communication technology, highlighting its significance as a key enabler for large-scale, low-power IoT applications. From the literature, it is evident that LoRa offers substantial advantages in terms of long-range communication, energy efficiency, and cost-effectiveness, making it highly suitable for domains such as smart cities, agriculture, healthcare, and industrial systems. Recent advancements including mesh networking, AI-driven optimization, signal reconstruction techniques, and satellite-based LoRa communication have significantly enhanced its performance, scalability, and reliability. However, challenges such as limited data rates, packet collisions, interference, and scalability constraints in dense deployments still persist and require further research. Future work should focus on intelligent resource allocation, hybrid network architectures, and integration with emerging technologies to overcome these limitations. Overall, LoRa technology demonstrates strong potential to support next-generation IoT ecosystems by enabling efficient, reliable, and scalable wireless communication solutions.

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