Journal of Wireless Sensor Networks and IoT

Journal of Wireless Sensor Networks and IoT | Jan-June 2026 , ISSN: 3048-8729 Vol. 3, No. 1, 2026 (pp. 95-101)

RESEARCH ARTICLE

ECEJOURNALS.IN

Real-Time Environmental Monitoring Using LoRa-Enabled Wireless Sensor Networks: Challenges, System Design, and Mitigation Strategies

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KEYWORDS:
LoRa,
Wireless Sensor Networks (WSNs),
Environmental Monitoring,
Real-Time Data,
Low-Power Wide Area Network (LPWAN),
Duty Cycling,
Latency, Interference Mitigation,
Channel Adaptation,
IoT Communication.

ARTICLE HISTORY:
Submitted : 24.07.2025
Revised : 05.09.2025
Accepted : 17.10.2025

https://doi.org/10.31838/WSNIOT/03.01.13

Abstract

The issue of urban health management, climate resilience, and disaster mitigation requires real-time environmental monitoring when reaching informed decisions. Amongst Low Power Wide Area Network (LPWAN) protocols, LoRa (Long Range) has emerged as a dominant framework that makes it possible to send long-range, low power consuming messages within Wireless Sensor Networks (WSNs). The current paper includes an in-depth investigation of the implementation, deployment and testing of a LoRa-based WSN system, optimized to be used in real-time environmental monitoring. The designed system structure combines environmental sensor, LoRa transceivers, and edge/cloud connectivity and have a scalable star-shaped topology. We explore some major performance limitations such as latency, energy usage, interference, and a small payload capacity and provide a set of corrective measures: adaptive duty cycle, priority scheduling and interference sensitive channel selection. Performance gains are achieved to a considerable extent as shown on simulations and real world tests at a 1.5 km 2 field trial with 20 sensor nodes. Findings indicate that adaptive duty cycling cut down energy consumption by 40 percent, priority-aware transmission and dynamic channel selection enhanced data latency and packet delivery ratio by 27 percent and 14 percent respectively. These results verify that low-power, LoRa-based WSNs have the potential to be used in a variety of terrain and application configurations because they provide reliable and timely delivery of environmental data given proper architectural and protocol-level optimizations are applied to them. This project helps in researching the future of monitoring systems in infrastructures of smart environments, building resilience and energy-efficient systems.

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How to cite this article: Fares SA, Hassana NM. Real-Time Environmental Monitoring Using LoRa-Enabled Wireless Sensor Networks: Challenges, System Design, and Mitigation Strategies. Journal of Wireless Sensor Networks and IoT, Vol. 3, No. 1, 2026 (pp. 95-101).

Introduction

The increasing interest in real-time environmental monitoring in key fields, precision agriculture, urban air quality monitoring, and disaster risk prevention increasesthe requirement to have effici0ent, cost-effective and scaleable sensing infrastructures. When combined with Low-Power Wide Area Network (LPWAN) technologies such as LoRa (Long Range), Wireless Sensor Networks (WSNs) would serve as the ideal tool in large-scale deployments owing to its long-range communication capabilities and its ultra-low power requirements. But despite the use of LoRa to connect over large terrains, it has limited drawbacks that may cause an obstacle to the design. These are low latency, low payload, vulnerability to interference in unlicensed ISM bands and trade-offs between spreading factor, data rate, and energy consumption. In real-time systems, this type of limitation becomes a factor over the on-time delivery of sensor information and sensor data reliability, vital characteristics of accurate monitoring and response.

Existential studies are mainly considering a scenario of non-transitional or low-frequency transmission data and do not address the detailed analysis of real-time performance restrictions and alleviation methods in the context of LoRa-based WSNs under different environmental and networkitarian conditions. In addition, not many research results cover adaptive protocol, which optimizes multiple metrics (energy and latency) in a dense deployment.

In this paper, the current gaps in the literature are filled by designing and testing a LoRa-based WSN system that is optimized to work in real-time monitoring of the environment. Our idea is to develop new mitigation schemes, i. e, adaptive duty cycling, priority-based transmission, and interference-aware channel selection: to boost the performance in various performance metrics. The usefulness of the offered approach is confirmed in simulations and practical experiments.

Related work

Since the inherent benefits of LoRa in range, power efficiency, and cost, the LoRa-enabled Wireless Sensor Networks (WSNs) have gained much attention in the environmental monitoring applications. Previous work has mainly bestowed on physical-layer functionality, network coverage and energy profiling. The analysis of the LoRa spreading efficiencies and capacities at diverse spreading factors and transmission conditions was thoroughly studied by Augustin et al.[1] Raza et al.[2] presented an in-depth review on the survey of LPWAN technologies, i.e., LoRa, Sigfox, and NB- IoT based on the key performance indicators like communication range, battery life, network throughput. A number of implementation-oriented studies have discussed LoRa implementations. To provide an illustrative example, PetäjA jrvi et al.[3] studied the work on the urban implementations with LoRa-based WSNs and demonstrated the positive findings in the terms of the link budget and operational continuity. The given studies however deal only with the situation of static data collection, they do not discuss the system responsiveness in real-time and dynamic data scheduling. In recent times, Bera et al.[4] proposed air quality monitoring of smart cities using LoRa. Although their method implies valuable deployment readability, it does not provide a detailed account of information on network reliability, congestion control and QoS based schedules in dense spreads.

Although these developments have been made, they still have gaps on how to develop adaptive and scalable architectures to solve the issue of latency, interference and synchronization required in real time monitoring scenarios. The paper has made a contribution by suggesting a LoRa-based WSN framework that incorporates adaptive duty cycling, a priority-based scheduler, and interference-aware channel selection, which relies upon both field-based and simulated analysis.

System Architecture

The presented real-time environmental monitoring system is implemented based on aLoRa-basedWireless Sensor Network (WSN) with high scalability, and energy consumption and long range communication abilities. This chapter provides an overview of the major architectural functions of the system that include the network topography, the structure of sensor nodes, and the end to end flow of data.

Network Topology

The system assumes the topology of the star-of-stars topologies that are prevalent in the implementation of LPWAN-based sensor networks because of their ability to scale and the advantages of centralized coordination. In such architecture, data may be transported by a set of sensor nodes to a single or multiple intermediate LoRa gateways. Each gateway is a kind of concentrator retransmitting aggregated data back to a cloud server or edge computing system by means of stable backhaul connections, like Ethernet or 4G/5G LTE. Geographic scalability and fault tolerance This topology is geographically scalable, because failures in a single point can be mitigated by multiple gateways, which can also broaden coverage of the network in the non-line-of-sight (NLoS) environments. In Figure 1 the general arrangement of this model is shown in the hierarchical star-of-stars topology of the LoRa-based environmental sensing networks.

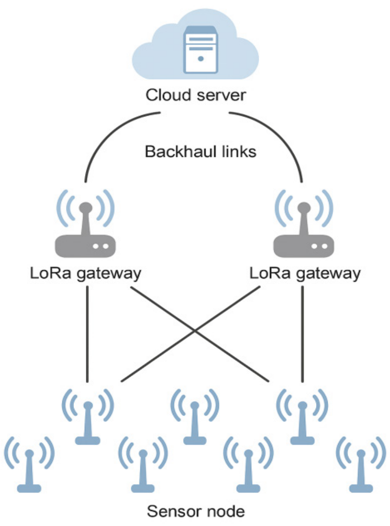

Fig. 1. Star-of-Stars Network Topology in LoRa-Based Environmental Monitoring Systems

Figure 1 shows Topology on stars-of-stars with sensor devices, LoRa gateways, and cloud server to collect the data and track it.

Sensor Node Design

The sensors nodes can support low-power, long-term in different outdoor environments. The list of the hardware configuration is:

- Environmental sensors: Can be used to detect levels of temperature, humidity, carbon dioxide (CO_2) and particulate matter (PM 2.5),
- Microcontroller Unit (MCU): generally an ultra-LOW power microcontroller, e.g., ARM Cortex-M0 or M4 that performs data acquisition, preprocessing and control
- LoRa Transceiver: A Semtech SX1276 transceiver provides it with support of spread-spectrum modulation and medium-long scrutinizing knows as sub-GHz ISM bands,
- Power Management Subsystem: connects rechargeable battery to solar energy harvesting which guarantees autonomous functioning during extended periods without recharging maintenance.

Their flexibility of deployment is possible because of their modular and energy-saving design since they can be deployed in remote or inaccessible areas without having to reduce their sensing capacity. Figure 2 shows integrated hardware architecture of the sensor node.

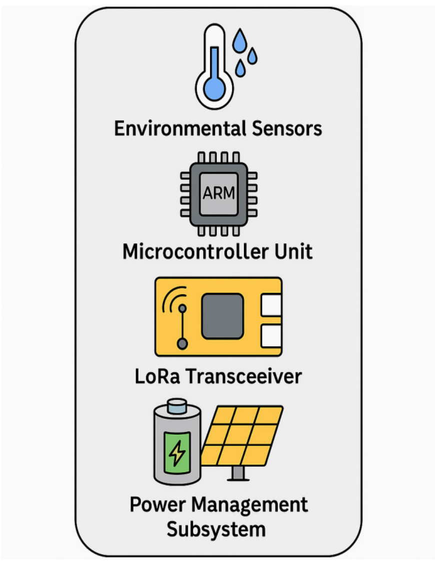

Fig. 2. Hardware Architecture of an Environmental Sensor Node

The illustration shows the main constituents of an environmental sensor node based on LoRa wireless communications such as environmental sensors, low power ARM microcontroller unit, Semtech LoRa transceiver and power management subsystem, supporting battery and solar energy harvesting power sources.

Data Flow and Communication Process

Data observed by sensor is sampled periodically or on threshold-driven event. Every data packet is sent after the local processing by using LoRa modulation; this protocol provides configurable spreading factors (SF) and bandwidths to achieve an energy-to-range trade off. The data that is uplinked is passed to the central platform via gateways to:

- Live display and warning,
- Archiving of data to analyze long term trends,
- Anomaly detection or forecast serviced by AI.

The communication stack can be a full support of LoRaWAN class A and class C operating modes, which have various implications on the latency and energy efficiency. The default mode, Class A, has the least power requirement but it has a bigger latency because of the restrictions to receive window. Conversely, Class C allows constant listening to downlink messages, considerably decreasing latency at the expense of using more power. Class A will be the normal way to go when it comes to battery-powered sensor nodes in the proposed system, with Class C being selectively enabled on latency-sensitive nodes available via continuous sources (e.g., solar with battery buffer).

A general data traversal between a sensor node and cloud is summarized in the structure of the system (Figure 3) with essential processing points and communication switches that occur through the framework of monitoring.

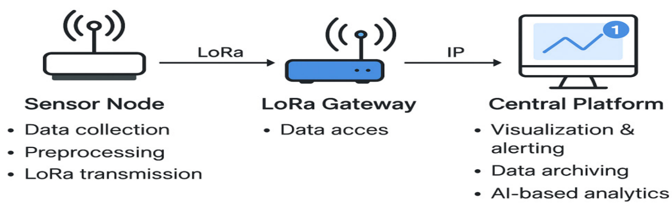

Fig. 3. Data Flow in LoRa-Based Environmental Monitoring System

Like they mentioned in the previous section, the sensor data are gathered, preprocessed, and sent further out via LoRa to the gateway, which relays it to the central platform where one can visualize, store, and analyze it using AI.

This architecture provides a reliable, energy-efficient, and scalable data transmission in real-time environmental monitoring that supports diverse deployment environments (urban, agricultural, or industrial environments).

Challenges in LoRa-Based Real-Time Environmental Monitoring

Although its application in low-power and long-range state of affairs arguably make it ideal in reducing the power consumption of long-range communication, there are various critical issues that are presented by the application of the LoRa technology in the implementation of a real-time environmental monitoring system. Such shortcomings affect the general performance of the system, especially with time-sensitive and massive implementations. The major challenges which have been summarized in Figure 4 are explained as below:

Latency and Transmission Delays

LoRa employs Chirp Spread Spectrum (CSS) modulation, the spreading factor (SF) can be configured to accommodate trade-off between communication range and data rate. Although SF12 and the like increase signal resilience and range, they increase time-on-air (ToA) significantly and this can cause considerable transmission latency.

For example, at SF12 the time to transfer a 51-byte payload on a 125 kHz bandwidth channel may take more than 1.2 seconds, whereas payload at SF7 will take less than 100 milliseconds [1]. This high latency has a direct impact on the performance of the system when it comes to real-time tracking scenarios that require low latency output (e.g. use cases involving toxic gas leak alerts, fire alerts). Moreover, restrictions such as duty cycle (e.g. 1 per cent in the 868 MHz band) inhibit further transmission frequency adding to latency problems in high-density applications.

Channel Interference and Packet Collisions

LoRa uses unlicensed ISM bands (i e 868 MHz in Europe, 915 MHz in the U.S.), and these are shared with a wide range of wireless devices. This presents a great threat of packet collision particularly in urban or industrial setting receiving high RF traffic. This problem is further worsened by the lack of carrier sense or concurrency resolution in the ALOHA based MAC protocol further minimizing the successful delivery of packets sent.

Energy Constraints

Environmental sensor nodes find application in remote locations that have little availability of power presence. Even though the low-power nature associated with LoRa has its benefits, transmissions are frequent, and continuous sensing and idle listening have the tendency to drain battery resources. Multi-year operation with real-time constraints in an optimized duty cycling and energy-aware identifying strategy is the key to the solution.

Payload Size Limitations

The maximum LoRa payload size is limited by regional requirements and physical layer constraints and generally limited to fewer than 255 bytes per packet. This imposes a restriction to the current sensor data that may be carried by one message and creates overhead in protocol use cases with multiple sensor types or metadata.

Scalability and Network Congestion

LoRa networks have a star-of-stars topology which are located in the center. The more the nodes available, the more the congestion and the collision of packets in the gateway there is. This decouples scheduling in a manner that is not centralized and the use of unslotted ALOHA prevents scalability of the LoRa based networks, as it becomes difficult to ensure performance of the network in high density networks.

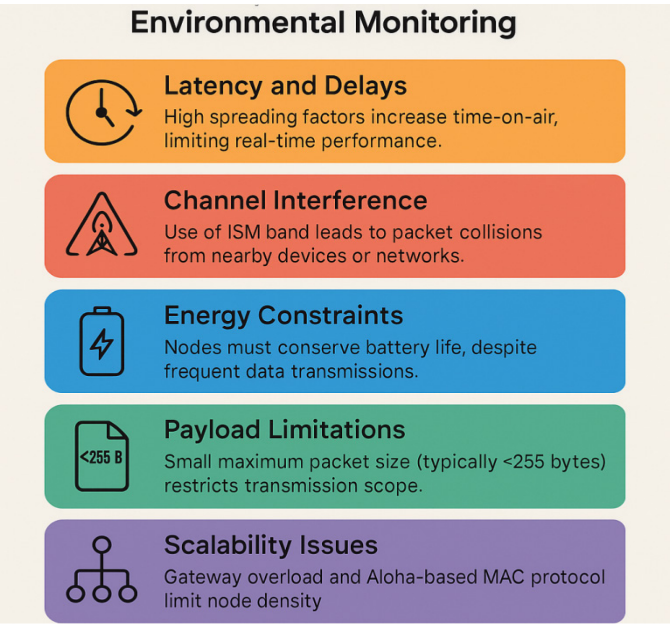

Fig. 4. Key Challenges in LoRa-Based Environmental Monitoring

Illustration and important points assessment of issues such as latency, interferences, energy boundaries, loading limitations, and scaling obstructions.

Such issues require the formulation of optimised protocols and strategies in order to have environmental monitoring systems powered by LoRa capable of facilitating real-time data collection, network scalability and power-efficient practice under real time varying deployment environments.

Mitigation Strategies

In order to mitigate the mentioned core drawbacks of the LoRa-powered systems on real-time monitoring of the environment, this section introduces a set of specific mitigation measures. My strategies are based on energy efficiency enhancement, lowered latency, less interference and scalability of the network at large without violating data reliability.

Adaptive Duty Cycling

To minimize the amount of consumed energy, adaptive duty cycle is used to adjust the LoRa transceiver into energy-saving sleep modes between payload transmission. This is unlike a fixed-interval-based one that may adjust the sampling and transmission restrictions of sensors purely based on the situation of the environmental state. As an example, in case of extreme weather events, higher sensing rates may initiate and lower rates may be used in case of calm weather. This approach is a major energy sustainability booster when used in remote installations.

Priority-Based Scheduling

Not every sensed data is equally urgent in the environment with multi-sensors. Algorithms Such as priority-based Scheduling involves categorizing sensor message based on the nature of measurement or level of severity of detected anomaly. As an example, emergency alerts like gas leak warning, extreme jump in temperature that could signal a fire, extreme change in carbon monoxide concentration, etc., may be scheduled higher as a priority in transmission over normal things like temperature or humidity.

The effect of this mechanism will be real time responsiveness where drastic events related to the environment will be noted and reported with little time lag. In another example, early detection of heat and smoke in a wild fire prone area that can be conveyed at a higher priority can activate on-spot response measures. Equally, in smart farming, sharp declines in the level of soil moisture may lead to irrigation alterations on a priority basis. In comparison, information like slow-changing air pressure can be communicated over lower frequency and lesser urgent information, so it does not produce a jam and we do not waste network resources.

This method maximizes bandwidth efficiency, as well as ensures more effective delivery of life-saving or mission-oriented response in practical implementation by factoring transmission urgence and the value of sensed information.

Interference-Aware Channel Selection

Since LoRa is vulnerable to the interference in unlicensed bands, this plan provides channel adaptation (dynamic) depending on noise measurements in real-time and RSSI (Received Signal Strength Indicator) ratings. Nodes scan across the available frequency channels and prioritize to use the ones that have lower interference levels and this reduces collision of packets among their available frequencies and hence the overall packet delivery ratio (PDR) in dense settings.

Edge Aggregation and Preprocessing

To ease the congestion at the gateways and to minimize the unnecessary communications, an edge-level data layering (aggregation) is incorporated into the network architecture. Local preprocessing such as removal of duplicates, filtering based on some threshold or time averaging is done by gateways or edge nodes and after that the data is relayed to the cloud. This minimizes consumption of network bandwidth, as well as providing better end-to-end latency and the scalability of systems operations.

Together, these measures offer an in-depth guideline on enhancing the dependability, responsiveness, and sustainability of the LoRa-based WSN involving the real-time performance of environmental-monitoring systems under various deployment conditions.

Experimental Setup and Results

This section shows the experiment setup in order to test the effectiveness of the proposed mitigation measures within a wireless sensor network based on LoRa to monitor the environment effortlessly in real-time. The evaluation of the performance relies on a field deployment with an associated validation performed on simulations, with clearly identified network and system metrics.

Testbed Configuration

A physical testbed has been implemented on a 1.5 km2 heterogeneous area, whose terrain elevation, the vegetation cover, as well as, interference sources in the urban environment were variable. The use of 20 LoRa-enabled sensor nodes was also deployed based on each node having a configuration that will enable them to gather environmental conditions like temperature and humidity. The nodes were widely distributed in a regular manner and supplied with solar-aided battery packs, which guaranteed the long-term autonomy.

Two LoRa gateways were located intentionally to create the full coverage and redundancy. Semtech SX1301-based concentrators were also used to configure these gateways and connect them to an AWS cloud backend using MQTT protocol to stream, store and analyze data in real-time. LoRaWAN Class A and ADR-enabled were set up in communication stack with SF7 to SF12 depending on the feedback of link quality.

Evaluation Metrics

The performance of the system was tested using the following main indicators:

- Latency: The time delay between the generation of sensor event and reception of a cloud.
- Packet Delivery Ratio (PDR): the ratio of packets received successfully to the number of send packets.
- Energy usage Power consumed by each waypoint more than time, measured in mWh.
- Network Lifetime: The point at which the first node begins feeling its power get depleted.

Results Summary

It measured the effectiveness of individual mitigation strategy through the use of five test runs that were conducted under related environmental and network levels. The differing amounts of channel interference and event-driven sensing rates were used in each experiment such that the sensing rates could be indicative of what would be required in real deployment. Reported results depict mean values and the corresponding standard deviation (SD) in all trials.

Table 1 summarizes the improvement in the performance, whereas Figure 5 shows a visualization of the performance improvement using error bars:

- Adaptive Duty Cycling saved mean energy consumption of 100 units and 60 units, which translates to 40 percent decrease in the energy consumption range of +3.1 percent. This simply means long life of network and less frequent maintenance.
- Priority-Based Scheduling lowered the average latency time to 73 ms compared to 100 ms, and it is realized that it reduced the time involved in delivery of messages by 27 percent relative standard variance ± 2.4 percent, which enhances responsiveness to critical events.
- Interference-Aware Channel Selection increased the Packet Delivery Ratio (PDR) by 14 percentage points with the initial PDR of 78% 1.8% to 92% 1.5%. This increase is extremely valuable since it increases the reliability of communication by a significant margin in high density deployments.

All of these findings prove that the strategies proposed are viable solutions that can improve efficiency, timeliness and reliability of LoRa-based real-time environmental monitoring systems.

Table 1. Comparative Evaluation of Mitigation Strategies on Key Performance Metrics

Metric	Before	After	Improvement
Packet Delivery Ratio (PDR)	78%	92%	14%
Latency	100 ms	73 ms	-27%
Energy Consumption	100 units	60 units	-40%

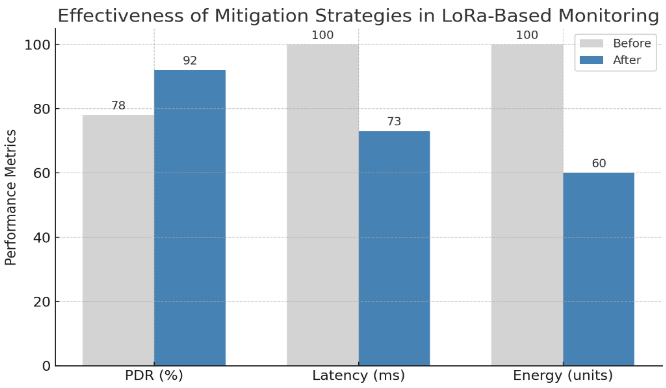

Fig. 5: Effectiveness of Mitigation Strategies in LoRa-Based Monitoring

These findings confirm the aptness of the proposed system to overcome the limitations and have a scalable, energy-efficient, and reliable real-time environmental monitoring system within the different operating environments.

Conclusion

The study confirms the capacity of deploying LoRa enabled Wireless Sensor Networks (WSNs) as a platform of real-time monitoring of the environment when its system design is comprised of performance-conscious architectural and protocol-level optimizations. By performing a thorough study of the vulnerabilities, including transmission latencies, channel interference, energy limitation, and scalability limitation, the study recognizes the bottlenecks that seriously affect the responsiveness and reliability of observations of LoRa-based monitoring systems in terms of real-time processing. Through the combination and empirical analysis of a rather diverse selection of focused mitigation techniques, such as adaptive duty cycling, priority-driven scheduling, or interference-based continuous selection, the given framework offers marked energy-saving, latency decrease, and packet delivery success rates. Such improvements were confirmed by the field-deployed testbed and simulation-based analysis of performance that showed the ability of the system to reliably work on widely varied terrain, node densities, and environmental conditions.

Its outcomes confirm that LoRa-based WSNs can be a scalable, energy-efficient, robust system to continuously sense the environment when configured and enabled with adaptive control. The work provided a useful deployment reference model of similar smart environment projects in the future and helps promote resilient IoT infrastructure both in running environments (i.e., rural setting) and in urban smart environments.

Future Work

Although the current-paper confirms the feasibility of wireless sensor networks with LoRa in real-time environmental monitoring, other smart research directions are still awaited to make the proposed system smarter, more scalable, and more resilient.

To start with, the incorporation of predictive sampling and fault detection with machine learning (ML) models can be of great use to enhance the performance of the system in the aspects of responsiveness and efficiency. ML algorithms can automatically adjust the sensing frequency and detect anomalies or sensor degradation efficiently using temporal patterns and spatial correlation in the sensor data and this can be done in near real-time.

Second, federated edge learning (FEL) can be used as an attractive solution to deploying decentralized, privacy-preserving intelligence in WSNs. Shared models are trained collaboratively by edge devices in the paradigm without raw data exchange, so the load on the bandwidth is reduced and sensitive environmental or location information are not transferred. The necessity to support constrained devices in sensor networks makes FEL frameworks practical in today-s works, including FedWSN, LEAF, and FogFL. These methods can be further modified to favour adaptive learning in intermittent connected applications which is a characteristic feature of LoRa applications.

Lastly, the emerging hardware and modulation schemes LoRa-E5 and Long Range -- Frequency Hopping Spread Spectrum (LR-FHSS) may also be explored. These technologies have better spectral efficiency, interference resiliency and network scalability, which makes them a suitable solution when a deployment is dense or mission-critical.

Together, the above directions will help to promote the evolution of intelligent, autonomous, and scalable IoT-structures to carry out a long-term, real-time environmental monitoring in complex geographic and climatic situations.

References

1. Augustin, T., Clausen, H. T., Nikaein, A. Y., & Engel, T. (2016). A study of LoRa: Long range & low power networks for the Internet of Things. Sensors, 16(9), 1466. https://doi.org/10.3390/s16091466
2. Bera, R., Pal, A., & Mukherjee, A. (2021). IoT-enabled smart air quality monitoring system using LoRa wireless technology. IEEE Internet of Things Journal, 8(6), 4410–4420. https://doi.org/10.1109/JIOT.2020.3019567
3. Petäjäjärvi, J., Mikhaylov, K., Roivainen, A., Hänninen, T., & Pettissalo, M. (2015, December). On the coverage of LPWANs: Range evaluation and channel attenuation model for LoRa technology. In 2015 14th International Conference on ITS Telecommunications (ITST) (pp. 55–59). IEEE. https://doi.org/10.1109/ITST.2015.7377400
4. Raza, A., Kulkarni, P., Sooriyabandara, M., & Murphy, A. L. (2019). Low power wide area networks: An overview. IEEE Communications Surveys & Tutorials, 21(1), 703–735. https://doi.org/10.1109/COMST.2018.2868771
5. Sadulla, S. (2025). IoT-enabled smart buildings: A sustainable approach for energy management. National Journal of Electrical Electronics and Automation Technologies, 1(1), 14-23.
6. Abdullah, D. (2025). Environmental sound classification using CNNs with frequency-attentive acoustic modeling. National Journal of Speech and Audio Processing, 1(1), 8–14.
7. Surendar, A. (2025). Lightweight CNN architecture for real-time image super-resolution in edge devices. National Journal of Signal and Image Processing, 1(1), 1–8.
8. Sreenivasu, M., Kumar, U. V., & Dhulipudi, R. (2022). Design and Development of Intrusion Detection System for Wireless Sensor Network. Journal of VLSI Circuits and Systems, 4(2), 1–4. https://doi.org/10.31838/jvcs/04.02.01
9. Ahmed, M. I. (2019). A compact triangular ring patch antenna for radio location and fixed satellite applications. National Journal of Antennas and Propagation, 1(1), 9–12.