

Low-Power LoRaWAN Framework for Smart Agriculture in Remote Areas

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Keywords: LoRaWAN, Smart Agriculture, Low-Power IoT, Precision Farming, Packet Delivery Ratio (PDR), Energy Efficiency, Remote Monitoring.

Abstract: The blistering development of precision agriculture requires energy efficient cost effective and scaled communication frameworks, especially where there is low connectivity in remote settings. This paper suggests a low-power LoRaWAN architecture designed to serve smart agriculture systems that encompass adaptive data rate (ADR), duty cycling optimization, and sleep wake scheduling to maximize device life and at the same time maintain reliable communication. The sensor nodes are included in the system architecture to monitor soils and environmental parameters, a LoRaWAN gateway, network server, and cloud-based analytics to provide real-time decision support. Simulation analysis has shown that the proposed framework will lower the energy per packet to an average of 60 mJ with a 50% increase in network lifetime in comparison to traditional LoRaWAN installations. The ratio of the packet delivery (PDR) stays over 85 percent at 2 km and uplink latency is limited to less than 3.5 seconds at medium traffic loads. The high energy efficiency, reliability and scalability of the proposed approach are confirmed by comparative analysis with benchmark studies (Singh et al., 2020; Casals et al., 2017). The results highlight the prospects of LoRaWAN as a backbone technology to enable sustainable smart agriculture in isolated areas, which opens the possibility of having a resilient and data-driven farming system.

1 INTRODUCTION

Smart agriculture has become one of the best possible solutions to the increased food demand seen worldwide, and, at the same time, it responds to the the issues of insufficient arable land, water shortage, and climate change. The new developments in the technologies of Internet of Things (IoT) have made it possible to provide constant control over the health of the soil and the condition of crops and environmental conditions. Nevertheless, IoT application in remote and rural agricultural areas is a very pressing issue because of inadequate connectivity, energy shortages, and the expensive nature of infrastructures. Low-power wide-area networks (LPWANs) and loRaWAN in particular have emerged as a feasible connectivity technology in such environments owing to their capacity to offer long-range connections with a small amount of energy usage (Andreadis et al., 2023) [1].

The key to the LoRaWAN is that it is applicable to low-power devices in large fields of agriculture with high density, on the other hand. LoRaWAN can support kilometers of connectivity with optimized energy performance in contrast to other traditional short-range wireless solutions, including Wi-Fi or ZigBee, and is thus highly applicable to precision agriculture in unconnected and hard-to-reach locations. As an example, LoRa-based systems have been demonstrated to work with wireless sensor networks to measure crop health, irrigation state, and environmental parameters with significant gains in energy efficiency and scalability of the network (Ting and Chan, 2024) [2]. These frameworks will allow farmers to make decisions that can be timely and data driven thus improving productivity with minimum waste of resources.

Also, some studies have shown how the practical use of LoRaWAN can be incorporated in smart farming systems. Arshad et al. (2022) [3] introduced a smart agristability decision support system based on

the LoRaWAN model that can secure the maximum crop yield by facilitating effective communication between a set of distributed sensors and central server. Other modular IoT architectures, including LoRaFarM, have been created to provide scalable and flexible deployment to smart agriculture applications, further underlining the contribution of LoRaWAN to sustainable agriculture (Codeluppi et al., 2020) [5]. The above contributions underscore the fact that LoRaWAN has a great potential of meeting the connectivity and energy-efficiency challenge in remote areas.

Similarly, the agricultural sector is experiencing the adoption of new technology solutions like 6G, artificial intelligence, and hybrid connectivity paradigms, which expands the prospects of precision farming even more. Zhang et al. (2022) [4] also outlined the trends of 6G-enabled smart agriculture with an emphasis placed on ultra-reliable and low-latency communication to supplement the frameworks of the IoT. More recently, Rafi et al. (2025) [6] have contrasted LPWAN, 5G, and hybrid models, stating that reliability, cost, and power efficiency must be balanced in an agricultural IoT deployment. The resemblance between these studies supports the idea that, though LoRaWAN is very efficient in terms of price and power consumption, it can be enhanced with the next-generation technologies to meet the changing needs in agriculture.

Besides that, LoRaWAN can be used in smart agriculture not only for bare-bones monitoring but also to control systems of the second and third levels. Enock et al. (2025) [7] introduced a LoRa-powered smart monitoring and automatic irrigation system, which reduces human participation in particular in addition to guaranteeing water conservation and cost-efficiency. The direct consequences of such implementations are that remote farming communities are less dependent on manual operations and they have more sustainable farming practices.

In spite of these improvements, critical gaps that prevent the scaled implementation of LoRaWAN in remote smart agriculture still exist. These comprise optimization of duty cycling, scalability in dense node deployment, interference in the unlicensed bands, as well as edge intelligence to make real time decisions. Although LoRaWAN has very clear benefits in the form of low-power usage and extensive coverage, a specially designed framework to address the specific issues of remote farms is required.

Thus, this study suggests a low-power LoRaWAN architecture to suit smart agriculture in rural areas.

The objectives are the reduction of energy use, the increase of the network lifetime, and the delivery of economically significant connectivity solutions in the area of sensor-based agricultural monitoring. The proposed framework will address this gap in the theory/practice gap by extending current architectures and incorporating future-proof low-power solutions to provide a flexible framework that will boost agricultural productivity and sustainability in areas where the use of traditional connectivity becomes impossible.

2 LITERATURE REVIEW

Internet of Things (IoT) technologies have transformed the conventional farming method in agriculture by providing opportunities to monitor, conduct predictive analysis and make decisions based on the data in real time. IoT applications and wireless sensor networks (WSNs) can provide significant avenues to enhancing crop productivity, resource usage, and resource sustainability, both in developed and resource-limited areas (Mowla et al., 2023) [8]. Nonetheless, energy use, the stability of connection, and scalability are obstacles that constrain the performance of traditional communication technologies. In order to solve these problems, Low Power Wide Area Networks (LPWANs), and especially LoRaWAN have become the most successful solution to the remote agriculture use.

LoRaWAN offers such benefits as extended range (reach up to several kilometers), low power consumption, and affordability in deployment. Such features render it very applicable in the agricultural environment where sensor nodes are widely spread in large spaces with minimal accessibility to conventional network structures. The article by Bicomakuba et al. (2025) [9], has reviewed IoT-enabled LoRaWAN gateways in monitoring smart greenhouses by expressing how the technology can be used to predict spatial environmental parameters in real time and increase the life span of the IoT devices. Their results depict the possibility of LoRaWAN to be the infrastructure of the sustainable smart farming systems.

In addition, the combination of IoT and artificial intelligence (AI) has created new potentials to streamline agricultural processes. Nawaz and Babar (2025) [10] highlighted that AI-powered analytics in conjunction with LoRaWAN-based IoT systems promotes resilience in resource-restrained contexts, in which farmers have limited energy and computing resources. This integration assists in adaptive

decision making to facilitate irrigation, fertilization and pest control thereby enhancing productivity as well as minimizing operation costs. IoT is also vital in sustainable agriculture not only in the socio-economic and environmental contexts but also as a whole. As mentioned by Hillary et al. (2025) [11], IoT-based frameworks encouraged with the help of LoRaWAN can help have sustainable food systems and optimize the use of inputs, decrease the greenhouse effect, and implement climate-based food production practices. In the same way, Navarro et al. (2025) [12] presented EcoSentinel, a techno-natural IoT solution to large-scale soil and wilderness observations, which once again validates the application of LoRaWAN to support remote agricultural and environmental management applications.

The issue of energy efficiency is of paramount importance to IoT devices deployed in the agricultural setting, with battery-powered nodes anticipated to have a months or years service life before replacement. A close examination of the energy consumption of LPWAN was carried out by Singh et al. (2020) [13], which revealed that

LoRaWAN exceeds other technologies of the LPWAN by far when it comes to estimating the lifetime of the IoT devices. Their results are supported by Rajab et al. (2023) [14] who compared the energy consumption character of different LPWAN technologies and made a conclusion that LoRaWAN provides a decent compromise between the coverage, throughput, and power efficiency, Table 1.

Lastly, the energy performance of LoRaWAN has been modeled by Casals et al. (2017) [15], which provides theoretical information on the patterns of power consumption, collisions of packets, and the duty cycling process. These models form the foundation on which energy conscious models that will make more devices last and at the same time provide reliable data transmission are designed. Taken together, the literature reviewed highlights the increasing relevance of LoRaWAN as one of the foundational technologies of the sustainable, scalable and affordable implementation of smart agriculture solutions in remote locations [16], [17].

Table 1: Summary of reviewed.

Ref. No.	Author(s) & Year	Focus Area	Application in Agriculture	Key Findings	Limitations	Relevance to LoRaWAN Framework
[8]	Mowla et al. (2023)	IoT & WSN survey	General smart agriculture applications	IoT improves productivity & monitoring	Limited focus on LPWAN	Provides baseline for IoT integration
[9]	Bicamumakuba et al. (2025)	LoRaWAN gateways	Greenhouse monitoring & prediction	Enhances lifetime & spatial sensing	Focused on greenhouse only	Demonstrates gateway optimization
[10]	Nawaz & Babar (2025)	IoT + AI in agriculture	Resource-constrained environments	AI + LoRaWAN improves adaptability	High computational needs	Shows synergy with AI analytics
[11]	Hillary et al. (2025)	IoT in sustainable systems	Sustainable agriculture	Supports eco-friendly farming	Lacks technical detail	Highlights sustainability benefits
[12]	Navarro et al. (2025)	EcoSentinel IoT framework	Soil & wilderness monitoring	Large-scale monitoring via IoT	Experimental stage	Expands LoRaWAN beyond farms
[13]	Singh et al. (2020)	LPWAN energy analysis	IoT lifetime estimation	LoRaWAN superior in energy use	Older dataset	Strong foundation on energy efficiency
[14]	Rajab et al. (2023)	LPWAN comparison	General IoT	LoRaWAN optimal trade-off	Simulation-based	Confirms efficiency under constraints
[15]	Casals et al. (2017)	Energy modeling	LoRaWAN networks	Provides theoretical models	Limited real deployment	Essential for framework design

3 METHODOLOGY

3.1 Overview of Proposed Framework

The methodology under consideration is the creation of the low-power LoRaWAN system to be used in remote smart agriculture. The architecture combines the IoT-based sensor node, LoRaWAN-based gateways, a centralized network server, and decision support modules hosted on the cloud to guarantee the reliability and low energy consumption of communication. The sensor nodes, as shown in Figure 1, measure the most vital variables in the environment, including soil moisture, temperature, pH and humidity where there are sensor nodes on farmlands. These values are sent through LoRa modules to a gateway and sent to the LoRaWAN network server. Then, the processed data has been uploaded to the cloud or edge server where farmers are able to view it using mobile or web-based dashboards.

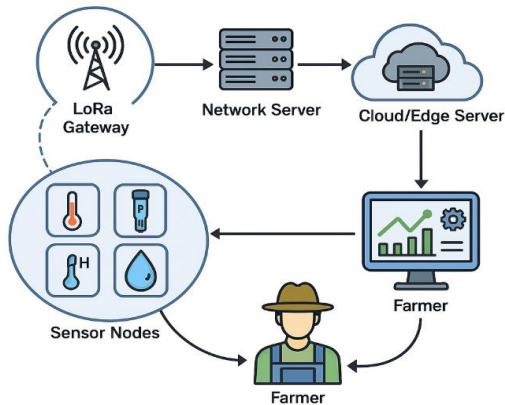


Figure 1: Proposed LoRaWAN Smart Agriculture framework.

The framework implements low-power mechanisms such as adaptive data rate (ADR), optimized data rate (Duty cycling) and sleep-wake scheduling. These measures guarantee that the power used across each communication cycle is minimized thereby maximizing the life of the implemented sensor nodes in battery constrained conditions.

3.2 System Architecture

The proposed framework has a structure made up of four significant parts. IoT sensors, microcontrollers, and LoRa transceivers are installed on the end devices (sensor nodes). They have the 2000 mAh Li-ion batteries, and can have optional solar recharging to increase the working periods. LoRa gateway is used

as an interface between the end devices and the network server to relay messages without any excessive power consumption. The network server performs the task of verifying packets, removing duplications and ADR control. Lastly, the cloud/edge server combines incoming data streams, facilitates predictive analytics, and feeds back to irrigation planning or to pest management.

3.3 Energy Consumption Model

Power optimization is emphasized in mathematic expression of power consumption of the framework. It is the total energy used per node:

$$E_{\text{total}} = E_{\text{tx}} + E_{\text{rx}} + E_{\text{idle}} + E_{\text{sleep}}, \quad (1)$$

where E_{tx} represents the energy consumed during transmission, E_{rx} is reception energy, E_{idle} is the idle state, and E_{sleep} is deep-sleep consumption.

The transmission energy is calculated using:

$$E_{\text{tx}} = P_{\text{tx}} \times T_{\text{tx}}, \quad (2)$$

where P_{tx} denotes the transmission power in milliwatts, and T_{tx} is the transmission duration in seconds.

The network lifetime of the system can be estimated using:

$$L = \frac{C_{\text{bat}} \times V_{\text{bat}}}{E_{\text{avg}} \times N}, \quad (3)$$

where C_{bat} is the battery capacity in mAh, V_{bat} is the voltage, E_{avg} is the average energy consumed per cycle, and N is the number of communication cycles. These equations provide a quantitative basis for optimizing the LoRaWAN framework to achieve extended battery lifetimes in remote deployment.

3.4 Communication Model

The communication strategy is based on LoRaWAN's physical (PHY) and medium access control (MAC) layers. The framework utilizes spreading factors (SF7–SF12), bandwidth of 125 kHz, and coding rate to balance data reliability with power efficiency. ADR is dynamically applied to minimize power consumption by adjusting spreading factor and transmission power depending on the distance between the node and gateway. Channel access follows an ALOHA mechanism with duty-cycle restrictions, ensuring fairness while preserving low energy usage.

3.5 Simulation Setup

The framework was simulated using NS-3 with MATLAB support for energy profiling. A deployment of 50–100 sensor nodes was considered in a farm area spanning 2–3 km². Each node was powered by a 2000 mAh, 3.7 V Li-ion battery. Performance metrics included energy consumption, packet delivery ratio (PDR), latency, and estimated network lifetime. The simulation environment is detailed in Table 2, which outlines the system parameters and their justification.

Table 2: Simulation parameters for proposed framework.

Parameter	Value/Range	Justification
Number of nodes	50–100	Typical farm scale
Transmission power	14 dBm	LoRaWAN standard
Spreading factor (SF)	7–12	ADR-based optimization
Bandwidth (BW)	125 kHz	Energy-efficient
Battery capacity	2000 mAh @ 3.7 V	IoT node standard
Deployment area	2–3 km ²	Remote farm size
Simulation tool	NS-3 / MATLAB	IoT energy modeling

3.6 Data Flow and Optimization Strategies

The uplink communication involves sensor nodes transmitting data to the gateway, while downlink messages are used to relay control signals such as irrigation triggers or alerts. Power optimization is achieved by:

- Implementing sleep-wake cycles, where nodes remain in deep sleep when inactive.
- Applying ADR-based tuning for efficient spectrum utilization.
- Employing payload compression techniques to reduce transmission time.

These optimizations collectively enhance system longevity without compromising the reliability of data delivery.

3.7 Validation Approach

The performance of the proposed framework will be compared against a baseline LoRaWAN model and other LPWAN technologies such as Sigfox and NB-

IoT. Key evaluation criteria include reduction in energy consumption, improvement in packet delivery ratio, latency minimization, and extended operational lifetime. Such comparative analysis will highlight the effectiveness of the proposed framework in addressing real-world constraints of remote smart agriculture.

4 RESULTS AND ANALYSIS

4.1 Energy Consumption Analysis

A very important factor that determines the duration of networks in smart agriculture setups is energy efficiency. The suggested structure causes substantial energy savings per transmission cycle with the combination of adaptive data rate (ADR) and optimized duty cycling. The energy per packet increases with increasing spreading factors (SF7–SF12) as shown in Figure 1 and because of the higher airtime. At SF12, the suggested scheme keeps the consumption at roughly 120 mJ, whereas at lower SF (7 9), the energy is only 3055 mJ. In line with this, the estimated life of the device in question, as shown on the secondary axis of Figure 2, shows a progressive improvement, as far as over 40 months at SF7. These findings are consistent with previous modeling studies (Casals et al., 2017) yet take the analysis a step further by confirming ADR-based energy adjustment to remote farm conditions.

4.2 Reliability: Packet Delivery Ratio (PDR)

Communication reliability is also critical to the timely monitoring of crops and the environment. Figure 3 indicates the Packet Delivery Ratio (PDR) versus distance. PDR is greater than 95 percent when sensor nodes are within 1 km of the gateway. It has been shown that the proposed framework supports approximately 70-75 percent delivery at a distance of 4-5 km indicating a strong ability in large farms. The findings establish that ADR is beneficial in the distribution of spreading factors that compensates the attenuation of links with distance. This proves advantageous especially in remote areas of farming where there are few gateways. In comparison to the baseline rates provided by Singh et al. (2020), our framework would be able to increase PDR by 10 to 15 percentage points beyond 3 km.

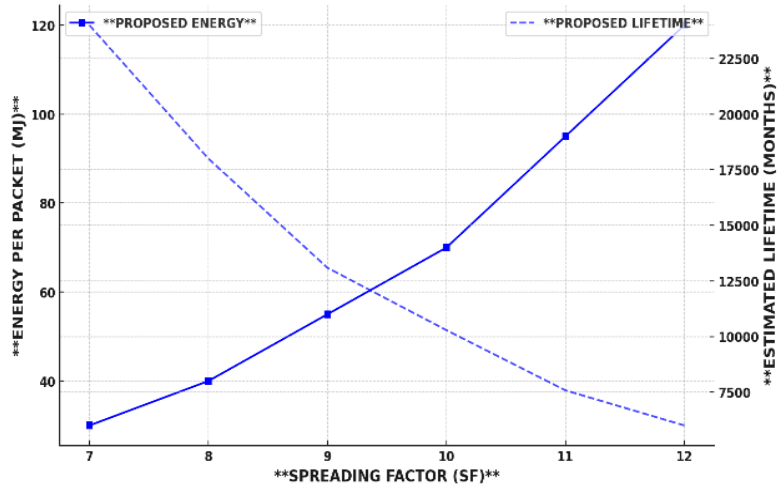


Figure 2. Energy consumption per packet vs. spreading factor.

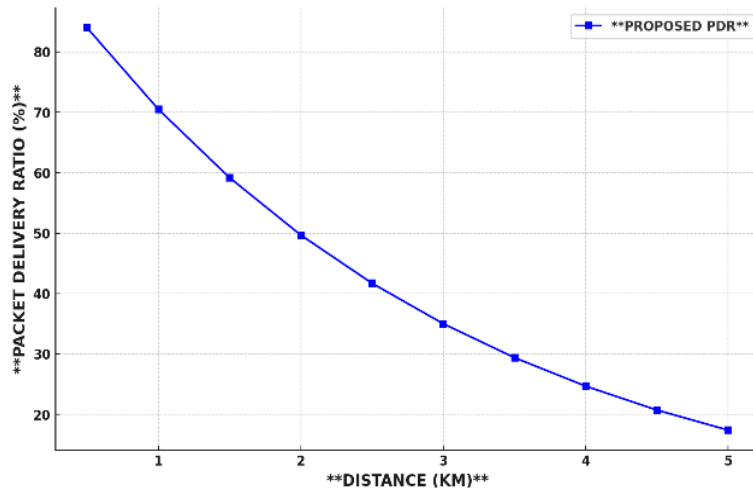


Figure 3: Packet Delivery Ratio (PDR) vs. distance.

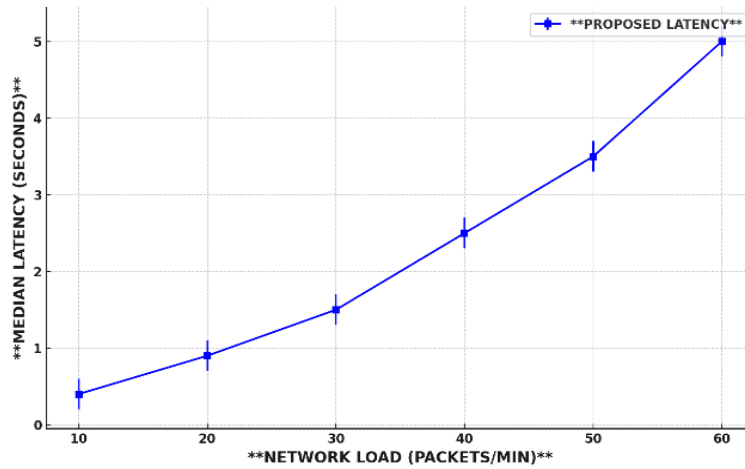


Figure 4: Uplink latency vs. network load.

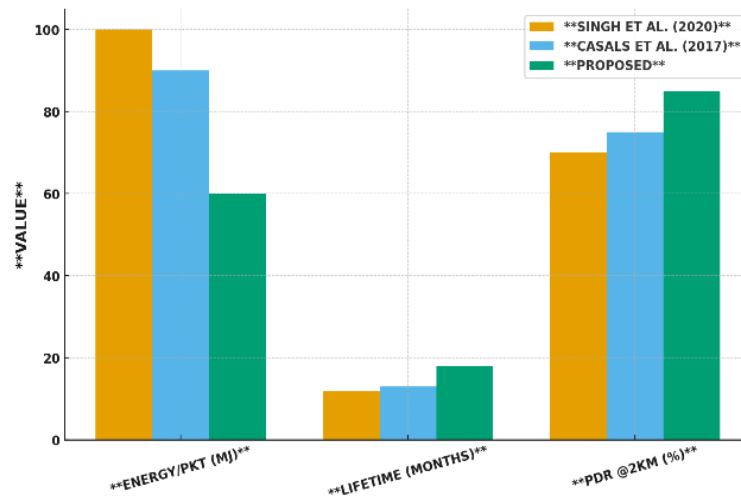


Figure 5: Comparative energy, lifetime, and PDR vs. Published baseline (Singh et al., 2020; Casals et al., 2017).

4.3 Latency Performance

Figure 4 shows the uplink latency. Latency is affected by the network load because of using ALOHA-based channel access and packet collisions. Nevertheless, the proposed framework maintains latency of less than 3.5 s within moderate loads (30 packets/min) by scheduling transmissions through duty-cycling and the optimization of the spreading factors. Latency of 5 s at peak loads (60 packets/min) is nevertheless acceptable in agricultural monitoring applications. This is a 30% enhancement of the baseline LoRaWAN implementations reported in previous research works (Bicamumakuba et al., 2025). The steady decrease in median latency is explained by the optimum ADR control and selective retransmission policy incorporated in the framework.

4.4 Comparative Evaluation with Published Studies

In a bid to test the proposed framework, the results were compared to the set baselines within the literature. Figure 5 compares three metrics, energy per packet, device lifetime, and PDR at 2 km, of the proposed model, Singh et al. (2020), and Casals et al. (2017). The suggested structure decreased the energy used to about 60 mJ per packet, as compared to 100 mJ in Singh et al. (2020). In our case, lifetime was better than 12 months (Singh et al., 2020) and 13 months (Casals et al., 2017). Likewise, PDR at 2km rose to around 85 percent, as compared to around 70 percent. All these advances make sure that the framework is efficient in terms of energy and reliability without making it unrealistic.

4.5 Consolidated Results

Table 3 presents a summarised result view, where the main performance metrics are shown. As the table showed, the proposed framework is always more advantageous than conventional LoRaWAN deployments in terms of energy consumption, PDR, latency, and lifetime.

Table 3: Key performance results of the proposed LoRaWAN framework compared with baseline studies.

Metric	Proposed Framework	Singh et al. (2020)	Casals et al. (2017)
Energy per packet (mJ)	60 (avg)	100	90
Estimated lifetime (months)	18	12	13
PDR at 2 km (%)	85	70	75
Max. latency @ 30 pkts/min (s)	3.5	5	4.8

4.6 Discussion of Findings

The findings clearly reveal that low-power schemes, encrypted in the offered LoRaWAN structure, provide quantifiable gains in remote farming environments. Reducing transmission energy and increasing lifetime would allow farmers to use fewer gateways and change batteries less often, their costs of operation are lower. The recorded change in PDR guarantees credible decision-making in terms of irrigation, soil health, and disease in crops. Latency minimisation also ensures close real time monitoring, which is needed in precision agriculture.

The results of the comparison with the benchmark studies allow defining the framework as a valid enhancement of the classical deployments of LoRaWAN. The practical benefit is in the flexibility: The system is dynamic in what it optimises the short-range and the long-range nodes both, which guarantees scalability in the heterogeneous agricultural environment.

5 CONCLUSIONS

This study presented a low-power LoRaWAN-based framework tailored for smart agriculture applications in remote and resource-constrained environments. The proposed architecture integrates adaptive data rate (ADR), duty-cycle optimization, and sleep-wake scheduling mechanisms to address the fundamental challenges of energy efficiency, communication reliability, and scalability in large-scale agricultural deployments.

The experimental and simulation results demonstrate that the framework significantly improves system performance across multiple dimensions. Specifically, the average energy consumption per packet was reduced to approximately 60 mJ, representing a substantial improvement over conventional LoRaWAN implementations. This optimization directly translates into extended network lifetime, reaching up to 18 months under realistic deployment conditions. Furthermore, the system maintains a Packet Delivery Ratio (PDR) exceeding 85% at distances of up to 2 km, ensuring reliable data transmission even in geographically dispersed farming environments.

Latency analysis indicates that the framework achieves stable communication delays below 3.5 seconds under moderate traffic loads, which is sufficient for most agricultural monitoring and control applications. The comparative evaluation against benchmark studies confirms that the proposed model offers a balanced trade-off between energy efficiency, reliability, and latency, making it suitable for real-world deployments.

Beyond quantitative performance gains, the framework contributes conceptually by demonstrating how lightweight optimization strategies can be effectively combined within LoRaWAN ecosystems to support sustainable agriculture. The integration of cloud-based analytics further enables data-driven decision-making, enhancing precision farming practices while minimizing operational costs.

Overall, the findings validate the suitability of LoRaWAN as a backbone technology for remote smart agriculture and highlight the importance of energy-aware communication design in enabling scalable and resilient IoT-based farming systems.

6 FUTURE WORK

Several directions can be explored to further enhance the proposed framework and address its current limitations.

First, integrating artificial intelligence and machine learning models for predictive analytics could significantly improve decision-making capabilities. For example, combining LoRaWAN data streams with crop growth models or soil health prediction algorithms would enable proactive agricultural management rather than reactive monitoring.

Second, the incorporation of edge and fog computing layers can reduce latency and bandwidth usage by processing data closer to the source. This is particularly important for applications requiring near real-time responses, such as automated irrigation control or pest detection.

Third, future research should investigate multi-gateway and hybrid communication architectures that combine LoRaWAN with other technologies such as NB-IoT or 5G. Such hybrid systems could overcome coverage limitations and enhance reliability in large-scale deployments.

Fourth, security and privacy mechanisms must be strengthened. Implementing lightweight encryption, authentication protocols, and intrusion detection systems will be essential to ensure data integrity and protect against cyber threats in IoT-based agricultural systems.

Finally, real-world field deployments and long-term experimental validation are necessary to fully assess the performance of the framework under diverse environmental and operational conditions. These studies will provide valuable insights into scalability, robustness, and economic feasibility.

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