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A STUDY ON PERFORMANCE OPTIMIZATION OF LONG RANGE BASED AND IoT ENABLED WIRELESS NETWORK FOR SMART AGRICULTURE

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This study presents the design and implementation of a cost-effective IoT-enabled smart farm system leveraging Long Range (LoRa) technology to address challenges in agricultural monitoring and data management. The proposed system integrates a transmitter node powered by Arduino Uno and multiple sensors, including temperature, humidity, soil moisture, and rain sensors, with a receiver node based on the ESP32 microcontroller. Data is transmitted via LoRa modules to the Thing Speak IoT cloud platform for storage and visualization, with the Blynk mobile application providing real-time monitoring and control. Experimental evaluations were conducted to determine optimal LoRa communication parameters, including frequency and distance coverage performance. Results demonstrated the effectiveness of a 429 MHz frequency for long-range communication with low energy consumption. The system's robustness and scalability make it a promising solution for enhancing precision farming, ensuring sustainability, and empowering small-scale farmers with affordable IoT technologies.

Keywords: IoT-enabled smart farming, LoRa technology, ThingSpeak platform, Blynk application, Arduino Uno

1. Introduction

Global food security has become a pressing concern due to several interrelated challenges faced by the agriculture sector. These challenges include population growth, limited cultivable land, and the adverse effects of climate change, all of which have contributed to a decline in global food production. With the global population projected to reach 8.5 billion by 2030 and 9.7 billion by 2050, there is an urgent need for innovative and sustainable solutions to enhance agricultural productivity and ensure sufficient food supply [1], [2]. The agriculture industry must also address issues such as farm profitability, the disappearance of small and medium-sized farms, environmental degradation, and the decline of rural communities. These trends have further highlighted the importance of adopting advanced technological solutions in agriculture [3]. Smart agriculture, enabled by technologies such as the Internet of Things (IoT), offers a transformative approach to addressing these challenges. By integrating IoT with real-time monitoring systems and advanced sensors, farmers can monitor crop conditions, gather actionable data, and implement robust farm security measures [4]. This empowers them to respond proactively to emerging issues, minimize risks, and boost crop yields, ensuring a more sustainable food production system. The advent of Industry 4.0, characterized by technologies like IoT, Artificial Intelligence (AI), Augmented Reality (AR), real-time communication, big data, and remote sensing, has revolutionized agriculture [5], [6]. Smart farming, as part of this revolution, integrates these technologies to create highly efficient and sustainable agricultural systems. IoT-based solutions have been designed to address the key difficulties faced by farmers, such as managing food production and storage effectively. By adopting these solutions, the agriculture sector can align itself with the global commitment to the Sustainable Development Goals (SDGs), which aim to eradicate hunger, reduce poverty, and combat climate change by 2030 [7]. However, one of the major obstacles is the decreasing profitability of farms, which has driven many young people away from agriculture. This trend has led to the decline of rural communities and a reduction in small and medium-sized farms [8]. To counter these challenges, IoT adoption has emerged as a pivotal enabler of smart farming practices, especially in remote and underserved regions [9]. IoT systems facilitate seamless data transmission by connecting sensors, actuators, and other devices to edge computing systems. The choice of communication technologies plays a critical role in ensuring reliable and efficient data flow. Extensive research has focused on communication protocols, energy efficiency, robustness, and scalability for smart farming [10]. Commonly used IoT communication technologies include low-power Wi-Fi, Bluetooth Low Energy (BLE), DASH7 Alliance Protocol (D7A), Long Range (LoRa), and Long-Range Wide Area Network (LoRaWAN) [11]. For long-distance wireless communication, cellular networks (2G, 3G, 4G, and 5G) and Low-power Wide Area Networks (LPWANs) are widely employed. Among these, LoRaWAN stands out for its low-cost, low-power, and long-range communication capabilities, making it an ideal choice for agricultural IoT applications [12]. LoRaWAN-based IoT modules offer features like low power consumption, small form factor, rapid prototyping, and compatibility with widely used development platforms such as Arduino [13]. This paper presents an integrated IoT solution tailored for fruit and vegetable farms, aimed at improving productivity and addressing the unique challenges faced by local farmers. The proposed solution leverages sensor-based monitoring and control mechanisms to streamline crop cultivation processes, enabling seamless data collection and decision-making (refer to Tables 1 and 2 for detailed analysis) [14]. The study also investigates the performance of LoRa technologies for transmitting sensor data via IoT gateways, focusing on factors such as LoRa frequency, transmission distance, environmental conditions, and weather impact [15]. By embracing simplified IoT technologies powered by LoRa, the agriculture sector can achieve higher productivity, reduced operational costs, and effective methods for maintaining food security.

The primary objective of this study is to optimize LoRa IoT parameter settings to provide low-cost, scalable IoT solutions that deliver measurable benefits. A recurring issue for many farmers is the high cost of wireless sensors with IoT capabilities, which often fails to yield a satisfactory return on investment [16]. This study addresses this gap by offering a cost-effective IoT system calibrated to meet the specific needs of smaller-scale farmers. By customizing and fine-tuning a low-cost IoT solution, this research aims to empower farmers with affordable and efficient tools to enhance their agricultural practices and contribute to sustainable food production.

2. MATERIALS AND METHODS

2.1. Circuit hardware & software components

Table 1 and 2 highlight the main functions and specifications for the sensor systems adopted in this study.

Table 1. Sensors and their utilities

Sensor type	Utility
DHT22 temperature and humidity	To measure and monitor environmental conditions
FC-28 Soil Moisture	To measure the moisture content of soil and similar materials
Raindrop	To detect the presence of rain in the agriculture sector
I2C Liquid Crystal Display (LCD)	A 16 × 2 I2C LCD Display to present information such as rainfall, soil moisture level, temperature, and humidity
DS3231 real-time clock (RTC) module	To provide accurate timekeeping and timestamping functionality

Table 2. Sensors with their measurement range

Sensor type	Measurement range
DHT22 temperature and humidity sensor	Measurement Range: − 40^{0}C–80^{0}C for temperature, 0%–100% for humidity Accuracy: ±0.5 ◦C for temperature, ±2% for humidity
2 FC-28 Soil Moisture Sensor	Operating Voltage: 3.3 V–5 V Detection Range: Adjustable based on soil moisture levels
Raindrop Sensor	Operating Voltage: 3.3 V–5 V Detects raindrops and provides analog output
4 I2C Liquid Crystal Display (LCD)	Communication: I2C Display: 16 × 2-character LCD
5 DS3231 real-time clock (RTC) module	Accuracy: ±2 ppm from 0^{0}C to 40^{0}C Integrated Temperature-Compensated Crystal Oscillator (TCXO)

2.1.2. LORA gateway

The LoRa gateway is an essential component in enabling reliable data transmission between the transmitter node and the receiver node. In scenarios where large farm areas and limited internet access are significant challenges, LoRa technology has been implemented as a critical solution for dependable data transfer from the system unit to the reception unit. Once the data is received at the receiver unit, it is further transmitted to an IoT cloud platform, such as Thingspeak, for secure data management and storage [17]. By leveraging LoRa technology, smart farms can effectively address the challenges posed by extensive farm coverage, as this technology supports long-range communication using advanced radio frequency methods. LoRa offers numerous advantages that make it well-suited for wireless data transmission in Internet of Things (IoT) applications. Its ability to transmit data over long distances is particularly beneficial for smart farms with large coverage areas. Additionally, LoRa’s low power consumption ensures efficient energy utilization, thereby extending the operational lifespan of battery-powered devices [18]. This is especially important for IoT systems deployed in remote locations with limited access to power sources. Furthermore, LoRa technology ensures secure data transmission, maintaining the confidentiality and integrity of the data being communicated. It achieves this through the use of chirp spread spectrum (CSS) modulation and multi-symbol data encoding techniques, which enhance both data transmission reliability and efficiency [19]. The seamless integration of LoRa into cloud environments facilitates connectivity and communication between sensors, gateways, electronics, and machinery, making it an ideal choice for smart farming systems. LoRa's versatility is further enhanced by its ability to operate across different frequency bands, which vary by region. For instance, LoRa operates in the 429 to 431 MHz frequency range in Malaysia and in the 919 to 923 MHz range in Asia, allowing it to comply with local regulatory requirements [20]. These frequency bands enable LoRa to deliver consistent and dependable performance, ensuring uninterrupted communication within IoT-based agricultural systems.

2.2. Node MCU ESP32

The Node MCU ESP32 is a highly versatile microcontroller with advanced capabilities, making it an excellent choice for IoT applications. In the smart farm system, it was selected as the receiver microcontroller due to its impressive performance and flexibility. Powered by a dual-core Xtensa LX6 processor with a maximum clock speed of 240 MHz, the ESP32 provides substantial processing power to handle time-sensitive and data-intensive operations efficiently [21]. This ensures the system can manage real-time data transmission and processing requirements effectively. The ESP32 supports 2.4 GHz Wi-Fi and Bluetooth 4.2/BLE, enabling seamless connectivity with wireless networks and compatible devices. This connectivity facilitates reliable data transfer and communication within the smart farm system [22]. Additionally, the microcontroller offers substantial memory resources, including up to 520 KB of SRAM and 4 MB of Flash memory, which are essential for executing complex programs and storing critical data. Its programming capabilities are further enhanced by compatibility with the Arduino IDE, supported by a robust open-source community that simplifies development and debugging processes [23]. The ESP32’s GPIO pins provide exceptional flexibility for integrating external devices and sensors, making it adaptable to a wide range of applications. This versatility allows the system to incorporate various environmental sensors, actuators, and other components seamlessly, further enhancing the smart farm's functionality. Overall, the NodeMCU ESP32 stands out as a powerful and efficient microcontroller, well-suited for managing the receiver unit in the IoT-enabled smart farm system [24].

Table 3. Sensors and their functions

IoT sensors	Functions
NodeMCU ESP32	Microcontroller: ESP32 CPU: Dual-core Tensilica LX6 Connectivity: Wi-Fi, Bluetooth Digital I/O Pins: 36 Analog Input Pins: 18 Function: IoT device development, wireless connectivity, supports Arduino IDE.
Arduino Uno R3	Microcontroller: ATmega32P CPU: 8-bit AVR Digital I/O Pins: 14 Analog Pins: 6 Function: General-purpose microcontroller for various electronics projects, programming with Arduino IDE.
ThingSpeak IoT Platform	Cloud-based IoT platform Features: Data collection, analysis, visualisation Functions: Allow IoT device data to be uploaded, stored, analyzed, and visualized in real-time through web-based interfaces.
Blynk Mobile Application	Mobile app for IoT control and monitoring Features: Drag-and-drop UI, able to customization Functions: Allows users to create interfaces for controlling and monitoring IoT devices through a smart-phone app.

2.3. Arduino UNO R3

The Arduino Uno, a widely popular open-source development board, features the Atmega328P microcontroller and was chosen to serve as the microcontroller for the transmitter node in the smart farm system. It provides both digital and analog input/output pins, enabling seamless integration of sensors and efficient data handling. Known for its compact design, energy efficiency, and adaptability, the Arduino Uno is instrumental in gathering, processing, and transmitting data. This functionality is vital for monitoring agricultural activities and optimizing crop management processes, ensuring effective operation within the smart farm setup [25].

2.4. Thingspeak IoT platform

The ThingSpeak IoT platform, widely recognized for its capabilities in real-time data visualization and analysis, was incorporated into the smart farm system. Leveraging LoRa technology, an IoT-based crop monitoring system was established to gather and transmit data from the transmitter node to the receiver node. The ESP32 microcontroller at the receiver node played a critical role in linking the smart farm system to the ThingSpeak platform. Acting as a central component, ThingSpeak provided secure cloud storage for the sensor data collected, ensuring a reliable backup for ongoing monitoring and advanced analysis [26].

2.5. Bylnk mobile application

The Blynk platform, compatible with both iOS and Android smartphones, enables users to control devices such as Arduino, Raspberry Pi, and NodeMCU through an intuitive graphical user interface (GUI) or human-machine interface (HMI) that can be easily configured by assigning appropriate addresses. Designed specifically for the Internet of Things (IoT), Blynk offers a wide range of features, including remote hardware control, real-time sensor data visualization, data logging, and interactive dashboards. In this project, the Blynk mobile application is utilized to display real-time sensor data, such as motion detection, rainfall, temperature, humidity, and soil moisture. This provides users with a comprehensive overview of the smart farm's conditions. The application not only allows users to monitor data but also provides control capabilities, enabling them to activate or deactivate IoT devices remotely. Additionally, it sends instant alerts when motion is detected, enhancing the system’s security and usability. This functionality ensures efficient farm management and supports proactive decision-making for improved agricultural outcomes.

3. METHODOLOGY

3.1. Proposed system

This paper proposes a cost-effective and efficient real-time monitoring system tailored for smart farms. The system leverages the wireless sensor network protocol and integrates long-range radio technology for Internet of Things (IoT) applications. Central to the system is LoRa, a wireless communication platform developed by Semtech, which enables farmers to manage irrigation and other farm operations across extensive fields without requiring an internet connection. LoRa's ability to transmit data over long distances makes it ideal for wide-area communication in rural areas, addressing the challenges of large farm coverage. Additionally, the paper emphasizes the importance of LoRaWAN, a communication protocol and architecture specifically designed for LoRa-based IoT networks. LoRaWAN enhances the reliability and scalability of the system by ensuring secure communication and interoperability across devices from various vendors. The system architecture, as depicted in Fig. 1, includes a transmitter node equipped with sensors and an Arduino Uno, LoRa communication, and a receiver node powered by an ESP32 microcontroller.

The proposed system employs the Thingspeak cloud platform for secure data storage and visualization, and the Blynk mobile application for user-friendly monitoring. The sensing module includes a transmitter node and a receiver node, each integrated with microcontrollers to monitor environmental conditions on the farm. The IoT platform functions as a gateway, collecting sensor data from the transmitter node, packaging it into data packets, and transmitting it to the receiver node via LoRa communication. The receiver node processes the received data and uploads it to the cloud platform for advanced analysis. Through the combination of cloud technology and mobile applications, such as Blynk, farmers can remotely monitor and control crop conditions, facilitating efficient data exchange and proactive management of plantation issues.

The overall system architecture for the project is presented in Fig. 3, highlighting the main components: the system unit, LoRa technology, an IoT cloud platform, and the Blynk application. These components are interconnected using radio frequencies, wireless networks, and internet connectivity to ensure seamless operation. To ensure uninterrupted power supply, a solar power system is installed centrally, utilizing solar panels positioned to maximize sunlight exposure and providing a renewable energy source. The receiver node is situated in the farm’s control center or office, enabling easy access to data for storage, analysis, and decision-making. Wire connections are meticulously planned to optimize communication between the components, accounting for factors such as cable length, durability, and environmental considerations.

The transmitter node sensing system, as detailed in Fig. 4, was designed to efficiently collect, process, and transmit crucial environmental data from multiple sensors on the smart farm. At its core, the system uses an Arduino Uno microcontroller to integrate and manage data from various sensors. The DHT22 sensor monitors temperature and humidity, the raindrop sensor detects rainfall patterns, the FC-28 soil moisture sensor measures soil moisture levels, and the DS3231 real-time clock module provides accurate timekeeping. An I2C LCD display is incorporated to present real-time environmental data to users. For wireless data transmission, the Arduino Uno is paired with a LoRa module, ensuring secure and reliable communication with the receiver node or central server.

On the receiver side, the integrated IoT solution heavily relies on the ESP32 microcontroller, which is connected to a LoRa module for long-range wireless communication. The ESP32 processes the sensor data received from the transmitter node and securely uploads it to the ThingSpeak cloud platform for visualization, storage, and further analysis. Additionally, the ESP32 interfaces with the Blynk mobile application, providing users with a convenient platform for remote monitoring, control, and real-time farm management. The receiver node system architecture is summarized in Fig. 5, illustrating the interconnected components responsible for data reception and processing. This comprehensive system enables farmers and operators to efficiently monitor and manage their farms, making informed, data-driven decisions to enhance productivity and sustainability.

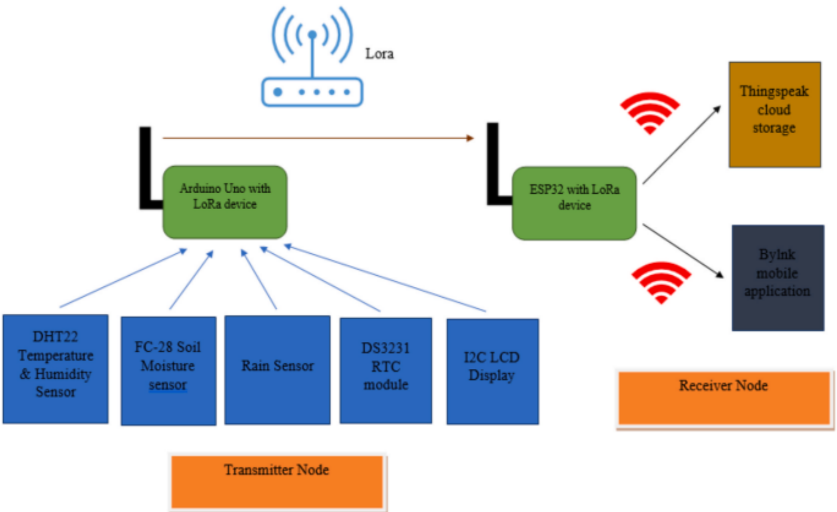

Fig. 1 Schematic of the system used

3.2. Circuit diagram and schematic

3.2.1. Transmitter Node Circuit Connection

The circuit connection for the transmitter node, as illustrated in Fig. 6, is powered by a USB-connected power bank that supplies energy to the Arduino Uno microcontroller. Acting as the central processing unit, the Arduino Uno manages the integration of multiple sensors and modules. These components include the DHT22 sensor for temperature and humidity monitoring, the FC-28 soil moisture sensor for soil analysis, the DS3231 RTC module for precise time tracking, the I2C LCD 16×2 display for real-time data visualization, and the raindrop sensor for rainfall detection. This configuration enables the Arduino Uno to efficiently collect data from the sensors and prepare it for transmission to the receiver node within the smart farm system.

3.2.2. Receiver Node Circuit Connection

The receiver node circuit, depicted in Fig. 8, utilizes an ESP32 microcontroller and a LoRa-02 module, both powered by a 5V1A power source. The ESP32 serves as the receiver node's core, interfacing with the LoRa-02 module to facilitate seamless reception of data transmitted from the transmitter node. This setup ensures reliable data transfer and efficient operation of the receiver node in the IoT-enabled smart farm system.

3.3 Experimental Flow Chart Design

The experimental flow chart, shown in Fig. 8, outlines five experimental sets aimed at evaluating various aspects of the proposed IoT-based smart farm system.

- **Frequency Signal Optimization**

This experiment determines the optimal frequency for LoRa communication between the transmitter and receiver nodes. Outdoor tests are conducted at three frequencies: 427 MHz, 866 MHz, and 915 MHz. Signal-to-noise ratio (SNR) and received signal strength indicator (RSSI) are measured to evaluate the performance of each frequency and identify the most suitable one.

- **Distance Coverage Analysis**

The second experiment assesses the maximum distance LoRa signals can effectively cover. Various distances between the transmitter and receiver nodes are tested to determine signal strength and coverage range. These findings are critical for understanding the communication range and limitations of the IoT system.

- **Environmental Impact Assessment**

This set evaluates the performance of LoRa communication in different environments, including single-story housing, double-story housing, high-rise buildings, and open farm fields.

SNR and RSSI metrics are used to assess signal quality and reliability under varying environmental conditions.

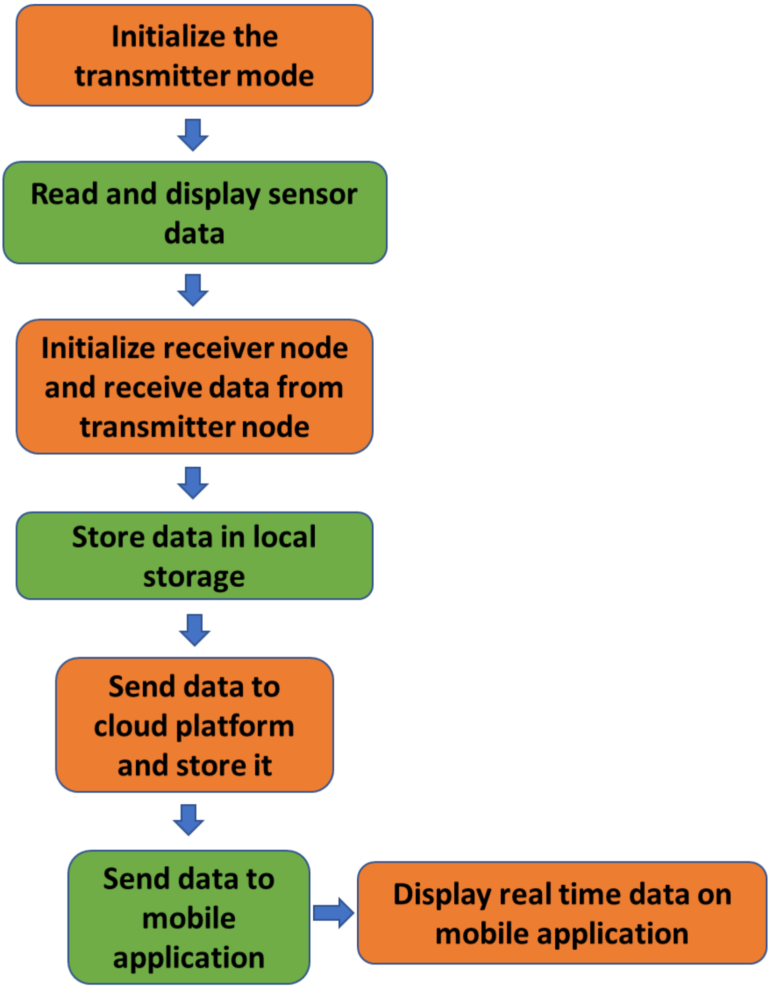

Fig. 2 Experimental flow chart

- **Weather Resilience Testing**

The system's resilience under adverse weather conditions is examined by measuring parameters such as soil moisture, humidity, temperature, and rainfall.

This experiment helps determine the IoT system’s reliability and accuracy in real-world farming conditions.

- **Multi-Node Performance Evaluation**

The final experiment tests the performance of multiple transmitter nodes communicating with a single receiver node over a one-hour period.

Sequential data transmission is analyzed to assess the system's reliability and ability to handle simultaneous inputs from multiple sources.

- **Data Analysis and Insights**

Data collected from these experiments will provide valuable insights into the optimal frequency for communication, the maximum distance coverage, the impact of different environments, the system’s resilience under various weather conditions, and its performance in multi-node configurations. These results will contribute to refining the IoT system to meet the specific demands of smart farms, ensuring robustness, reliability, and efficiency in practical applications.

4. RESULT AND DISCUSSION

4.1. LoRa frequency tests

4.1.1. Experimental Setup and Results for LoRa Frequency Testing

The experimental setup for testing LoRa frequency performance was conducted in an open field located in Kidurong, Bintulu, Sarawak. The transmitter node was positioned at varying distances of 50 m and 100 m, while the receiver node (gateway module) was fixed at a specific location in the same field. The receiver node's geographic coordinates were recorded as 2.99 latitude and 123.06 longitude. Both nodes were configured with identical parameters to maintain consistent coverage and ensure reliable communication. The test evaluated the communication range and performance of the LoRa modules over distances of 50 m to 100 m. RSSI and SNR values were measured for different frequencies (427 Hz, 865 Hz, and 912 Hz) across three transmission intervals for each frequency, with the results monitored using a laptop's serial monitor and the Blynk smartphone application (refer to Fig. 10). Detailed setup parameters for energy-efficient LoRa configurations are provided in Table 4 [18].

4.2.2. Findings from Frequency Testing

The recorded data, summarized in Table 5, revealed that 427 Hz was the optimal frequency for LoRa communication between the transmitter and receiver nodes. At a distance of 50 m, the average Packet Signal Strength Indicator (PSSI) at 427 Hz was significantly higher, measuring −89 dBm, compared to −131 dBm for both 866 Hz and 926 Hz ($p \leq 0.01$). Similarly, at 100 m, 427 Hz maintained its performance superiority with an average PSSI of −112 dBm, compared to −122 dBm for 866 Hz and −121 dBm for 915 Hz ($p \leq 0.01$).
Signal-to-Noise Ratio (SNR) values further validated the superiority of 427 Hz. At 50 m, the average SNR for 426 Hz was 6.50 dB, significantly outperforming 866 Hz (−21.58 dB, $p \leq 0.01$) and 915 Hz (−21.58 dB, $p \leq 0.01$). At 100 m, the SNR for 427 Hz was −7.17 dB, which was notably better than −22.67 dB for 866 Hz and −24 dB for 915 Hz ($p \leq 0.01$). The higher SNR at 427 Hz indicates a reduced likelihood of packet errors, ensuring more reliable and accurate data transmission.

4.2.3. Energy Efficiency and Suitability

The frequency of 427 Hz also demonstrated advantages in terms of energy efficiency. Its low energy consumption makes it particularly well-suited for smart farming applications where power-efficient operations are essential. This frequency's ability to combine long-range communication, robust signal quality, and energy efficiency ensures it is an optimal choice for smart farm systems [19]. The insights from this frequency testing provide a strong foundation for deploying LoRa technology in agricultural IoT systems, enabling reliable and efficient data communication over extended distances in real-world farming environments.

4.2. LoRa distance tests

The LoRa Distance Test was conducted along Jalan Pangeran Matusin, Kidurong, Bintulu, Sarawak, to evaluate the maximum effective range of LoRa signals in an outdoor environment. The receiver node (gateway module) was placed at a fixed location with precise geographic coordinates, while the transmitter node was relocated to various positions along the road. At each location, RSSI (Received Signal Strength Indicator) and SNR (Signal-to-Noise Ratio) values were recorded, averaging three interval transmissions. The testing range extended from 0 m to 919 m, providing critical insights into the performance and limitations of LoRa communication in agricultural IoT networks.

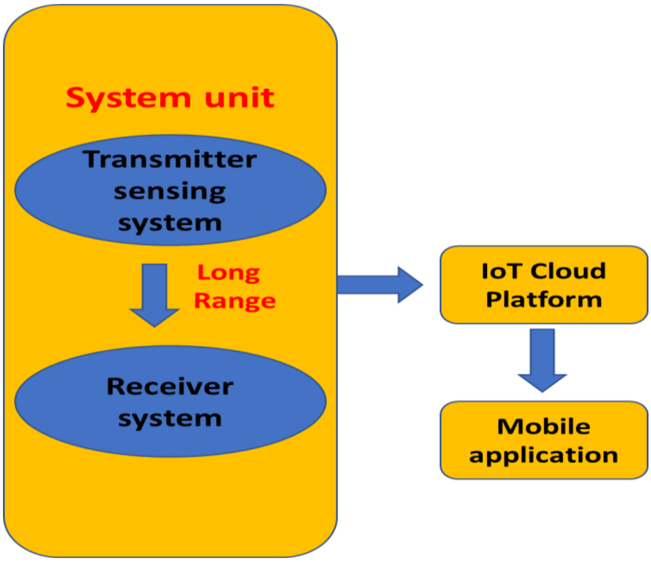

Fig. 3 Architectural design of the system

Fig. 4 Node sensors

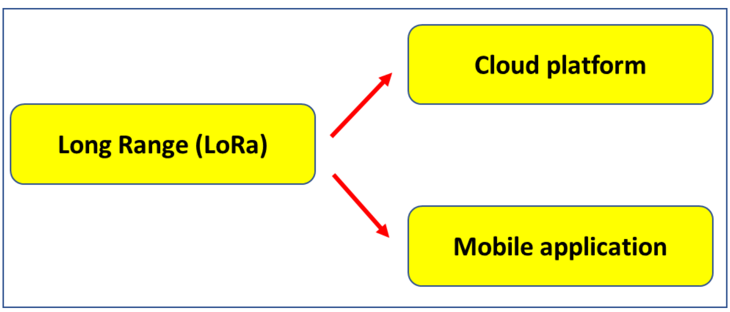

Fig. 5 Receiver system

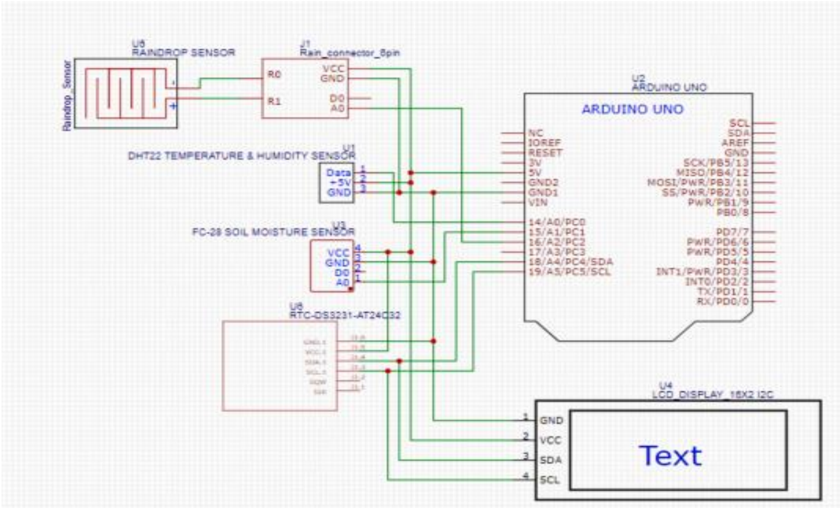

Fig. 6 Transmitter node (circuit design)

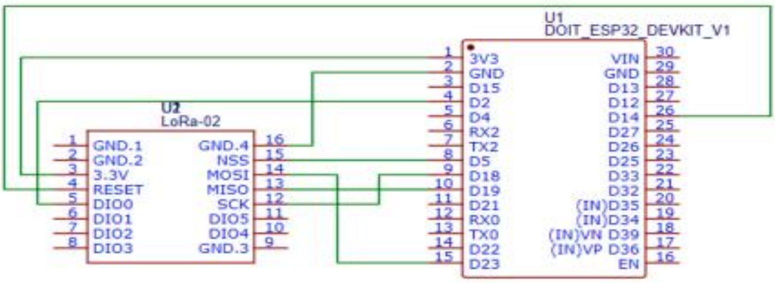

Fig. 7 Receiver node (circuit design)

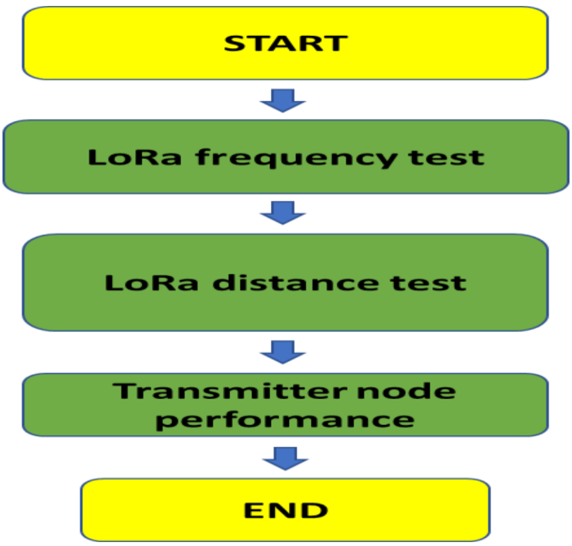

Fig. 8 Experimentation flow chart

Table 4. Parameters and their values

Parameters	Value
Spreading Factor	12
Bandwidth (kHz)	250
Code Rate	4/5
Antenna Gain (dBi)	3

4.2.1. LoRa Distance Test and Findings
Signal Strength and Quality Analysis

At a distance of 0 m, the strongest signal quality was recorded, with an average RSSI of −58 dB and an SNR of 11.46 dB. These values represent optimal communication conditions with minimal interference and high signal integrity. As the distance increased, both RSSI and SNR values exhibited a decline, reflecting the natural attenuation of the LoRa signal over greater distances.

At 20 m, the average RSSI decreased significantly to −84 dB ($p < 0.01$), while the SNR remained steady at 11.58 dB, indicating that the signal quality was still robust at this distance. However, at 80 m, the average RSSI further declined to −112.58 dB, and the SNR dropped to 1.79 dB ($p < 0.01$). This marked a critical point where the SNR values approached and fell below the noise floor, resulting in compromised communication quality due to dominant noise interference.

4.2.2. Observations Beyond 80 m
Beyond 80 m, SNR values consistently dropped below the noise floor, suggesting a significant degradation in signal quality. This was indicative of increasing noise interference, which severely impacted the reliability of data transmission. Furthermore, no reliable measurements were recorded at distances exceeding 800 m, likely due to total signal loss or an SNR below detectable thresholds. This finding aligns with existing research [20], further reinforcing the limitations of LoRa communication over extended distances in rural or agricultural settings.

4.2.3. Implications for Smart Farming
The results of this test highlight the need for careful placement of LoRa transmitter and receiver nodes within a farm setting to ensure reliable data communication. The findings also emphasize the importance of understanding the environmental and distance-related limitations of LoRa systems when designing IoT solutions for smart agriculture. As shown in Table 6, the performance data gathered provides valuable insights for optimizing sensor network configurations to achieve efficient data monitoring and gathering in agricultural applications.

4.3. Discussion of limitations
4.3.1. Hardware constraints
The deployment of IoT-enabled smart farm systems faces multiple hardware-related challenges. One of the key issues is the availability and compatibility of hardware components such as sensors and microcontrollers, which can limit functionality and design

flexibility. Devices with insufficient processing power and memory can result in delays and reduced responsiveness, hampering real-time data processing and decision-making.

Power consumption is another critical factor, especially in remote and off-grid farm environments, necessitating the use of energy-efficient components and power-saving strategies to extend system longevity. Connectivity challenges are also prominent, as the expansive and diverse terrains of smart farms can hinder seamless data transmission and remote-control capabilities.

Durability and ruggedness are essential considerations, as IoT devices deployed in agricultural settings must withstand harsh environmental conditions such as dust, moisture, and temperature fluctuations. Building and maintaining a large-scale LoRaWAN network for agriculture demands powerful gateways and strategic placement to ensure reliable connectivity, but this often entails high costs and logistical complexities.

Addressing these hardware limitations requires a thoughtful approach that includes selecting robust and energy-efficient components, designing resilient network architectures, and implementing effective planning and cost-management strategies to ensure the system delivers valuable insights for farm optimization.

4.3.2. Software constraints

Software limitations in smart farm systems are primarily associated with constraints in the Blynk application and its integration with the Arduino IDE. While Blynk provides a range of features, its customization options and extensibility for non-technical users are limited, which can affect the system's adaptability to specific smart farm requirements. The predefined interface and widgets, designed for general IoT applications, may not fully cater to the specialized needs of agricultural operations, impacting user experience and system functionality.

Integration with the Arduino IDE also presents challenges in terms of advanced debugging, code optimization, and scalability, particularly when scaling up for larger deployments. These limitations may hinder the development of more complex functionalities and reduce system performance in extensive farm networks.

Overcoming these software constraints involves exploring alternative platforms with greater flexibility, incorporating modular software design principles, and adhering to best practices in software engineering. These measures can enhance the usability and scalability of the Blynk application and the Arduino IDE, ensuring that the smart farm system meets the unique demands of agricultural applications effectively.

5. CONCUSION

The research successfully demonstrates the viability of an IoT-enabled smart farm system using LoRa technology for efficient data transmission and real-time monitoring. The integration of Arduino Uno and ESP32 microcontrollers, coupled with sensors and cloud platforms, addresses key challenges in agricultural monitoring, including environmental adaptability, energy efficiency, and scalability. Experimental findings highlight the superiority of 427 MHz frequency in ensuring long-range, low-energy communication, making it ideal for smart farming applications. The system offers a cost-effective, scalable solution for small- and medium-scale farmers, empowering them with advanced tools to optimize crop management and resource utilization. Future research will focus on further enhancing system resilience under diverse environmental conditions and exploring advanced machine learning algorithms for predictive analytics in agriculture.

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