

Article

UAV-Assisted LoRa-Based Wireless Sensor Network for Environmental Monitoring

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Abstract: Unmanned Aerial Vehicles (UAVs) integrated with Wireless Sensor Networks (WSNs) present a transformative approach to environmental monitoring by enabling real-time, low power, wide-area, and high-resolution data collection. This paper proposes a UAV-based WSN framework designed for efficient ecological data acquisition, including parameters such as temperature, humidity, various gases, detection of motion of a material, and safety features. The system leverages UAVs for dynamic deployment and data retrieval from distributed sensor nodes in remote or inaccessible areas, reducing the reliance on fixed infrastructure. Long Range Communication (LoRa) technology is also integrated with a WSN to enhance network coverage and adaptability issues. The proposed system covers vast areas through LoRa communication ensuring minimal energy consumption and cost-effective sensing capabilities. Field tests and simulation findings show how well the system captures spatiotemporal environmental fluctuations, making it an invaluable tool for monitoring climate change, ecological research, and disaster response.

Keywords: wireless sensor network; unmanned aerial vehicle; long range communication; low power consumption; environmental data monitoring



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1 Introduction

Environmental preservation and protection are more important than ever for contemporary society. Over-exploitation of natural resources, unpredictable climate change, and controllable pollution levels are all seriously impairing human health and societal well-being while also impeding the global economy's ability to grow sustainably^[1]. Consequently, throughout the past 20 years, sophisticated information and communication technologies (ICTs) emerged to develop monitoring systems for human activity and the maritime environment. In this regard, the use of unmanned aerial

vehicles (UAVs), sometimes referred to as drones, for environmental monitoring has gained popularity over the past 20 years. UAVs' aerial inspection capabilities enable them to access hard-to-reach places and take advantage of their adaptable flying characteristics to conduct monitoring operations at various spatial resolutions (i.e., different altitudes and view angles) while ensuring significantly higher sampling rates^[2].

The effectiveness of the Internet of Things (IoT) in offering practical solutions for environmental monitoring operations is becoming more and more apparent. The Internet of Things' data processing capabilities enable intelligent object control and the rapid creation of

applications that promote biodiversity preservation and economic prosperity^[3]. Wireless Sensor Networks (WSNs) are a key technology for IoT implementation. They consist of separate gadgets placed across an area of interest to monitor physical or environmental variables^[4]. However, issues with modeling, energy supply, range, and bandwidth restrict the usage of WSNs in this context, and integrating IoT in the environmental monitoring remains a very difficult undertaking. Compared to their terrestrial equivalents, the environmental data monitoring is now lagging far behind in the adoption of these technologies. Furthermore, a comprehensive and contextualized study of wireless communication technologies in environmental data acquisition is still lacking.

To overcome these challenges, this study introduces a modular communication protocol called low power long range network (LoRa), which is intended for Environmental Intelligence (EI) applications^[5]. LoRa promotes the scalability and integration of environmental sensing networks by improving the connectivity and data transmission capabilities of IoT devices in remote and difficult natural environments. Energy efficiency and long-range capabilities are given top priority in the joint integration of LoRa to WSN in order to ensure long-term operation and broad coverage. The implementation of extensive sensor networks in environmentally sensitive locations is further facilitated by its support for mesh

networking and scalability to different hardware configurations. LoRa enables sensors on an oceanographic buoy to gather information on humidity, water temperature, and oxygen concentration^[6]. Therefore, the ability to collect and analyze data in real-time enhances our understanding of the environment and enables proactive actions for environmental protection.

1.1 LoRa-Enabled Environmental Intelligence Systems

The straightforward way to take advantage of LoRa technology is to implement LoRaWAN, an open-standard access protocol supervised by the LoRa Alliance and situated at the MAC layer of the OSI Reference model^[7]. It uses a star-of-stars architecture, where a gateway connects to Internet of Things devices via a single-hop link. As a low-cost, long-range communications solution for environmental parameter sensing and monitoring, LoRaWAN is widely supported. Nevertheless, a single hop is not enough to provide long-range coverage in places with poor infrastructure, rendering the LoRaWAN star-of-stars topology inappropriate for difficult networks^[8]. Consequently, Multi-LoRa may be the best option for deploying sensors on a broad scale and for deploying IoT, particularly in smart agriculture on fields that span hundreds of square kilometers as shown in Figure 1.

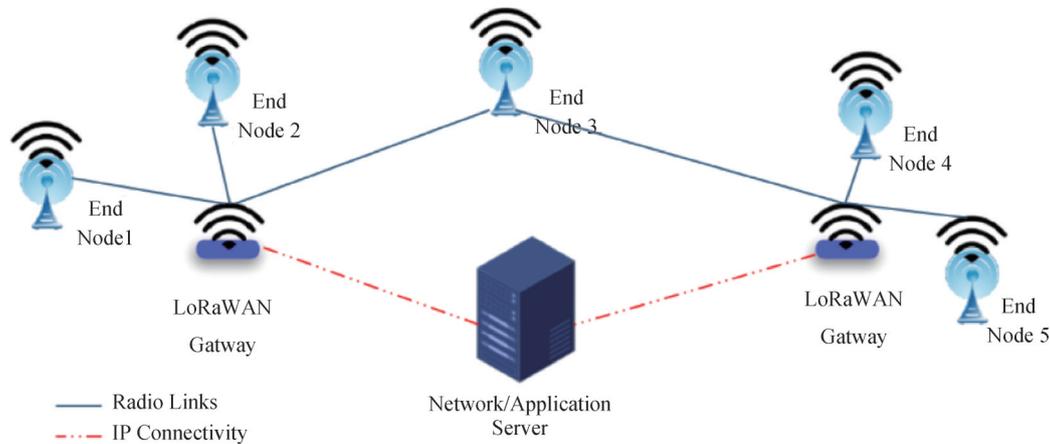


Fig.1 Dynamic LoRaWAN Gateway Architecture [8]

1.2 Constraints and Considerations for WSNs in Environmental Data Monitoring

In recent decades, there has been a surge in the number of technical solutions based on WSNs. For monitoring the environment, its biodiversity, and the activities that take place there, WSNs have several advantages, such as autonomous operation, real-time supervision (saving staff hours and effort), and comparatively low cost^[9]. Since the costs of using these technologies are declining, they are actually becoming more cost-effective when compared to more traditional monitoring techniques^[10]. The deployment of land-based

WSNs for environmental data monitoring is quite challenging^[11] due to its existing protocols and design specifications that may be modified to meet the requirements of modern data acquisition applications^[12].

In light of the enormous volume of data in environmental monitoring, it should be noted that in recent years, there has been a notable increase in the number of monitoring systems needed for vessel navigation and monitoring as well as marine traffic^[13]. This indicates that the amount of data gathered has also grown to the same extent and is suitable for integration into a network based on LoRa. A terrestrial WSN-based environmental monitoring system usually consists of

hundreds or thousands of low-cost sensor nodes positioned in strategic points across the monitored site, the location of which is assumed to be known, and one or

more monitoring centers responsible for collecting and processing all of the data collected by the sensor nodes as depicted in figure 2 (a,b).

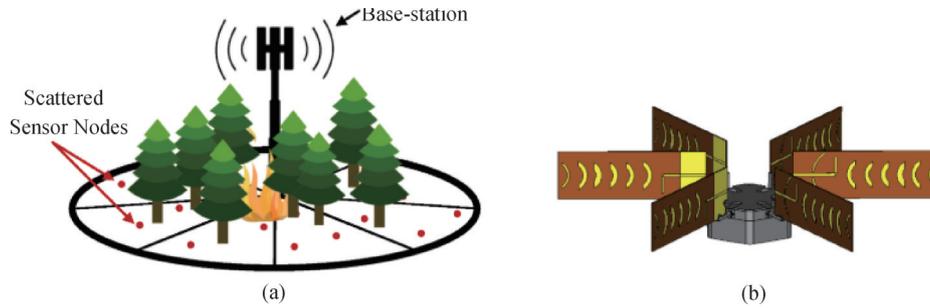


Fig.2 (a) Multi-sector WSN and (b) Base Station antenna [13]

Each WSN sensor node is a low-power device with the following characteristics:

- A microprocessor unit that controls, monitors, and performs basic computations on the gathered data.
- Small batches of the gathered data are kept in an internal memory with a limited capacity before being transmitted to the monitoring centers.
- A transceiver that establishes channels of communication with other network nodes and monitoring centers.
- A sensing unit uses a variety of specialized sensors (such as chemical, thermal, and biological) to detect and monitor the pertinent environmental parameters.

The parameters of given sensors provide real-time data for environmental, climate trends, and ecosystem health, enabling timely intervention and sustainable management of marine environments.

1.3 Motivation and Contributions

Integrating LoRa communication with WSN in a marine setting can yield numerous significant advantages, including long-range communication, low power consumption, high scalability, and resilient communication in real-time monitoring. In this regard, the main contributions of this study are:

1. The design and development of different WSN-based sensors.
2. Obtaining physical parameters by integrating a LoRa module with WSN-based sensors by the assistance of UAVs.
3. Monitoring data from several sensors in real time.
4. Lab testing with an experimental configuration that includes both software and hardware components.

The proposed modular protocol in this study differs from prior UAV-LoRa architectures in several important ways like design, energy efficiency, adaptive LoRa parameters, optimization, and multiple environmental scenarios.

1.4 Paper Organization

This work is divided into numerous sections, the

first of which introduces the joint integration of the LoRa module with UAV-assisted WSN. Section 2 presents the related work aligned with the proposed study. The state-of-the-art guidelines for deploying a LoRa network in a marine environment are shown in Section 3. In order to attain the intended outcomes, Section 4 examines the operating scenario and the suggested solution. The system design model for both the transmitting and receiving sides is covered in Section 5. The laboratory-created experimental setup exhibiting the intended results is shown in Section 6. The outcomes of every sensor that is connected to the LoRa module are shown in Section 7. Conclusions and upcoming problems for the assessment of this joint integration of wireless sensors with the LoRa module are presented in Sections 8 and 9.

2 Related Work

Given the increasing frequency of maritime activities, it is strategically imperative that maritime communication technology be developed^[14]. However, due to the complex and ever-changing environmental monitoring and the disparate standards of communication systems, the development of marine communication lags significantly behind that of land-based communication. For data transmission and sharing, the Marine Internet of Things (MIoT) depends on dependable communication networks assisted with UAVs^[15]. Therefore, the network may use cellular networks, wireless sensor networks, UAV assisted LoRa, and other technologies to span vast ocean areas^[16]. Real-time data monitoring and remote control between nodes are made possible by an efficient communication network known as a LoRa network, which can also satisfy the needs of numerous application scenarios. According to^[17], the main forces behind the MIoT include the expansion and administration of marine resources, the safety of maritime transport, the monitoring and preservation of the marine environment, cross-border collaboration and the sharing economy, scientific and technological breakthroughs, and application needs. Therefore, due to the continuous development of related technologies and the continuous

extension of application scenarios, the MIIoT is becoming increasingly important in the maritime sector and marine environmental protection^[18].

LPWAN technology uses a unique spread spectrum modulation method based on the chirp spread spectrum (CSS) to provide long-range wireless communications at exceptionally low power^[19]. Chirps help LoRa withstand noise, fading, and interference. LoRa has been highly suggested for IoT solutions due to its ability to provide long-range communications, ranging from 2 to 5 km in urban areas and 15 km in suburban areas^[20]. Recent research indicates that UAV-assisted LoRa is an essential technology for providing reasonably priced long-range coverage and satisfying the connectivity requirements of Internet of Things applications^[21]. Tangible implementations have shown that LoRa can be deployed successfully in smart applications. Nevertheless, these applications have issues and challenges, including concerns about network security, scalability, and lifespan^{[22],[23]}.

LoRaWAN technology used in^[24] creates a sensor network that comprises a buoy for tracking of water temperature, salinity, turbidity, fuel and oil presence, and meteorological indicators. In this regard, long range low cost communication investigated in^[25] to develop coastal IoT services. Measurements such as water temperature, wave period, and current height or direction may be shared via a mesh network. The study of monitoring large aquatic ecosystems presented in^[26] in support of the Ocean of Things, which uses a distributed network of low-cost sensors for real-time data collecting to support the sustainable management of aquatic environments.

The UAV-assisted LoRa network, which aims to provide wide-range coverage at a lower energy cost and creates a modular protocol implementation to facilitate deployment in heterogeneous devices while providing a simple and efficient solution, shares the background of these technologies.

3 Latest Trends in UAV Assisted LoRa Based Environmental Monitoring

A new sector called "smart agriculture" is using the Internet of Things to change farming practices. Fadhil et al. focuses^[27] use of environment sensors for air pollution detection based on various wireless protocols, such as Wi-Fi, Bluetooth, ZigBee, LoRa, GPS, and 4G/5G. This study also emphasizes the difficulties and restrictions that drones encounter when attempting to detect air pollution. Li et al. introduce^[28] an integrated emergency environmental monitoring system that integrates real-time monitoring, UAV-mounted LoRa gateway relaying, and backend data processing is established using sensors, LoRa long-distance communication, and line-of-sight communication with unmanned aerial vehicles (UAVs).

Environmental emergency data can be acquired in real time, transmitted seamlessly, stored, managed, and visualized with this system. Zhao et al. proposed^[29] a UAV-assisted LoRaWAN network system architecture that combines the conventional LoRaWAN architecture of "End-Device + Gateway + Server" with the UAV architecture of "UAV + Remote Controller + Server." In this study, the remote controller relay and UAV gateway implementation considered to be a key components for the suggested LoRaWAN architecture.

As unmanned aerial vehicles (UAVs) technology advances, it can now be used in a wider range of fields, such as environmental monitoring, smart power grid monitoring, military applications, surveillance, and commerce. Osmani et al. evaluate^[30] and critically examine the electronics hardware that is classified inside UAVs, with a full analysis of the corresponding performance metrics. This study examines several algorithms used in communication, data processing, flight control, surveillance, navigation, and protection. Dobrilovic et al. address^[31] the issue of UAV path planning for use in diverse urban environment scenarios. The proposed UAV path planning technique used for the situation of monitoring urban garbage. In order to identify potential infractions of waste disposal regulations, the system intended to monitor public containers, uncontrolled landfills, and urban green spaces. The technology and suggested approach designed to detect abnormalities in garbage disposal and to monitor the area in real time using drones with programmed paths.

Recent trends in UAV-assisted LoRa-based environmental monitoring highlight the growing use of drones combined with low-power, long-range LoRa communication for efficient data collection in remote or hard-to-reach areas. These systems offer enhanced flexibility, energy efficiency, and scalability for real-time monitoring of environmental parameters such as air quality, temperature, and water levels. Key advancements include autonomous flight path optimization, edge computing integration for on-board data processing, and hybrid communication models for improved connectivity. This approach is proving especially valuable in climate monitoring, disaster response, and precision agriculture.

UAV-based LoRaWAN gateways offer unprecedented flexibility, coverage, and rapid deployment, making them highly suitable for environmental monitoring, disaster response, and any situation where infrastructure is lacking or dynamic. While there are trade-offs in power and flight time, their mobility and adaptability give them a significant advantage over traditional fixed gateways in certain use cases.

4 Problem Context and Proposed Architecture

Environmental monitoring in remote and vast areas

often faces challenges such as limited connectivity, high deployment costs, and difficult terrain. To address these issues, this work proposes a UAV-assisted wireless sensor network (WSN) leveraging LoRa technology. The UAV serves as a mobile gateway, collecting data from widely distributed LoRa sensor nodes and transmitting it to a central system. The proposed architecture ensures energy efficiency, wide-area coverage, and scalability, making it suitable for real-time monitoring of environmental parameters such as air quality, temperature, humidity, and pollution levels.

5 Design Framework

UAV assisted Long-range data communication in environmental monitoring normally require a number of components on both the transmitter and reception sides to create a WSN. Here is a thorough rundown of the functioning components for the transmitter and receiver:

5.1 LoRa Transmission Unit

a) Marine Sensor Node (Sensor Array)

○ Sensors: The sensors used in this study include DHT 11 (temperature & humidity), MQ9 (gas sensor), SW-240 (vibration sensor), MPU 6050 (Gyroscope), and Rain sensor respectively.

○ Microcontroller (MCU): The sensor data is gathered and prepared for transmission by the microcontroller. Additionally, it is capable of preprocessing, basic data aggregation, and maybe basic local storage.

○ Power Supply: In order to ensure long term, sustainable operations, sensor nodes usually powered by batteries or renewable energy sources like solar power.

b) Data Communication Module (Transmitter)

○ Long-Range Communication Module: Technologies such as satellite communication systems, Sigfox, or LoRa may be used for long distance communication. In this proposed study, LoRa module operating at 433MHz spectrum to achieve our desired outcomes.

○ Data Packetization: Sensor readings, timestamps, identifiers, and other pertinent metadata typically included in the data packet containing the sensor data.

○ Modulation & Encoding: The transmitted data is encoded and modulated to suit the communication protocol (LoRa modulation or similar). This is handled by the communication module.

c) Antenna: The antenna used in this work aligned for RF signal reception that are critical for ensuring good signal reception and transmission. For RF (Radio Frequency) communication, the type of antenna used impacts the system's range, signal quality, and efficiency.

In marine environments, the focus is on rugged, low-power, low-data-rate sensors that are cost-effective and resilient, even if that means sacrificing some accuracy. Advanced sensors like the DHT22 or MEMS-based

devices are used selectively, typically in well-protected or power-rich deployments.

5.1.1 Mathematical Representation of Sensor Data

Here are the mathematical equations for the sensor data:

DHT11 (Temperature & Humidity Sensor)

• Humidity Equation:

$$RH(\%) = \left(\frac{H_{raw}}{256} \right) * 100 \quad (1)$$

Where, RH=Relative Humidity, H_{raw} is the 8-bit raw data value for humidity (between 0 and 255).

• Temperature Equation:

$$Temp(\text{centigrade}) = T_{raw} \quad (2)$$

Where, T_{raw} is the 8-bit raw data value for temperature (between 0 and 255).

MQ9 (Gas Sensor)

The Gas Concentration Equation is observed as:

$$R_s = R_{load} \left\{ \frac{V_{cc} - V_{out}}{V_{out}} \right\} \quad (3)$$

Where, R_s = Sensor resistance, R_{load} = Load resistance, V_{cc} = Supply voltage, V_{out} = Output voltage from sensor SW-240 (Vibration Sensor)

$$V_o = V_{cc} \text{ (if vibration detected)} \quad (4)$$

Where, V_o = Output voltage

MPU-6050 (Gyroscope)

$$w = \text{Raw value/Sensitivity} \quad (5)$$

Where, w = angular velocity

Rain Sensor

$$\text{Wet}(\%) = \left(1 - \frac{v_{out}}{v_{max}} \right) * 100 \quad (6)$$

Where, V_{out} = Output voltage, V_{max} = Maximum output voltage

5.1.2 Mathematical Equations of Long Range Communication module (Transmitter)

The mathematical formulas for a long-range communication module differ based on the technology being used, such as LoRa, RF modules, or other wireless systems. Based on the fundamentals of LoRa, the following generic equations for transmitter side are:

• Transmit Power (dB):

$$P(Tx) = \text{Power set of LoRa module (dBm)} \quad (7)$$

Where, $P(Tx)$ = Transmitting power (dB)

• Effective Isotropic Radiated Power (EIRP):

$$EIRP = P_t + A_t + L_t \quad (8)$$

Where, P_t = transmit power, A_t = Transmit Antenna gain, and L_t = Transmission line losses

5.2 LoRa Receiver Module

a) Receiver Communication Module

○ Long-Range Communication Module (Receiver):

Data sent by the sensor nodes is received by this module. The LoRa (Ra02 module) in this study makes receiver-side communication feasible. To recover the transmitted

sensor data, it demodulates and decodes the received signal.

○ Signal Processing: To accurately recover the original data from the received signals, error checking, decoding, or signal conditioning may be necessary.

b) Base Station (Gateway)

○ Microcontroller/Processor With its many I/O pins, several sensors, and sophisticated communication protocols, the Arduino Mega (ATmega 2560) is a viable option for bigger system like wireless sensor networks (WSN).

○ WiFi module: The ESP-8266 WiFi module, which works well with embedded systems, is employed in this suggested study. Incoming data from the receiver module is processed and stored by this module. It might also integrate with cloud-based systems or carry out extra data analysis.

c) Power Supply: A steady power source, which is frequently coupled to an external power source or renewable energy if necessary, is also employed to maintain the receiver system's functionality.

d) Antenna (Receiver Side): The same antenna used by the transmitter and receiver sides, which must be compatible in order to receive long range transmissions.

5.2.1 Mathematical Equations of Long Range Communication module (Receiver)

The mathematical formulas for a long-range communication module differ based on the technology being used, such as LoRa, RF modules, or other wireless systems. The following general equations for the receiver side are based on the principles of LoRa:

• Received Signal Strength (RSSI):

$$RSSI = Pt + Gt + Gr - Lp(d) \quad (9)$$

Where, Pt=Transmit power (dBm), Gt=Transmit Antenna Gain (dBi), Gr=Receive Antenna Gain (dBi), Lp(d)=Path loss at distance d in dB.

• Signal to Noise Ratio (SNR):

$$SNR = Pr - N \quad (10)$$

Where, Pr= Received signal power (in dBm), N=Noise (in dBm)

5.3 Integrated System Design

An RF module allows a transmitter and receiver to wirelessly broadcast and receive data over a predetermined frequency range using radio waves. Applications for wireless communication, including sensor networks, remote controls, and Internet of Things (IoT) devices, frequently use RF (Radio Frequency) modules.

5.4 Effects of Wireless Transmission, Transmission rate and Communication amongst the deployed sensors

a) Transmission Effects

Packet loss and delay resulted in DHT11 (Digital

Humidity & Temperature) sensor. Quantization error occurred in using MQ9 sensor. Missed transitions and delay observed in SW-240. Packet drop and high data volume are the effects of MPU-6050 sensor while the state change losses occurred in rain sensor.

b) Transmission Rates

The energy waste resulted in DHT11 sensor. Battery drain occurred via using MQ9 sensor. Vibration effects observed in SW-240. High bandwidth utilization and battery drain are the effects of MPU-6050 sensor while no significant effect of transmission rate in rain sensor.

c) Communication Effects

In terms of LoRa, upto 10km range is covered in DHT11 sensor. Very low communication effects occurred in both MQ9 sensor and SW-240 sensors. High communication rate observed in MPU-6050 sensor. No significant effect resulted in rain sensor.

5.5 Core Elements of RF Communication Systems

a) Transmitter Module:

○ The transmitter module is in charge of turning the input data such as a sensor reading or binary message into a radio signal.

○ Examples: 433 MHz RF Transmitter, Ra02 (2.4 GHz), LoRa (Long Range).

b) Receiver Module:

○ Receiving radio signals, turning them back into data, and transmitting them to a microcontroller or CPU are the responsibilities of the receiver module.

○ Examples: 433 MHz RF Receiver, Ra02 receiver, LoRa receiver.

c) Antenna:

○ Antennas used by the both transmitter and receiver to send and receive radio waves. The signal's quality and range are greatly influenced by the antenna's design.

○ In this proposed study, Omni-directional antenna is used with a gain of 2-5 dBi and efficiency of 60-80% respectively.

d) Microcontroller (MCU):

○ The data is processed by the microcontroller on both the transmitter and receiver sides. It reads sensor data, for instance, encodes it, and then transmits it through the transmitter. The microcontroller on the receiving end decodes the signal and acts on the information (e. g., displaying information, triggering an action).

6 Experimental Setup and Testing

The purpose of this research is to assess a UAV assisted LoRa-based WSN's performance in an environmental monitoring. In order to address transmission and reception issues in an environment, an experimental setup was created in the lab. The lab

environment replicates key environmental stressors — such as temperature, humidity, RF interference, and enclosure performance — to approximate real-world marine deployment conditions. While dynamic flight factors are limited in a lab, ground-based tests provide critical validation before outdoor trials. Figures 3 and 4 respectively show key performance indicators such as communication range and reliability, power consumption, data rate analysis, interference, and long-range communication. An example of a standard experimental setup is as follows:

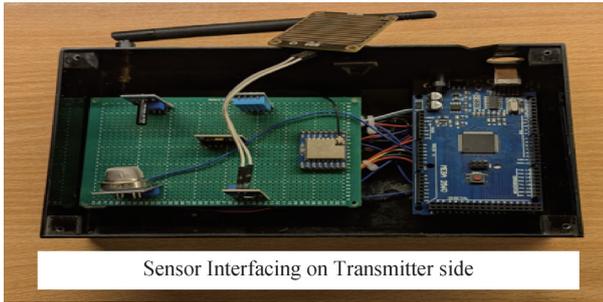


Fig.3 Transmitter Circuit

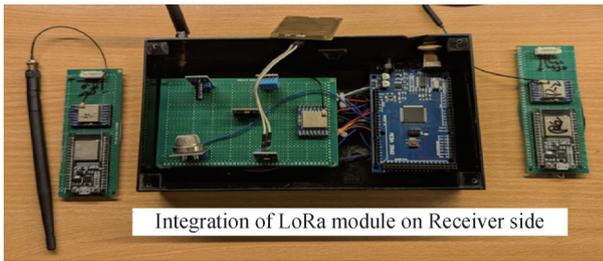


Fig.4 Receiver Circuit

7 Results and Discussion

The monitoring and management of environmental ecosystems has advanced significantly with the integration of UAV assisted LoRa modules and WSNs in a marine context. The main conclusions of the physical characteristics of each sensor employed in this investigation are covered in this part. These sensors' findings are:

Figure 5 displays the temperature and humidity parameters as a function of time using a thermistor and a capacitive humidity sensor. The capacitive humidity sensor adjusts its capacitance in response to variations in the air's water vapor content. A digital signal is created from this modification. The resistance varies with temperature, and the thermistor detects the temperature. After that, a digital value is created from this alteration.

Figure 6 shows the time-dependent results of a gas sensor made up of a heating element and a sensor array mode from tin oxide (SnO₂). The sensitive tin oxide layer on the sensor is heated by the heating element when it is powered on. The electrical conductivity of the sensor changes as a result of interactions between the target gases and the tin oxide surface.

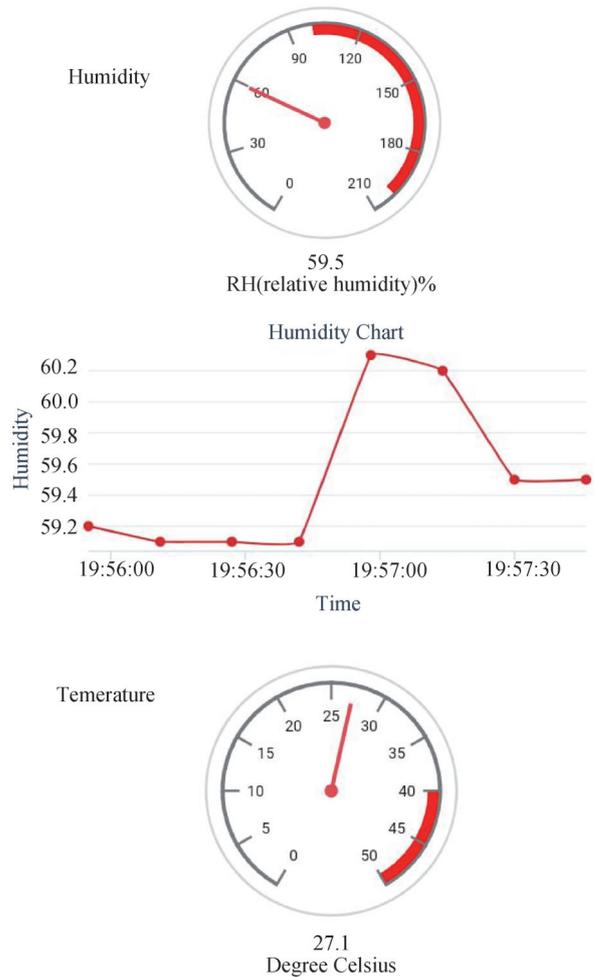


Fig.5 DHT 11 Sensor outcomes

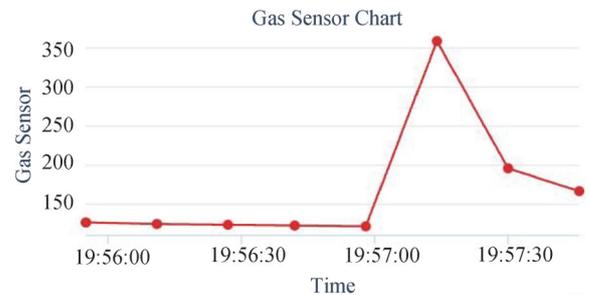


Fig.6 MQ9 Gas Sensor outcome

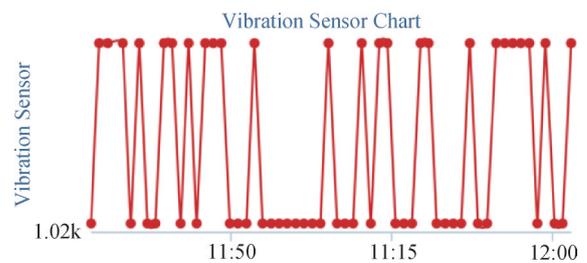


Fig.7 SW-240 Vibration Sensor outcome

The graph for the SW-240 sensor's vibration or shock detection in relation to time is displayed in figure 7. It works by combining a spring mechanism with the idea of a mechanical switch. The metal ball within the

sensor rests in a way that maintains the internal switch open (no circuit) when the sensor is in a stable position. Nevertheless, the ball moves in response to vibration or shock to the sensor, cutting the circuit and setting the digital output to HIGH.

The graph for the MPU 6050 sensor's rotation and acceleration detection in relation to time is displayed in figure 8. The waveform output from the MPU6050 is a visual representation of sensor data over time, and it's based on how the sensor internally works. These waveforms represent the time series data of motion. It depends on how fast and in which direction the sensor is moved. These waveforms help in analyzing patterns like tilt, rotation, or vibration.

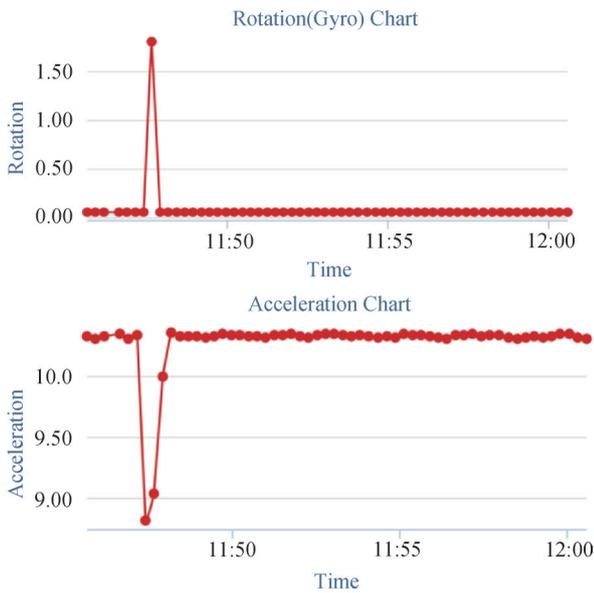


Fig.8 MPU 6050 Gyro Sensor outcome

Figure 9 displays the result of amount of rain detected by the integrated sensor with respect to the time. A rain sensor (commonly used in weather stations, automatic wipers, or home automation systems) detects the presence and intensity of rain. The sensor has a conductive plate. Water droplets reduce resistance between the traces. The circuit senses this change and outputs a signal accordingly.

Finally, the comparison of system's performance of proposed study is far better in terms of range (12-15km),

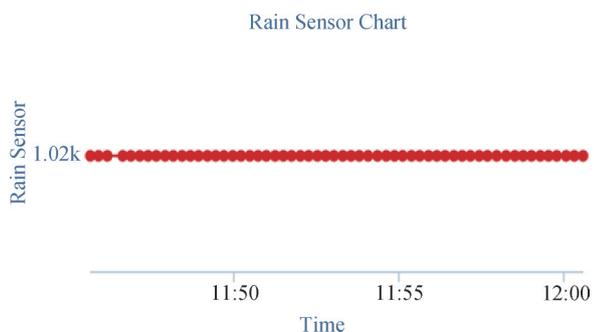


Fig.9 Rain Sensor outcome

and effective power consumption (up to 10µA) respectively.

8 Conclusion

Data monitoring and transmission across great distances in the environment made possible by the UAV assisted LoRa's success as a long-range communication technology. LoRa's low power consumption is particularly advantageous for WSNs installed in isolated or challenging-to-reach areas. The LoRa modules in this project demonstrated good transmission range, covering many kilometers. However, the network's performance affected by elements including data rate analysis, power consumption, and communication dependability. The network's scalability successfully tested and verified, allowing for the addition of more sensors and coverage expansion as required. The UAV assisted LoRa network is appropriate for extensive environmental monitoring because it enables a dense placement of nodes. Additionally, real-time monitoring of environmental parameters like temperature, humidity, pH levels, and other oceanographic characteristics are presented by the proposed architecture. In order to achieve long-term success, the integration of various data points into a centralized system improved situational awareness and decision-making for environmental management and research.

9 Limitations & Future Challenges

LoRa communication may cause RF noise and multipath fading. The integration of UAVs and sensor nodes results in limited flight time and lower bandwidth. Therefore, the reliability of the network under difficult conditions (such strong storms or extreme tides) may be further assessed in the proposed study. The efficacy and sustainability of marine sensor networks could also be improved by combining cutting-edge sensor technologies with more reliable power sources, such as solar or tidal energy. Moreover, the other challenges like sensor node power limitations, LoRa interference, and security vulnerabilities may be addressed in future studies.

Author Contribution:

Muhammad Aamir Khan: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. Zain Anwar Ali: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. Supervision, Funding acquisition, Conceptualization. Rana Javed Masood: Methodology, Investigation, Formal analysis.

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Data Availability:

Authors confirm data, supporting the findings are available within article.

Conflicts of Interest:

The authors declare no competing interests.

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