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Design and Implementation of an Emergency Environmental Monitoring System

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Abstract: The collection and real-time transmission of emergency environmental information are crucial for rapidly assessing the on-site situation of sudden disasters and responding promptly. However, the acquisition of emergency environmental information, particularly its seamless transmission, faces significant challenges under complex terrain and limited ground communication. This paper utilizes sensors, line-of-sight communication with unmanned aerial vehicles (UAVs), and LoRa long-distance communication to establish an integrated emergency environmental monitoring system that combines real-time monitoring, UAV-mounted LoRa gateway relaying, and backend data analysis. This system achieves real-time acquisition, seamless transmission, storage management, and visualization of environmental emergency information. First, a portable emergency environmental monitoring device was developed to collect and transmit environmental factor data. Second, a UAV-mounted LoRa gateway was designed to extend the data transmission coverage, ensuring seamless communication. Finally, multiple field experiments were conducted to evaluate the system's performance. The experimental results indicate that the system possesses reliable capabilities for emergency data collection and transmission in complex environments, providing new technical solutions and practical support for developing and applying emergency environmental monitoring systems.

Keywords: environmental monitoring; UAV; LoRa; data transmission

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1. Introduction

In recent years, global climate change has increased extreme weather events [1], significantly raising the frequency and severity of natural disasters such as forest fires, floods, and earthquakes. These sudden disasters cause severe damage to ecosystems and infrastructure and pose a significant threat to public safety and property protection. The situation changes rapidly during a disaster, making real-time and accurate environmental monitoring and swift response a key research issue in emergency management. Most environmental monitoring systems rely on wired transmission or data transfer through cellular networks and satellite communication [2,3]. However, in remote mountainous areas or when infrastructure is damaged by disasters, traditional communication networks may fail, severely impacting the timeliness and reliability of monitoring systems. Therefore, developing an

emergency environmental monitoring system that can adapt to complex environments and does not rely on traditional infrastructure, ensuring the rapid acquisition and transmission of information, is a pressing issue that needs to be addressed in emergency scenarios.

The rapid development of Internet of Things (IoT) technology has provided new solutions for environmental monitoring. IoT technology has been widely applied in various fields, such as smart agriculture [4], industrial monitoring [5], intelligent transportation [6], earthquake monitoring [7], and healthcare [8], enabling real-time data collection and tracking through sensor networks. Low Power Wide Area Network (LPWAN) is a wireless communication technology suitable for IoT applications, specifically designed for long-distance communication and low-power devices. Standard LPWAN technologies include LoRa, NB-IoT, and Sigfox. Portable monitoring devices incorporating LPWAN technology can collect and transmit real-time environmental factor data, such as temperature, humidity, wind speed, and wind direction. However, efficiently transmitting these data in remote areas or under insufficient infrastructure remains challenging [9]. LoRa (Long Range) technology has emerged as an effective means of IoT data transmission due to its long-range capabilities, low power consumption, and high sensitivity. LoRa technology provides stable communication connections in areas with limited signal propagation, such as mountainous regions or densely vegetated areas, demonstrating significant advantages in long-distance data transmission for disaster emergency scenarios. Moreover, the low power consumption of LoRa significantly extends the battery life of devices, which is particularly critical during the execution of complex emergency tasks, offering robust support for the efficient operation of the system.

On the other hand, unmanned aerial vehicles (UAVs), with their flexible deployment and high maneuverability, can serve as temporary communication relay devices, effectively compensating for the coverage deficiencies of traditional networks. Compared to ground-based LoRa communication, UAV–LoRa communication networks benefit from Line-of-Sight (LOS) propagation advantages [10]. Compared to conventional "ground-to-ground" data collection methods, aerial data transmission is less affected by obstacles and offers a broader wireless signal coverage range. More importantly, UAVs can flexibly approach endpoint devices, unlike fixed deployment gateway models, enabling data communication at lower transmission power and higher transmission rates. This significantly reduces the energy consumption of endpoint devices and effectively extends the wireless network's overall lifespan. Therefore, combining LoRa technology and UAVs in monitoring systems can provide a more adaptive and reliable solution for data collection and transmission in complex geographical environments and emergency scenarios [11–13].

In recent years, several domestic and international scholars have explored the combination of unmanned aerial vehicles (UAVs) and LoRa communication. Arroyo, P. et al. integrated LoRa with UAVs to acquire data from ground sensors [14]. Sobhi S. et al. studied the mobility of LoRaWAN gateways, enhancing the efficiency of environmental monitoring through UAV-mounted LoRa gateways, particularly in signal-deprived pristine ecological areas [15]. Chen et al. integrated multiple sensors and a LoRa transceiver into a UAV, creating an automated air quality monitoring platform [16]. Behjati et al. designed an intelligent UAV system for livestock monitoring [17]. In this work, a multi-channel LoRaWAN gateway based on the SX1301 was carried on the UAV. To address the issue of unstable network connections in airborne scenarios, a local small server was designed on the UAV to store LoRa data packets. Omkar Mujumdar et al. investigated the reliability and coverage performance of LoRa for remote UAV identification under multi-user interference and different spreading factor conditions. They evaluated LoRa's performance under various interference scenarios through ray-tracing models and MATLAB simulations [18].

This paper constructs an emergency environmental monitoring system. The system comprises three components: a portable emergency environmental monitoring device, a UAV-mounted LoRa gateway, and backend analysis software. The portable monitoring device can collect critical environmental parameters such as wind speed and direction accurately in real-time. The UAV-mounted LoRa gateway expands the data transmission coverage of ground monitoring devices through aerial relay communication. The backend analysis software provides data analysis capabilities, supporting emergency decision-making.

2. Development of the Emergency Environmental Monitoring Device

2.1. Mechanical Structure Design

The composition of the portable environmental monitoring device is shown in Figure 1, which mainly consists of a device enclosure, ultrasonic wind speed and direction sensor, circuit board, and so on. The device enclosure features an OLED display, a switch, charging, and data exchange interfaces on its surface. Internally, it is equipped with a PCB, LoRa module, an ultrasonic wind speed and direction sensor, Beidou + GPS dual-mode positioning sensor, temperature and humidity sensor, carbon monoxide concentration sensor, lithium battery, and so on. This device is characterized by its compact and lightweight design, measuring 5.7 cm in length, 3.8 cm in width, and 17.1 cm in height, weighing approximately 400 g. It offers greater portability and flexibility than traditional large fixed environmental monitoring stations. A schematic diagram of the device is shown in Figure 2.

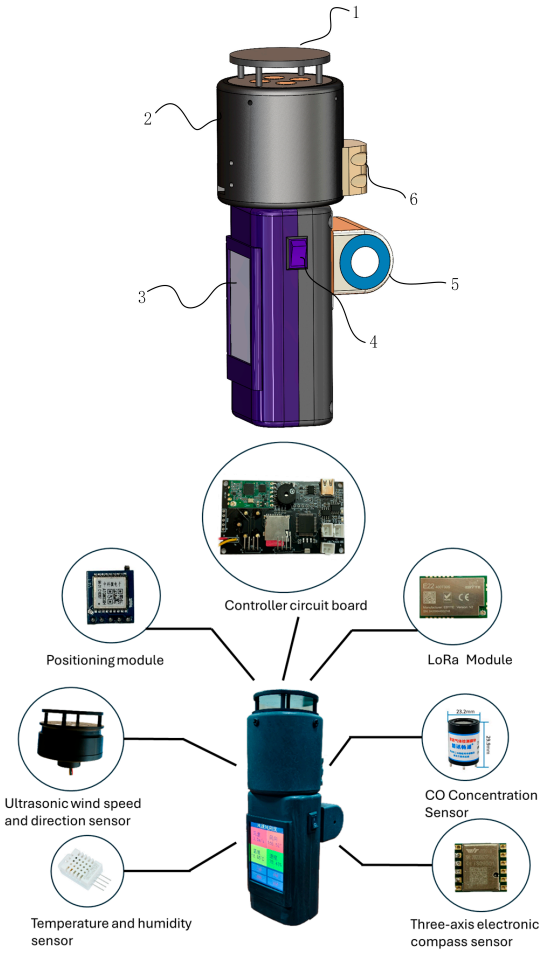


Figure 1. Structure diagram of the portable environmental monitoring device. 1. Ultrasonic wind speed and direction sensor. 2. Device enclosure 3. OLED display. 4. Switch. 5. Carbon monoxide concentration sensor. 6. Temperature and humidity sensor.



Figure 2. Schematic diagram of the device.

2.2. Circuit and Component Integration Design

The circuit structure of the device is shown in Figure 3, integrating functional modules such as the central control module, environmental sensing module, power module, interaction module, and communication module. The main control module coordinates the operation of all the modules. The main control module uses the STC15 series microcontroller, the STC15W4K56S4 model, which offers advantages such as low power consumption and anti-interference solid capabilities. The power management module includes a step-down circuit, battery monitoring, control switch, and power input modules. The step-down circuit distributes different voltages to the corresponding modules, achieving multi-gradient voltage output. The device has a built-in 4000 mAh lithium battery, which allows the power management module to monitor the battery status in real-time, ensuring stable system operation. The device's operational time can reach 8 h through field testing and battery life calculations, providing reliable power support for emergency environmental monitoring tasks. The environmental sensing module is utilized for the real-time monitoring and extraction of environmental factors, including temperature, humidity, wind speed and direction, carbon monoxide, PM2.5, atmospheric pressure, altitude, and so on. The LoRa communication module transmits the collected data to the LoRa gateway, which then uploads the data to the server. The Bluetooth communication module facilitates communication with the Android host software, transmitting real-time data to the Android device. The storage module has an SD card, allowing real-time data storage to prevent data loss. The real-time interaction module displays all detected data to the user via the OLED screen, allowing users to select and utilize various functions through the touchscreen.

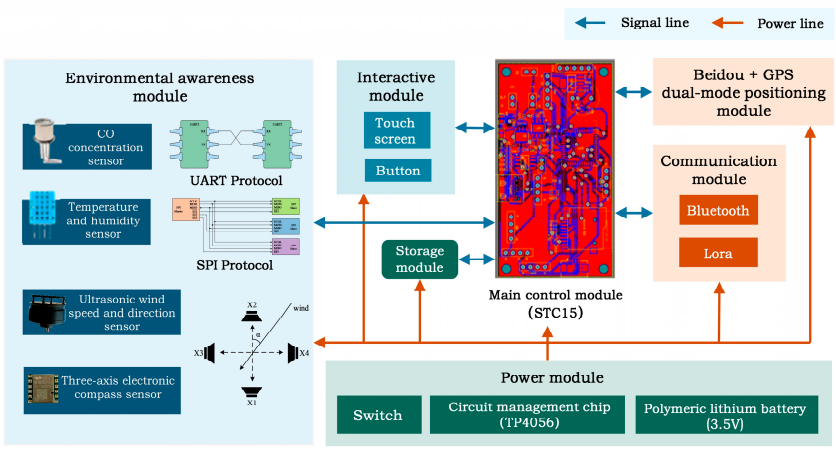


Figure 3. Circuit framework diagram of the portable environmental monitoring device.

The portable environmental monitoring device designed in this study employs a dual-layer printed circuit board. Based on the design principles of the modules above, the components are arranged in a rational layout. The PCB of the device is shown in Figure 4.

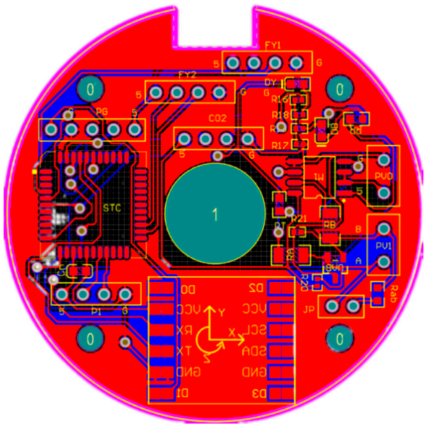


Figure 4. PCB of the portable emergency environmental monitoring device.

2.3. Design Principles

Principles of Wind Speed and Direction Measurement

The portable emergency environmental monitoring device utilizes an ultrasonic wind speed and direction sensor to measure wind parameters, as shown in Figure 5. The technique is based on the time difference method, which focuses on accurately capturing the flow information conveyed by the sound waves. Wind speed is reflected by measuring the time difference in the propagation of ultrasonic pulses under equivalent path lengths in both downwind and upwind conditions [19]. The principle of the time difference measurement is illustrated in Figure 6.



Figure 5. Structure of the ultrasonic wind speed and direction sensor.

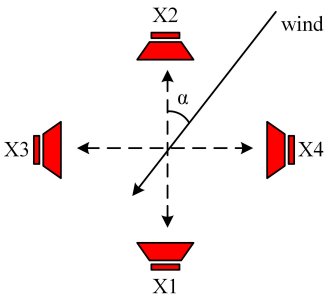


Figure 6. Time difference measurement principle diagram. X1, X2, X3 and X4: The physical locations of four ultrasonic transducers, used to measure the propagation time difference of ultrasonic waves under the influence of airflow. α: The angle of airflow passing through the sensor, used to determine the wind direction.

2.4. Software Design

The data interaction sequence diagram of the emergency environmental monitoring system is shown in Figure 7. The sequence diagram illustrates the interaction logic and data flow among various modules during the system's operation. It details the interactive operations between the user and the portable emergency environmental monitoring device, as well as the data transfer and processing between the device, the UAV LoRa gateway, and the network server. The device program is written in C on the Keil5 platform and burned into the STC15 microcontroller. It has vital functions such as current data initialization, storage of environmental factor data changes, and wireless network transmission. The Android application is developed in Java and built on the Android Studio platform, using the Room library to manage the SQLite database. This ensures the system operates efficiently on Android devices while maintaining good compatibility. The user interface, shown in Figure 8, intuitively displays the various environmental factors detected by the device. In addition, the device is integrated with the OneNET cloud platform. By connecting to the OneNET cloud server, users can view the device status and environmental monitoring data in real-time, enabling remote monitoring and data management functions.

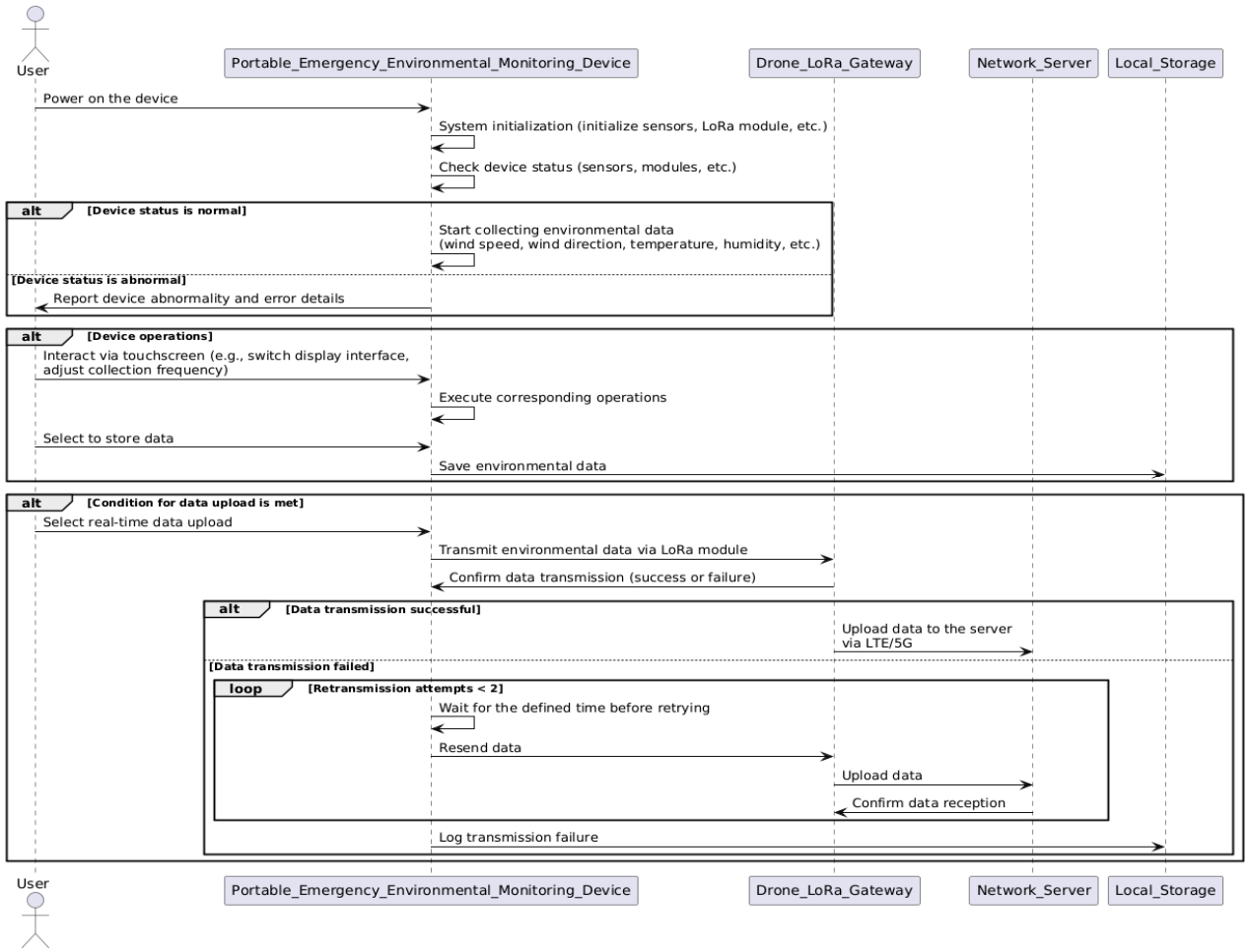


Figure 7. The system data interaction sequence diagram.

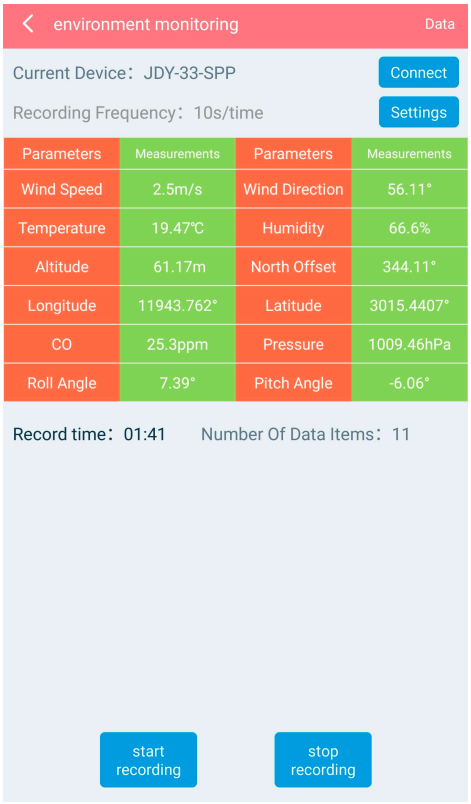


Figure 8. Upper machine software interface.

3. Data Transmission Design

3.1. Characteristics and Advantages of LoRa Communication

Selecting the appropriate wireless communication technology is crucial to meet the special communication requirements of the emergency environmental monitoring system. This system must operate for extended periods with low power consumption in complex and remote geographic environments while possessing long-distance data transmission capabilities. Standard wireless communication technologies, such as ZigBee, WiFi, and Bluetooth, have short-range transmission and high-speed data transfer advantages. However, in emergency scenarios, these technologies often need to provide sufficient coverage or power consumption control. The long-range communication capability and muscular flexibility of LoRa make it more suitable for large-scale emergency communication. Therefore, LoRa is chosen as the communication technology for the system in this study. A comparison of these communication technologies is shown in Table 1.

Table 1. Comparison of performance metrics for common wireless communication technologies.

Communication Technology	Transmission Rate	Transmission Distance	Power Consumption
LoRa	0.3–62.5 kbps	5–15 km	Low
ZigBee	250 kbps (Maximum)	10–1000 m	Low
WiFi	11–54 Mbps (Maximum)	10–100 m	High
Bluetooth	1–2 Mpbs (Maximum)	10 m (Approximately)	Low

3.2. Data Transmission Design Architecture

The LoRa communication module is installed in the portable emergency environmental monitoring device, responsible for transmitting real-time data of key environmental factors such as wind speed and wind direction to the LoRa gateway. Given that the transmission range of LoRa can reach several kilometers in flat terrain, the system utilizes UAVs equipped

with LoRa gateways to act as relay stations in emergency data collection areas, thereby expanding the communication coverage. The application scenario diagram of the UAV-mounted LoRa gateway is shown in Figure 9. The design architecture is as follows:

1. Ground Equipment: The sensors in the ground equipment collect environmental data, such as wind speed and wind direction, which are then modulated by the LoRa module. Using Chirp Spread Spectrum (CSS) technology, the LoRa module converts the digital signals into spread-spectrum signals. The LoRa module represents different digital signal values by altering the frequency of linear frequency modulation, thereby completing the signal transmission. These spread-spectrum signals are subsequently transmitted via LoRa to the LoRa gateway mounted on the UAV. Upon receiving the signals, the gateway uses reverse spread-spectrum modulation to demodulate the signals and performs decoding and verification to ensure the integrity and accuracy of the data.
2. UAV Relay: The UAV is equipped with a LoRa gateway (Model: E90-DTU) manufactured by Ebyte, which is responsible for receiving data from ground monitoring devices. After receiving the LoRa data, the gateway utilizes its built-in functionality to complete the conversion from the LoRa protocol to the TCP/IP protocol, including data demodulation, decoding, verification, and encapsulation. The converted data are then uploaded to the network server via the LTE/5G network, ensuring the reliability and integrity of data transmission. Additionally, by adjusting the UAV's flight altitude and position, the transmission distance and signal strength can be further optimized, thereby enhancing the overall communication performance.
3. Network Server: All collected data are transmitted to the server for analysis and storage after the UAV relays.

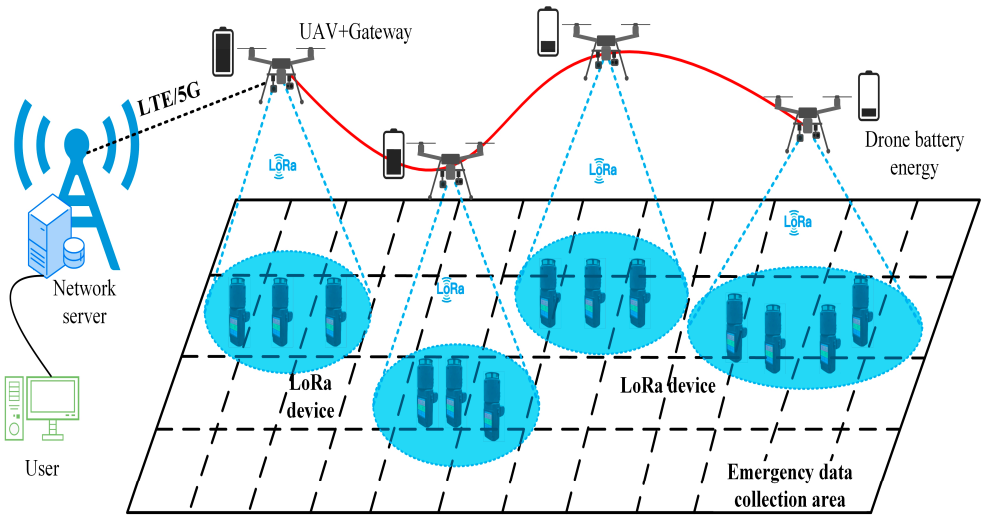


Figure 9. The application scenario diagram of the UAV-mounted LoRa gateway.

3.3. Transmission Reliability and Fault Tolerance Mechanism

In complex emergency environments, data transmission encounters challenges such as signal interference and obstruction by physical barriers. The system incorporates redundant data transmission and automatic retransmission mechanisms to ensure transmission reliability. When data are lost or corrupted during transmission, the device can automatically detect errors in data packets and retransmit until the complete data are successfully received. This design effectively mitigates the risk of data loss. The specific implementation process is as follows:

1. After each data packet is sent, the device waits for an acknowledgment signal (ACK) from the LoRa gateway. If no ACK is received within the specified time, the device triggers an automatic retransmission mechanism, with up to two retransmissions to minimize the risk of data loss. This design effectively adapts to signal interference in complex environments, while ensuring the reliability of data transmission and minimizing the device's energy consumption.
2. Based on the characteristics of the LoRa protocol, communication parameters were optimized to meet the transmission requirements in complex environments. Specifically, a higher spreading factor (SF) was set to enhance the signal's anti-interference capability for long-distance transmission or under signal obstruction conditions. The channel bandwidth was optimized to reduce network congestion caused by the insufficient bandwidth. Additionally, the transmission power was dynamically adjusted to ensure signal coverage while minimizing device power consumption. These optimization measures further improve the system's adaptability and transmission performance in complex emergency environments.

4. Experimental Design and Validation

4.1. Device Evaluation

To verify the accuracy of data collection by the developed monitoring device, a handheld meteorological instrument (developed by Shandong Fengtu Internet of Things Technology Co., Ltd., Weifang, China) and an ultrasonic integrated meteorological station (developed by SIN Electronic Technology Co., Ltd., Jinan, China) were used for comparison. Experiments were conducted at the Donghu campus of Zhejiang Agriculture and Forestry University and in the surrounding mountains and forests. Parameters such as wind speed, wind direction, temperature, and humidity were measured in various environments to assess the performance of the developed monitoring device in complex real-world conditions.

During the experiment, the monitoring device described in this study and the comparison meteorological station were fixed at the experimental site (Figure 10a,b). This setup ensured consistent installation height and orientation of the devices, minimizing the impact of external factors on the data. Once the experiment started, both devices were activated simultaneously, and data such as wind speed, wind direction, temperature, and humidity were automatically collected every minute. Data were collected over 48 h to evaluate the devices' performance across different times and environments.



(**a**) (**b**)

Figure 10. Comparison Diagram of Devices. (**a**) Meteorological station a was fixed at the experimental site; (**b**) Meteorological station b was fixed at the experimental site.

Data Accuracy Evaluation

To verify the validity of the monitoring results, indicators such as the Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE), as defined in Equation (1), were used to evaluate the measurement data from each device. The evaluation results are presented in Table 2. The analysis results indicate that the monitoring device developed in this study is closer to the measurements from the ultrasonic integrated meteorological station, demonstrating higher measurement accuracy.

$$\begin{cases} \text{MAE} = \frac{1}{n}\sum_{i-1}^{n}\left|Z_i - \hat{Z}_i\right| \\ \text{MSE} = \frac{1}{n}\sum_{i-1}^{n}\left(Z_i - \hat{Z}_i\right)^2 \\ \text{RMSE} = \sqrt{\frac{1}{n}\sum_{i-1}^{n}\left(Z_i - \hat{Z}_i\right)^2} \end{cases} \quad (1)$$

In the equation above, Z_i represents the measurement value of the comparison device, $\hat{Z}_i$ represents the measurement value of this device, and n represents the number of data points.

Table 2. Comparison of measurement accuracy between different devices.

Environmental Factors	Handheld Meteorological Instrument			Ultrasonic Integrated Meteorological Station		
	MAE	**MSE**	**RMSE**	**MAE**	**MSE**	**RMSE**
Temperature	0.3745	0.3111	0.5578	0.3482	0.3054	0.5526
Humidity	3.3228	12.6183	3.5522	2.8532	9.6581	3.1077
Wind Speed	0.3066	0.1755	0.4189	0.2845	0.1657	0.4071
Wind Direction	6.6990	63.7143	7.9821	5.1468	50.6218	7.1149

4.2. Data Transmission Evaluation

This study conducted multiple outdoor experiments to evaluate the long-range data transmission capability of LoRa technology in environments without infrastructure, particularly in complex terrains such as forests and dynamic environments. The experimental site was at the Donghu campus of Zhejiang Agriculture and Forestry University in Hangzhou, Zhejiang Province, and the surrounding mountains and forests. This area features a complex environment with numerous natural barriers.

The LoRa transmission range is determined by factors such as transmission power, transmission rate, antenna performance, frequency, spreading factor, bandwidth, obstacles, channel interference, weather conditions, and receiver sensitivity. Reducing the data rate, increasing the transmission power, and improving the antenna gain will extend the LoRa transmission range [20]. The selected LoRa module and gateway are based on the SX1262 RF chip designed by SEMTECH, with a data rate range from 2.4 kbps to 62.5 kbps. The data rate between the LoRa gateway and module is set to 2.4 kbps, with a transmission power of 22 dBm, an antenna gain of 5 dBi, and the antenna positioned vertically.

4.2.1. Ground Test

This study performed ground tests in two distinct environments:

(1) Environment with many obstacles (such as buildings, hills, and trees): Test 1 was carried out on the eastern side of the campus, where the LoRa gateway was fixed at the east gate, and the LoRa module was carried by the staff, moving around the perimeter of the campus. The results indicate that, in this complex environment, the maximum communication distance reached 1.41 km (Figure 11a).

(2) Environment with fewer obstacles: Test 2 was carried out at the artificial lake near the school, where the LoRa gateway was fixed at one end of the lake, and the LoRa module moved along the lakeside track. The results indicate that the maximum communication distance in an open environment with fewer obstacles can reach 6.71 km (Figure 11b).



(**a**) (**b**)

Figure 11. LoRa Ground Communication Distance Test. (**a**) maximum communication distance; (**b**) maximum communication distance in an open environment.

4.2.2. UAV Ground Test

During the UAV ground test, the LoRa gateway and antenna were mounted on the UAV (as shown in Figure 12a), with the UAV hovering at 300 m to test communication performance in dynamic conditions. The UAV model is the DJI M210 v2, with a maximum takeoff weight of 6.14 kg. The LoRa module was placed in a moving car, which had departed from the school. The vehicle was able to receive data normally while in motion. The test results indicate that, with the UAV-mounted gateway, the maximum communication distance reached 17.28 km, as shown in Figure 12b.



(**a**) (**b**)

Figure 12. UAV-to-Ground Communication Distance Test. (**a**) LoRa gateway and antenna were mounted on the UAV; (**b**) maximum communication distance.

4.2.3. Communication Tests at Various Heights and Distances

To further evaluate the communication performance of the UAV-mounted LoRa gateway at different heights and distances, an experiment simulating a forest environment was conducted at the Zhejiang Agriculture and Forestry University East Lake Campus Botanical Garden (N 30°15′ E 119°43′). The settings of the LoRa gateway and LoRa module are identical to those in the previous tests. The experiment analyzed the communication performance between the UAV at heights of 50 m, 100 m, and 200 m and the ground LoRa device over distances ranging from 100 to 1800 m. The ground device monitored environmental parameters, including temperature, humidity, carbon monoxide, wind speed, and wind direction, and transmitted the data to the UAV-mounted LoRa gateway via the LoRa module. The gateway then uploaded the data to the server through the cellular network.

4.2.4. Experimental Results and Analysis

The transmission range of the transceiver was verified through testing. The test involved the portable environmental monitoring device transmitting data packets via the LoRa module, which were received by the LoRa gateway carried by the unmanned aerial vehicle (UAV).

As shown in Figure 13, flight altitude significantly affects RSSI signal strength. According to the Free Space Path Loss Model, signal attenuation generally decreases exponentially with increasing distance. However, transmission conditions improve at higher altitudes due to fewer obstacles.

- At 50 m altitude: The signal rapidly attenuates beyond 500 m, with significant degradation occurring, especially at distances of 1000 m and beyond, where the signal strength drops to the threshold level, making stable communication nearly impossible.
- At 100 m altitude: At a height of 100 m, the signal remains stable, with the RSSI value staying relatively constant even at a distance of 1000 m. This suggests that moderately increasing the flight altitude can effectively mitigate the impact of obstacles.
- At 200 m altitude: Signal attenuation is minimal, and even at a distance of 1800 m, the RSSI value remains around −70 dBm. The increased flight altitude effectively reduces signal reflection and loss, resulting in better long-distance communication performance than lower altitudes.

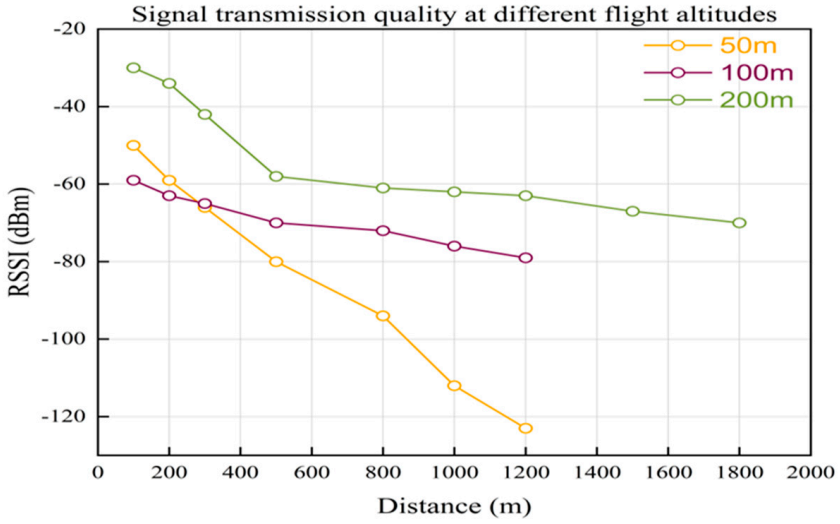


Figure 13. Signal transmission quality at different flight altitudes.

5. Results

This study validated the measurement accuracy of the emergency environmental monitoring device through comparative experiments. Four environmental factors—temperature, humidity, wind speed, and wind direction—were selected and compared against the measurement results from a handheld meteorological instrument and an ultrasonic all-in-one weather station. The experimental results showed that the measurement errors (MAE, MSE and RMSE) of the proposed device were all smaller than those of the handheld meteorological instrument and relatively close to the results of the ultrasonic all-in-one weather station, demonstrating high measurement accuracy and reliability. These findings confirm that the device meets the monitoring requirements in complex environments, providing strong support for its application in emergency scenarios. In the data transmission experiment, this study evaluated the transmission performance of LoRa signals and found that transmission distance is highly dependent on the communication environment. In the UAV-mounted gateway test, the transmission distance reached 17.25 km, significantly exceeding the 6.71 km achieved in the ground test. This demonstrates that, in obstructed environments, utilizing UAVs as communication relays can effectively mitigate the signal attenuation issues commonly encountered in traditional ground-based communication systems. In addition, this study conducts UAV communication experiments at different heights and distances to verify the significant impact of flight altitude on communication stability. Flight altitudes of 100 m and above effectively reduce signal interference from obstacles, enhancing signal transmission stability and extending the effective coverage range.

6. Discussion

This study innovates by combining the low-power, long-range transmission characteristics of LoRa technology with the flexible deployment advantages of unmanned aerial vehicles (UAVs), proposing an emergency environmental monitoring solution with wide-area coverage capabilities. Compared to traditional fixed monitoring stations, this system significantly enhances adaptability and practicality in complex terrains and environments without existing infrastructure. Additionally, it features high portability, flexible deployment, and simple operation. Its lightweight design allows for rapid deployment to disaster sites, reducing response time, while the UAV-mounted LoRa gateway further extends the data transmission range, effectively supporting temporary and dynamic monitoring needs. These features make the system more practical and efficient in emergency scenarios, providing a reliable solution for areas that traditional monitoring approaches cannot cover. Meanwhile, this study also provides important technical references for the future application of UAVs and IoT technology in emergency monitoring.

Although this study has achieved specific results in real-time acquisition of environmental factors, communication coverage, and data transmission stability, some limitations remain. Firstly, the flight time and energy management of the unmanned aerial vehicle (UAV) remain significant factors affecting the system's continuous operation. In the experiments, the single-flight endurance was approximately 30 min. Long-term real-time monitoring tasks over a large area may require multiple UAVs to rotate in execution or breakthroughs in UAV battery technology. Secondly, in the LoRa signal transmission process, interference factors such as weather conditions and obstacles have a complex impact on the signal. Further research can be conducted on the signal transmission characteristics under different environmental conditions to improve the system's robustness.

7. Conclusions

This study designed and implemented an emergency environmental monitoring system that integrates UAVs with LoRa technology, providing an efficient and reliable

technical solution to address emergency needs in remote areas and environments with limited infrastructure. By integrating a portable emergency environmental monitoring device, a UAV-mounted LoRa gateway, and a backend data analysis platform, the system enables real-time collection and long-distance transmission of key environmental factors such as wind speed, wind direction, temperature, and humidity. The experimental results demonstrate that the portable emergency monitoring device can accurately and efficiently collect real-time data on critical environmental parameters, such as wind speed and direction, and enable immediate data uploads. The system exhibits significant application potential in emergency scenarios, particularly in complex terrains or environments with poor line-of-sight signal conditions. The UAV-mounted LoRa gateway significantly extends the data transmission range, thereby enhancing the overall performance and adaptability of the system.

In conclusion, this study provides an effective technical solution for emergency monitoring in remote, disaster-prone environments with less infrastructure and verifies its feasibility and stability in practical applications. Future work can further improve the unmanned aerial vehicle's (UAV) flight path and energy consumption management strategies and optimize communication algorithms to enhance the system's performance in practical applications and promote the widespread use of this technology in more emergency scenarios [21–23].

Author Contributions: Conceptualization, C.L.; methodology, L.F.; formal analysis, L.S.; investigation, S.Z. (Shan Zhu); data curation, H.S. and L.F.; writing—original draft, C.L.; writing—review and editing, L.F. and H.S.; software K.Z. and J.W.; investigation S.Z. (Shaobin Zhang). All authors have read and agreed to the published version of the manuscript.

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