Cyprus University of Technology

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Master's thesis

Design of an Offshore Marine Environment Buoy Monitoring Platform Based on LoRa Wireless Technology

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Limassol, February 2024

MSc in Electronics Science and Technology

CYPRUS UNIVERSITY OF TECHNOLOGY

Faculty of Engineering and Technology

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Approval Form

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Acknowledgements

I would like to express my sincere gratitude to Professor Michalis Michaelides for his generous support and guidance throughout my study and research. His valuable advice and encouragement have greatly contributed to the completion of this work. I would also like to thank the faculty members of the Cyprus University of Technology for their assistance and support in both my academic and personal life during my time abroad. Their help created a productive and welcoming environment that enabled me to grow professionally and personally.

ABSTRACT

This paper presents the development of a near-shore marine environment monitoring platform based on LoRa communication technology. It begins by describing the disciplinary background and practical motivations behind buoy-based monitoring systems, highlighting their growing importance in marine environmental protection and resource management. Although LoRa technology has shown great potential for low-power, long-range communication, its integration into marine monitoring platforms remains underexplored.

The study investigates the theoretical and applied aspects of LoRa-based monitoring, offering new perspectives for sensor integration and data transmission in constrained marine environments. By comparing domestic and international research efforts, it highlights the advantages and limitations of current approaches in terms of methodology, data quality, and system cost, and it identifies opportunities for improvement.

Furthermore, the paper elaborates on the overall architecture and working mechanism of the proposed monitoring platform, which consists of three core components: the monitoring node, the LoRa concentrator, and the cloud platform. The monitoring node performs real-time data acquisition and preprocessing; the LoRa concentrator ensures reliable data aggregation and transmission; and the cloud platform enables remote storage, visualization, and analysis. This modular and energy-efficient design offers a practical solution for long-term monitoring in nearshore marine environments.

Keywords:LoRa communication, marine environment monitoring, buoy system, low-power wireless transmission, sensor integration

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LIST OF ABBREVIATIONS

LoRa	Long Range
IoT	Internet of Things
GSM	Global System for Mobile Communications
GPS	Global Positioning
4G	Fourth Generation Mobile Network
5G	Fifth Generation Mobile Network
MCU	Microcontroller Unit
PC	Personal Computer
PCB	Printed Circuit Board
ADC	Analog-to-Digital Converter
UART	Universal Asynchronous Receiver/Transmitter
MQTT	Message Queuing Telemetry Transport
TDMA	Time Division Multiple Access
LBT	Listen Before Talk

1 Introduction

1.1 Research Background

In recent years, with the increasing global demand for marine resource development, issues such as climate change, marine pollution, and other environmental problems have become increasingly severe. Marine environment monitoring has gradually become a focal point for governments, research institutions, and environmental organizations worldwide. The degradation of the marine environment not only threatens marine ecosystems but also directly impacts the economic development of coastal areas and the sustainable development of human society. Therefore, to better protect and manage marine resources, especially offshore resources, researchers have begun actively exploring real-time and accurate marine environment monitoring technologies, aiming to collect, analyze, and manage marine environmental data using advanced technological means.

- **Limitations of Traditional Marine Monitoring Methods:** Traditional marine monitoring systems typically rely on satellite remote sensing, coastal monitoring stations, and observation vessels. While these methods can collect certain marine environmental data, they also have notable limitations. Satellite remote sensing, although covering a wide area, has low data resolution and struggles to reflect minor changes in the marine environment in real time. Additionally, it is greatly influenced by weather conditions. Coastal monitoring stations are limited to offshore and coastal areas, making it difficult to cover broader regions. Observation vessels, while capable of collecting detailed data, are costly to operate and unsuitable for continuous long-term monitoring. As a result, traditional methods struggle to meet the demand for high-density, real-time data collection in offshore areas due to constraints in coverage, real-time capabilities, and monitoring density [1].

- **Application of IoT Technology in Marine Monitoring:** With the rapid development of Internet of Things (IoT) technology, new monitoring methods have gradually been applied in marine environment monitoring. IoT, through the integration of sensors, communication modules, and data processing systems, can construct a real-time, low-cost monitoring network, providing an economical and efficient solution for offshore environment data collection. Particularly, the advancement of Low-Power Wide-Area Network (LPWAN) technology has significantly addressed issues related to data transmission distance, power consumption, and cost. The introduction of LoRa (Long Range) communication modules offers new possibilities for offshore marine environment monitoring [2].

  As a low-power, long-distance data transmission technology, LoRa is particularly well-suited for application in marine buoy monitoring systems. The LoRa module's low power consumption, long-distance communication, and anti-interference properties enable it to transmit data over several kilometers under extremely low power conditions, which is critical for buoy sensor networks deployed for long durations at sea. Compared to traditional wireless communication methods, LoRa modules ensure stable data transmission and wide coverage with low energy consumption, making them a core technology for marine buoy monitoring platforms.

- **Advantages of LoRa-Based Buoy Monitoring Platforms:** A LoRa-based buoy monitoring platform distributes multiple sensor nodes across offshore regions to collect environmental parameters such as water temperature, salinity, and dissolved oxygen in real time, enabling comprehensive assessments of marine water quality and ecological conditions. This platform offers several advantages: Low Power Consumption: The platform's low power design ensures continuous operation in marine environments, reducing the need for frequent maintenance and power supply. Long-Distance Transmission: LoRa's long-range capability allows buoy data to be transmitted directly to shore stations or satellites and subsequently to a central data processing center, achieving real-time data transfer. Cost-Effectiveness: Compared to traditional methods, LoRa-based buoy systems significantly reduce monitoring costs while enhancing data real-time availability and completeness Furthermore, the monitoring platform constructed using LoRa modules can achieve high-density data collection in offshore and coastal regions. This approach is not constrained by changes in the marine environment or climatic conditions, offering flexibility in adapting to different water environments. The sensor network of the LoRa buoy monitoring platform can be freely configured to meet various marine monitoring needs. For example, by adding more sensor types, the platform can expand into a multi-parameter monitoring system, enabling the collection of complex environmental indicators such as pH levels and ammonia nitrogen concentrations, thus enhancing the richness and utility of the data [3].

- **Application Value of LoRa-Based Buoy Monitoring Platforms:** This LoRa-based buoy monitoring system holds significant practical value. Firstly, it can monitor key ocean ecological parameters such as water temperature, salinity, and dissolved oxygen in real time, providing reliable data support for coastal ecological protection, fishery resource management, and marine ranching. These parameters are crucial for assessing water quality and understanding the ecological status of water bodies. The buoy system's long-term operation capability ensures data continuity and reliability.

  Secondly, the platform can assist relevant authorities in early warning of environmental degradation, enabling prompt action. For instance, in some cases, excessive growth of harmful algae can cause significant changes in dissolved oxygen levels in water, potentially leading to eutrophication or massive fish die-offs. By monitoring dissolved oxygen data collected by the buoy platform in real time, government or management departments can detect anomalies early and take swift measures to control algae growth or adjust the ecological balance of the water, effectively preventing the escalation of ecological disasters [4].

  In conclusion, the LoRa-based buoy monitoring platform provides a low-cost, low-power, and highly efficient solution for marine environment monitoring, addressing the limitations of traditional monitoring methods in terms of coverage, real-time capabilities, and data density. This innovation not only offers new theoretical insights into the integration of IoT and environmental monitoring but also provides practical support for marine resource management, ecological protection, and disaster prevention. With the continuous advancement of sensor and communication technologies, the LoRa buoy monitoring platform is expected to play a more significant role in future marine environment monitoring, contributing to the sustainable development of the global marine environment.

1.2 Research Significance

This study constructs a water surface buoy monitoring platform centered on the LoRa communication module, expanding and innovating the theoretical framework of marine environmental monitoring systems. It aims to provide a low-power, long-range real-time data acquisition and transmission solution. Traditional marine environmental monitoring technologies often rely on high-power communication modules or satellite communications, which, while capable of long-distance transmission, are costly and difficult to maintain. This study proposes a solution based on the integration of IoT (Internet of Things) and wireless communication modules, offering a low-power, long-range data transmission method particularly suitable for real-time offshore monitoring. This provides new technological tools for coastal environmental protection, resource management, and disaster early warning.

- **Adaptability of LoRa Communication Modules in Marine Environmental Monitoring:** The LoRa module is characterized by its long-range and low-power features, with communication distances reaching several kilometers and stable transmission efficiency even in complex marine environments. Applying the LoRa module in marine monitoring can effectively extend the operational time of monitoring platforms, reducing energy consumption and maintenance frequency. Through a series of experiments, this study analyzes the performance of the LoRa module under various environmental conditions, focusing on factors such as signal attenuation in seawater and data transmission stability under different weather conditions. The results confirm that the LoRa module achieves relatively efficient transmission performance in offshore environments. By optimizing the architecture of the sensor network, this study proposes a low-power, high-coverage theoretical model, which can serve as a reference for other marine environmental monitoring platforms, providing a theoretical basis for constructing and optimizing IoT-based marine monitoring systems [5].
- **Long-Distance Transmission and Data Integrity of the LoRa-Based Monitoring Platform:** The proposed LoRa-based monitoring platform supports long-distance data transmission and ensures high data integrity. Experiments demonstrate that the LoRa module exhibits strong anti-interference capabilities, maintaining stable data transmission even in interference-prone offshore environments. This study shows that by setting appropriate frequency bands and enhancing data transmission redundancy, the LoRa module effectively addresses signal interference caused by tides, waves, and other marine factors. Experimental results indicate that LoRa communication performs well within a 10-kilometer range, making it suitable for environmental monitoring in coastal and offshore waters. This transmission solution outperforms other short-range wireless communication modules in terms of data integrity, providing foundational theoretical support for future sensor network designs in similar fields and insights for building more robust sensor network systems [6].
- **Application Value of the LoRa-Based Buoy Monitoring Platform:** Beyond theoretical innovation, the LoRa-based buoy monitoring platform designed in this study demonstrates significant practical value. First, the platform can monitor key environmental parameters such as water temperature, salinity, and dissolved oxygen in real time, providing accurate data support for coastal ecological protection and fishery resource management. Fluctuations in water temperature and

salinity can reflect environmental trends, such as rising water temperatures affecting the survival of certain fish species or salinity changes indicating potential seawater pollution. The buoy platform collects these data through sensors in real time, enabling rapid responses to environmental changes, particularly in coastal ecological monitoring, fishery resource conservation, and marine ranch management.

Second, the platform's low cost and efficient data transmission method make large-scale deployment feasible, providing an economical and practical environmental monitoring solution for governmental and research institutions. Compared to traditional monitoring methods, this platform significantly reduces application costs for coastal and offshore environments, enabling efficient environmental monitoring over large areas. Its cost advantage allows it to be widely applied in various environmental projects and offers high scalability, integrating additional environmental sensors and detection modules as needed.

Additionally, the LoRa buoy platform can establish a dynamic database of ecological environments through continuous data accumulation, providing early warnings for issues such as ecological degradation and water pollution. Marine pollution often has a latent nature, with pollutants gradually accumulating in water bodies before reaching a threshold that causes noticeable ecological harm. Relying on long-term monitoring data from this platform, potential pollution sources can be identified early, and timely warnings can be issued, effectively protecting ecological balance [7].

- **Potential Applications in Disaster Prevention and Mitigation:** In disaster prevention and mitigation, this platform can provide data support for marine disaster warnings. For example, abnormal increases in seawater temperature can trigger phenomena such as algal blooms, adversely affecting fisheries and aquatic ecosystems. The buoy monitoring platform can also, through long-term data accumulation, establish predictive models for extreme weather events, enabling rapid responses to sudden marine environmental changes (e.g., typhoons, storm surges). By transmitting and analyzing real-time data, the platform can relay changes in water quality and hydrological conditions to onshore systems, effectively reducing the economic losses caused by marine environmental disasters [8].
- **Advantages of Long-Term Deployment with the LoRa Monitoring Platform:** The low-power characteristics of the LoRa module make it highly suitable for long-term deployment in remote marine environments, addressing challenges associated with power supply. Traditional marine monitoring buoys often require periodic battery replacement or solar power systems due to power consumption issues. The low-power design of the LoRa platform significantly enhances buoy endurance, and in some configurations, enables self-powering, allowing the buoy to operate unattended for extended periods at sea. This feature is advantageous for long-term environmental monitoring in remote marine areas, improving the efficiency of data collection and spatial coverage compared to traditional methods.

  Furthermore, the theoretical and technological outcomes of this study provide valuable references for related management and research personnel. With broad application prospects, the platform holds significant practical value. By further optimizing sensor networks and data transmission protocols, the platform can be extended to more complex monitoring environments, such as deep-sea ecosystems and large lake water bodies. The results of this study lay the groundwork for constructing intelligent, low-power, and wide-coverage marine monitoring systems, offering more efficient solutions for marine scientific research and ecological protection.

In summary, this study not only innovates the design of a LoRa-based buoy monitoring platform from a theoretical perspective but also validates its application value in marine environmental monitoring through practice. The platform's long-distance transmission capabilities, low-power characteristics, and high data integrity provide valuable references for future environmental monitoring systems. Based on this system, advanced sensors and intelligent data processing functionalities can be integrated to build a more diversified marine environment monitoring framework, offering robust technical support for ecological protection and sustainable development.

1.3 Structure of the Thesis

The content of this article is organized as follows:

Chapter 1 - Introduction: This chapter primarily introduces the research background and significance, including the limitations of traditional marine monitoring methods and the advantages of applying LoRa wireless technology. Additionally, a brief overview of the chapters in the dissertation is provided.

Chapter 2 - Literature Review: This chapter investigates the research progress of several countries on buoy monitoring platforms, outlines their respective technical characteristics, and provides a comparative analysis, concluding with relevant recommendations.

Chapter 3 - Research Methodology: Based on the requirements, this chapter primarily designs the overall scheme of the buoy monitoring platform, analyzes the selection of key technologies, and finally formulates the overall technical approach based on the optimal selection plan.

Chapter 4 - Design of the Monitoring Node: This chapter provides a comprehensive explanation of the hardware structure and expected monitoring functions of the buoy monitoring platform by introducing its mechanical structure, hardware circuits, and software components.

Chapter 5 - Design of the LoRa Concentrator and Cloud Platform: This chapter primarily introduces and designs the hardware and software components of the LoRa concentrator.

Chapter 6 - Conclusion and Future Work: This chapter provides a comprehensive summary of the research presented in this thesis, highlighting the main achievements in system design and implementation. It also identifies existing limitations and outlines directions for future improvement and further research.

2 Literature Review

2.1 Research status

A floating monitoring buoy platform is a critical environmental monitoring device widely used in lakes, rivers, and coastal waters. It continuously collects water quality, hydrological, and meteorological data, providing essential support for water environment protection, ecological management, and disaster early warning. In recent years, with advances in sensor, communication, and data processing technologies, floating monitoring buoy platforms have developed rapidly both domestically and internationally.

Internationally, many countries have conducted extensive research on floating monitoring buoy platforms, achieving significant progress in areas such as multi-sensor integration, long-range data transmission, and low-power design. A comparison of different types of buoy systems is shown in Table 2.1.

Table 2.1: Different Types of Buoy Systems

Buoy System	Communication	Monitored Parameters	Power Supply	Remarks
This Study	LoRa + 4G	Temperature, Humidity, Pressure, Wind Speed, Wind Direction, Wave Height, GPS Position	Solar + Lithium Battery	Low power, long-range, modular design
MUnBuS System	Acoustic + Telemetry	Underwater Imaging, Water Quality	Battery-powered	Suitable for deepwater, supports underwater imaging
NOAA System	Satellite Communication	Marine Meteorological Parameters	Solar Power	High integration, global real-time transmission
Tsinghua LoRa Buoy	LoRa	Water Quality	Solar Power	10km range, suitable for lakes and inland rivers
European Multiparameter Buoy	Satellite Communication	Water Quality, GPS Position	Solar Power	Multiparameter acquisition, remote control

Countries like the United States and several European nations have developed highly integrated and adaptable buoy monitoring systems by leveraging advanced sensor and communication technologies. For instance, the National Oceanic and Atmospheric Administration (NOAA) in the U.S. uses a buoy network to monitor ocean parameters in real time, providing abundant data for global climate change research. NOAA's buoy system features low-power designs and integrates satellite communication systems to achieve real-time data collection and transmission on a global scale[9].

In Europe, water quality monitoring buoy platforms often combine GPS positioning technology with multi-parameter sensors, enabling buoy positioning and synchronous monitoring of multiple parameters.

These platforms excel in long-term monitoring and remote control capabilities.

Japan focuses on wave resistance and high-reliability designs for its buoy platforms, utilizing solar cell power supplies and efficient data compression algorithms to meet long-term monitoring needs in extreme environments. South Korea has integrated IoT (Internet of Things) technology with 5G communication for buoy network construction, enabling interconnection between buoys and real-time data transmission. This improves platform responsiveness and monitoring coverage. By continuously upgrading sensors and integrating satellite communication and IoT technologies, these advanced buoy platforms have significantly enhanced the scope and accuracy of data collection.

In China, research on floating monitoring buoy platforms started relatively late. However, with the growing emphasis on water environment monitoring, related technologies and equipment have rapidly advanced in recent years.

Several universities and research institutions in China have conducted in-depth studies on water quality parameter monitoring, long-range communication, and low-power design. For example, Tsinghua University, in collaboration with the Chinese Academy of Sciences, has developed a water quality monitoring buoy platform based on LoRa low-power communication, capable of stable data transmission over distances of up to 10 kilometers. This system is suitable for long-term monitoring of water quality in lakes and inland rivers.

Additionally, the Chinese Research Academy of Environmental Sciences has developed a series of intelligent buoy platforms integrated with multi-parameter water quality sensors to monitor key indicators such as dissolved oxygen, pH levels, and conductivity.

However, domestic buoy platforms still have room for improvement in terms of integration and standardization. There remains a gap between China's buoy platforms and internationally advanced systems, particularly in multi-parameter monitoring and data real-time capabilities. While domestic platforms often adopt low-cost, easy-to-maintain designs to suit complex water environments, further optimization is needed in wave resistance and the stability of offshore data transmission.

Both domestically and internationally, significant progress has been made in the research of floating monitoring buoy platforms. Foreign buoy platforms have accumulated extensive experience in multi-parameter integration, global monitoring, and remote communication. In contrast, domestic research focuses on low-cost designs and adaptability to inland water environments.

Future research can benefit from enhanced international collaboration to explore further advancements in platform integration, interference resistance, and intelligence. With the continued development of 5G, edge computing, and IoT technologies, buoy platforms are expected to achieve significant improvements in data processing capabilities and transmission stability. These advancements will provide more precise real-time data support for water environment protection[10].

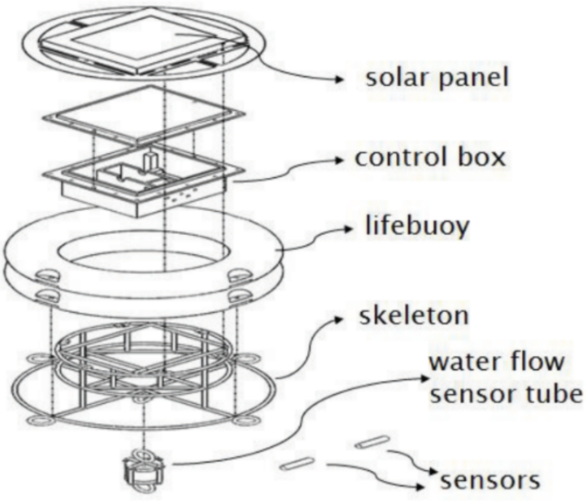


Figure 2.1: Structure of the buoy platform

Figure 2.2: Physical representation of the buoy platform

2.2 Key technology analysis

Buoy-based monitoring systems have emerged as a crucial tool for water environment monitoring, achieving significant technological advancements globally in recent years. This section analyzes the key progress and challenges in areas such as communication, energy management, data acquisition and processing, structural design, and scalability, based on multiple research papers.

1. Communication Technologies

Communication technologies are central to enabling real-time data transmission in buoy systems. LoRa and GSM are widely used in nearshore regions due to their low power consumption and moderate coverage[3][7]. However, GSM is limited by its reliance on terrestrial base stations, and LoRa is prone to interference in dynamic and complex environments[6][5]. For offshore monitoring, satellite communication technologies such as IRIDIUM and BeiDou offer broader coverage and higher reliability, but their high cost and energy consumption limit large-scale deployment[1].

2. Energy Management

Energy optimization is a critical focus in buoy system design. Most systems combine solar panels with lithium batteries to achieve long-term autonomous operation[3][1]. However, energy sustainability remains a challenge under prolonged low-light conditions[4]. Some studies have implemented dynamic power management strategies, such as reducing sampling frequency, to extend operational time[5].

3. Data Acquisition and Processing

Advanced buoy systems feature multi-parameter sensors and efficient data processing algorithms. For example, integrating sensors (e.g., temperature, pH, and oxidation-reduction potential) with fast Fourier transform (FFT) algorithms enables high-precision water quality monitoring[6]. Moreover, modular designs enhance system flexibility, allowing for the addition of sensors or replacement of communication modules based on requirements[8]. Nevertheless, challenges remain in sensor calibration and data processing in complex environments[1].

4. Structural Design and Applicability

Structural designs are increasingly modular and lightweight to adapt to different deployment scenarios. For instance, the MUnBuS system uses dual modules for surface and underwater monitoring, enabling comprehensive monitoring in oceans, lakes, and rivers[5]. Additionally, the use of corrosion-resistant materials and cost-effective designs improves device durability and economic feasibility[8]. However, the stability and reliability of some buoy systems under extreme conditions still require further validation[1].

5. Data Security and Scalability

Many buoy systems lack robust data security measures to prevent potential data breaches or tampering during remote monitoring[3][6]. However, modular designs offer strong support for scalability, such as incorporating efficient data compression algorithms and distributed sensor networks for large-scale monitoring[1].

6. Conclusions

Current buoy systems have progressively achieved modular designs, low power consumption, and efficient communication. However, future research should focus on the following directions:

- **Communication Technologies:** Developing more efficient and long-range communication solutions, such as NB-IoT or hybrid communication models.
- **Energy Management:** Enhancing energy utilization efficiency and exploring new power management strategies.
- **Applicability:** Conducting long-term tests in extreme environments to assess system robustness and adaptability.

3 Overall Scheme Design

3.1 Functional Requirements

This paper integrates embedded technology, sensor acquisition technology, wireless communication technology, and web technology to design a buoy system characterized by multi-element acquisition, long-distance transmission using LoRa, and low cost.

1. Multi-element acquisition: The buoy system, based on wireless transmission, is equipped with multi-element sensors to monitor various climatic factors on the ocean surface, enabling staff to comprehensively assess marine conditions.

2. LoRa wireless communication: Compared with traditional cellular networks or satellite communications, LoRa wireless communication has the advantages of low cost, low power consumption, and long-distance transmission. This design uses LoRa technology for data transmission without the need for base station support, reducing system deployment and maintenance costs[11].

3. Low cost: Compared to maritime satellite communication systems with high equipment costs and communication maintenance expenses, this design uses a low-cost long-distance wireless communication method for data transmission. This approach significantly reduces the development cost of the buoy system and its subsequent communication maintenance expenses.

3.2 Overall Scheme Design

According to the target requirements, the overall structural diagram of the buoy system was designed, as shown in Figure3.1. The system consists mainly of two main components: the monitoring nodes and the receiving platform. The receiving platform is further divided into two parts: the LoRa concentrator and the cloud monitoring platform. Each of these components is introduced in detail below.

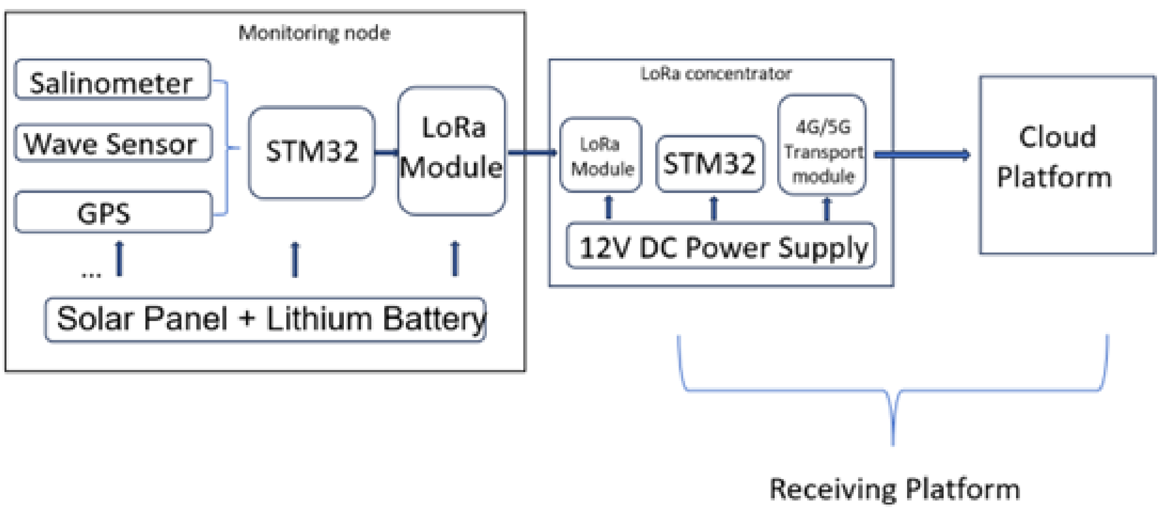


Figure 3.1: Overall structural diagram of buoy

(1) Monitoring nodes

The monitoring node is located on the sea surface and consists primarily of three parts: a buoy platform, a data acquisition and transmission system, and a power supply system. The platform carries the acquisition and transmission system, which collects and processes data such as temperature, humidity, atmospheric pressure, wave height, salinity, and geographic coordinates (latitude and longitude). The collected multi-element data are transmitted to the ground-based LoRa concentrator via the LoRa wireless communication module. At the same time, the power supply system ensures the normal operation of the entire monitoring node[12].

(2) LoRa concentrator

The LoRa concentrator is located within the ground monitoring station. It consists primarily of a LoRa communication module, a microcontroller unit (MCU), a 4G/5G communication module and a power supply system. The concentrator performs the following functions: (i) Relay function: The LoRa concentrator provides a relay function for communication between the monitoring platform and LoRa nodes. (ii) Data Processing and Transmission: Receiving and processing data from the LoRa buoy monitoring nodes, the system then transmits the data to the cloud monitoring platform via the internal 4G/5G network. (iii) Cloud Connection: The LoRa concentrator establishes a stable connection with the cloud monitoring platform, ensuring timely data transmission and reception of commands.

(3) Cloud monitoring platform

The cloud monitoring platform refers to a data monitoring system that can be accessed and logged onto any PC connected to the Internet. It can operate on a Linux operating system. The terminal primarily includes four main interfaces: the login interface, real-time data display, historical data query, and device control. Among these, the real-time data display and historical data query interfaces are designed to provide functionalities for real-time display and historical data query such as temperature, humidity, atmospheric pressure, wave height, and geographic location coordinates (latitude and longitude)[13].

3.2.1 Key Technology Selection

- **Selection of wireless communication technology**

  Wireless communication can be divided into long-range and short-range communication. The monitoring platform of this buoy system adopts a long-range wireless communication method to transmit monitoring data. Currently, there are various long-range wireless communication technologies available on the market, as shown in Table 3.1.

  This design focuses on low power consumption and long-distance data transmission, without placing high demands on transmission speed. Therefore, considering communication range, power consumption, data rate, coverage, and application scenarios, LoRa wireless communication technology meets the technical requirements of this study due to its low cost, low power consumption, long-distance transmission, and strong anti-interference capabilities. As a result, LoRa wireless technology is chosen as the communication module between the monitoring nodes and the LoRa concentrator.

- **Selection of processor models**

Table 3.1: Comparison of Common Communication Technologies

Technology	Communication Range	Power Consumption	Data Rate	Coverage
LoRa	>10 km	Low	Low (0.3–50 kbps)	No base station required, user-built networks
GPRS	1–10 km	High	High (56–114 Kbps)	Depends on operator network
Wi-Fi	1–100 m	Medium to high	High (~100s of Mbps)	Indoor, short-range
Zigbee	1–100 m	Low	Low (20-250 Kbps)	Smart home, sensor networks, industrial automation
Bluetooth	1–100 m	Medium to low	High (~several Mbps)	Indoor, short-range

Based on a comparative analysis of STM32F103ZET6, ESP32, ATmega328P, MSP430FR6989, and PIC16F877A, STM32F103ZET6 was chosen as the processor for the buoy monitoring node. This decision was made because of the balance between performance, power efficiency, and peripheral resources. STM32F103ZET6, with its ARM Cortex-M3 core operating at 72 MHz and 512KB of Flash memory, provides sufficient computational power and storage capacity for handling multisensor data acquisition, processing, and real-time communication. Compared to ESP32, which offers higher performance but consumes more power, STM32F103ZET6 is better suited for power-sensitive marine applications. Although ATmega328P and PIC16F877A are cost-effective and low-power, their limited processing capabilities and peripheral resources make them unsuitable for complex tasks required in the buoy system. MSP430FR6989 excels in ultra-low power consumption but lacks the processing power and memory capacity needed for multiparameter data processing and wireless communication. Therefore, STM32F103ZET6 strikes the optimal balance, meeting the functional and performance requirements of the buoy monitoring node efficiently. There are various commonly used processors available on the market, as shown in Table 3.2.

Table 3.2: Several Commonly Used Processors

MCU Model	Core Architecture	Main Frequency	Flash/RAM	Power Consumption
STM32F103ZET6	ARM Cortex-M3	72 MHz	512 KB/64 KB	Low (~5 mW)
ESP32	Xtensa Dual-Core	160–240 MHz	4096 KB/520 KB	Medium (~50 mW)
ATmega328P	AVR 8-bit	20 MHz	32 KB/2 KB	Low (~2 mW)
MSP430FR6989	TI MSP430	16 MHz	128 KB/2 KB	Ultra-low (< 1 mW)
PIC16F877A	PIC 8-bit	20 MHz	14 KB/368 B	Low (~3 mW)

3.2.2 Overall Technical Approach

Based on the functional requirements of the buoy, the overall scheme design, and the selection of key technologies, the research methods and approaches are illustrated as shown in Figure 3.2.

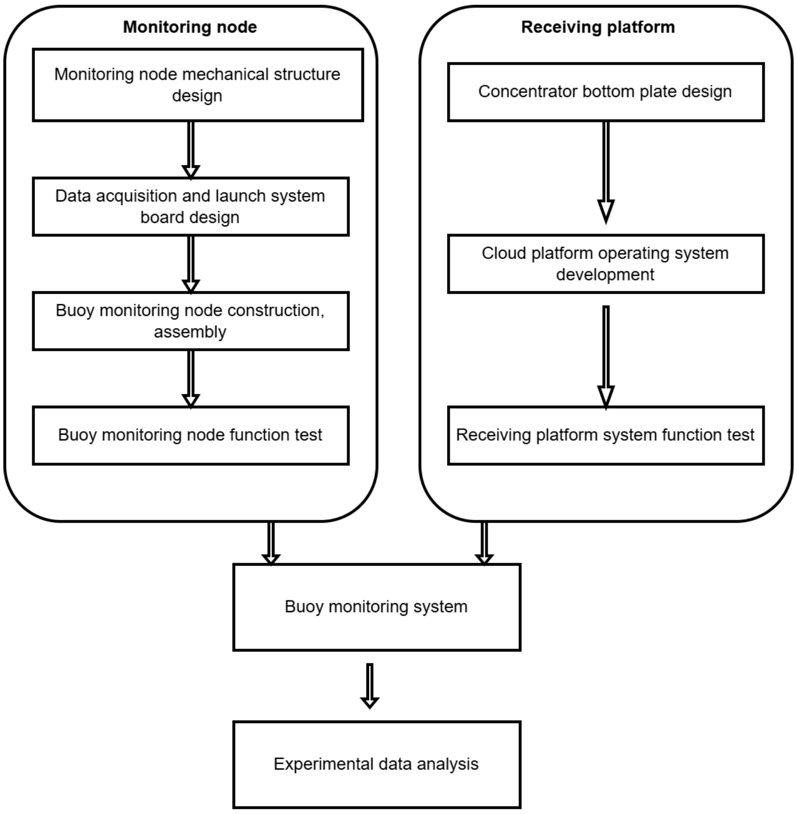


Figure 3.2: Overall technical approach

- **Design of the monitoring node system**

  First, the mechanical structure of the monitoring platform is designed using SolidWorks 3D design software, followed by processing and welding to create the carrier. Next, the physical circuit board of the acquisition and transmission system is designed using JLCPCB circuit design software, and the multi-element data acquisition, data processing, and data transmission functions of the monitoring platform are programmed using Keil software.Subsequently, the prototype of the entire monitoring platform is constructed by integrating temperature and humidity sensors, atmospheric pressure and wave sensors, salinometers, GPS modules, the LoRa wireless communication module, and the core circuit board of the acquisition and transmission system onto the carrier, along with a solar power supply system.Finally, basic functionality tests were conducted on the system to verify its feasibility.

- **Design of the Receiving Platform**

  First, the STM32F103 core board was selected, and the schematic diagram and PCB layout of the LoRa concentrator baseboard were designed using JLCPCB circuit design software. The physical circuit board was then produced, completing the hardware design of the ground receiving platform system. Then, the software development and runtime environment for the embedded device were set up and the upper computer system was designed. Finally, functional testing of the receiving platform system was conducted.

3.3 Summary

This chapter first designs the overall scheme based on the functional requirements of the buoy system, which primarily consists of two parts: the monitoring node located on the sea surface and the receiving platform at the shore station. Subsequently, a selection analysis of the key technologies used in the design and development process is conducted. Finally, an overall technical approach is formulated based on the requirement analysis, overall scheme, and key technology selection analysis, providing guidance for subsequent development stages.

4 Design of the Monitoring Node

In view of the fact that most buoy systems have few collected parameters, high costs and are difficult to recover, this chapter designs a low-cost and easily recoverable ocean buoy monitoring platform for multi-factor monitoring of offshore oceans. The platform is mainly composed of a carrier, a collection and transmission system and a power supply system. The main research content of this chapter is to develop a monitoring platform that meets the needs through the design of the mechanical structure, hardware circuit and software of the monitoring platform.

4.1 Mechanical Structure Design of Monitoring Node

The marine buoy monitoring platform occupies an important position in the entire buoy system. Its shell is the carrier of the entire collection end. The mechanical structure design of the monitoring platform needs to fully consider the installation position and moisture-proof and waterproof protection of different sensors, collection and transmission circuit boards, communication modules and power supply systems to ensure the safety and reliability of the monitoring platform.

The mechanical structure of the monitoring platform is designed using SolidWorks 3D software. The mechanical structure is shown in the figure 4.1. The platform consists of an upper bracket and a lower floating body. The floating body and the bracket are fixed by several screws and nuts.

The upper bracket is used to install the collection and transmission system and the power supply system. The outermost two ends of the top of the bracket are used to install wind speed and wind direction sensors to avoid the influence of the measurement accuracy when collecting wind speed and wind direction elements due to too close distance. Other various sensors, collection and transmission boards, wireless communication modules, batteries and power controllers are installed in a rectangular box of acrylic board with vents on a round tray. This installation method reduces the corrosion of salt and mold on the sea surface on electronic circuits. The waist of the bracket is designed to be inclined to facilitate the solar panel to better collect sunlight. The top of the bracket is designed to be flat, which is convenient for placing antennas for LoRa communication and GPS positioning signals.

The two semicircular holes above the float are used to facilitate the vertical release of the crane when the buoy is released, and the two semicircular holes below are used to connect the anchor chain and fix it in the water. The middle of the float is a sealed hollow body, which is placed on the water surface to generate buoyancy. The disc and central cylinder under the float are used to stabilize the placement when not released. When designing a buoy, it is necessary to determine a buoy overhaul cycle based on factors such as the material, anti-corrosion treatment, and cathodic protection design of the buoy body to constrain the buoy user's buoy usage cycle each time. The buoy designed in this article is made of stainless steel. Since the over-service of the buoy has a great impact on the life of the steel buoy, it is necessary to maintain good buoy maintenance habits in the future to ensure the life of the steel buoy[14][15].

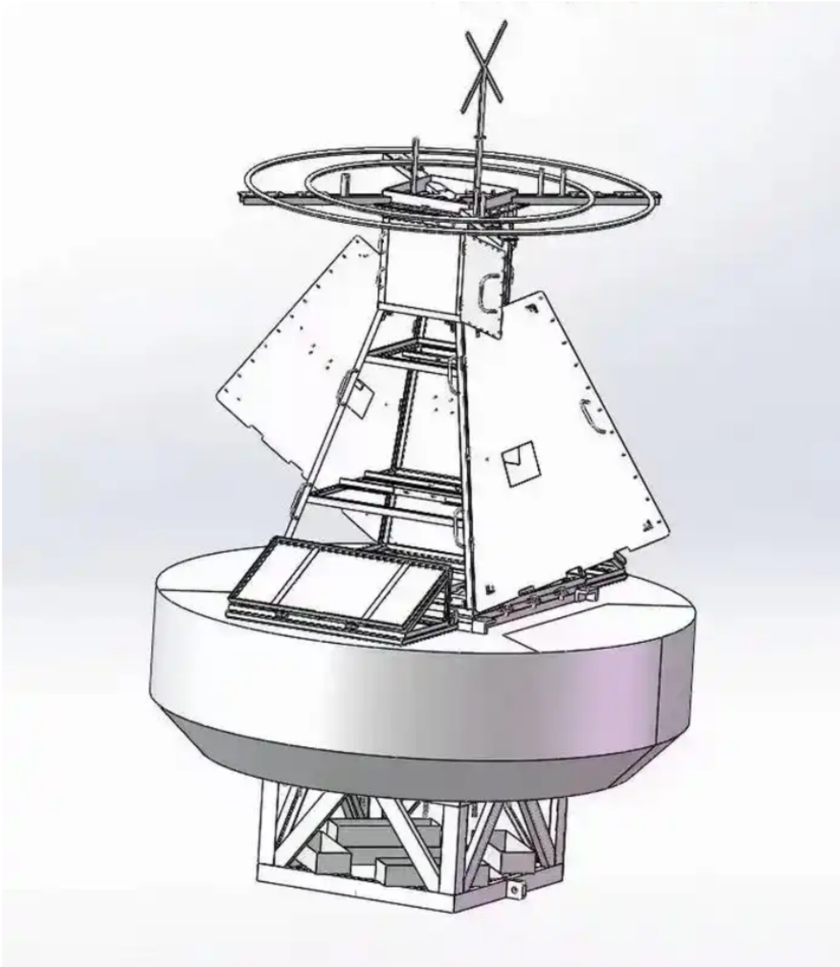


Figure 4.1: Mechanical Structure of Monitoring Node

4.2 Monitoring Node Hardware Design

The hardware structure of the monitoring node is shown in the figure 4.2, which is mainly composed of various sensor modules, acquisition and transmission boards, LoRa communication modules and power supply systems. Among them, the acquisition and transmission board is the core of the hardware circuit, which is connected to various sensor modules for data acquisition and processing, and then the data is sent back to the ground receiving station through the LoRa communication module. The entire collection and transmission process is powered by solar energy and lithium battery power supply systems[16].

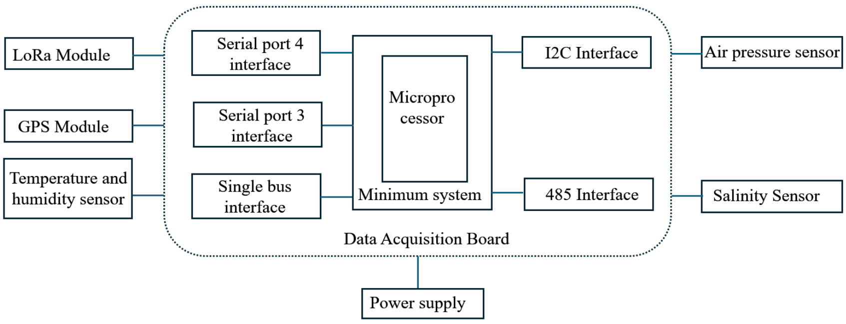


Figure 4.2: Monitoring Node Hardware Structure

The hardware design of the monitoring platform mainly designs the interface circuit of the acquisition and transmission board. This design uses JLCEDA circuit design software to design the circuit diagram shown in figure 4.3. The circuits are interconnected through network labels (Place NetLabel). The entire circuit is intuitive and clear, and has strong readability.

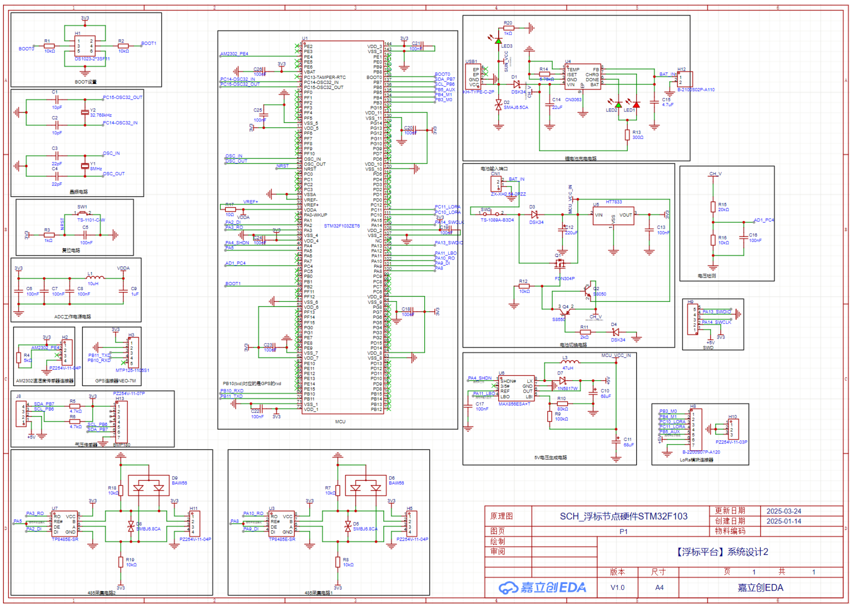


Figure 4.3: Collection and transmission board circuit diagram

4.2.1 Power Management Module

The monitoring node is located on the sea surface, and an independent power supply system is required to power it. This design uses the solar power supply system shown in Figure 4.4 as the power supply solution for the monitoring platform. The power supply system includes three parts: solar energy collection panel, power controller, and battery. Among them, the electric energy collected and converted by the solar energy collection panel is stored in the battery through the power controller, and the battery outputs 12V electricity. Since the 5V current voltage output by the controller cannot be directly used to power the core components of the monitoring node system, it is necessary to use a voltage conversion circuit to obtain the actual working voltage of the processor, sensor module, and wireless communication module. The working voltage of each module of the monitoring node hardware system is shown in Table 4.1.

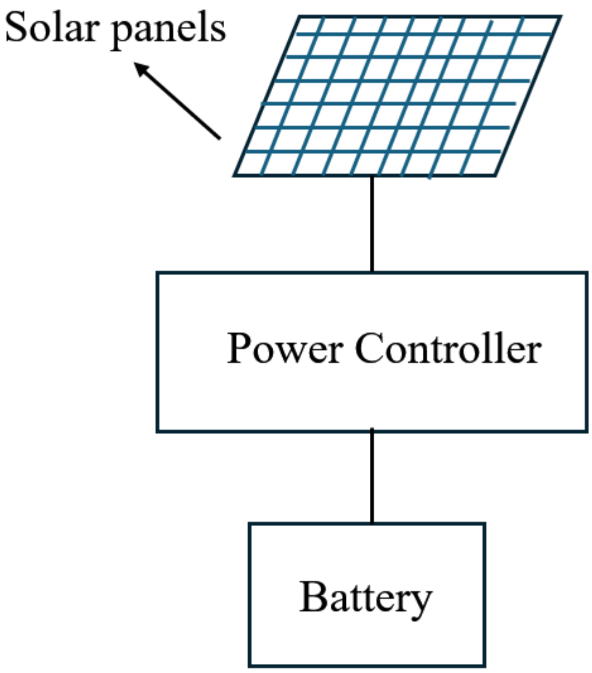


Figure 4.4: Solar power supply system

Table 4.1: Voltage conditions

Module Name	Required voltage
LoRa Communication Module	5V
GPS positioning module	3.3V
AM2302 Temperature and Humidity Sensor	3.3V
BMP180 Barometric Pressure Sensor	3.3V

It can be seen from Table 4.1 that the voltages required for each module of the monitoring node acquisition system are 5V and 3.3V. The power supply circuit designed according to the requirements of each module is shown in Figure 4.4.

The node power supply is powered by lithium batteries, which have high requirements for low power consumption, so a well-designed power management circuit is crucial for the long-term stable operation of the system. The node power management module is divided into four parts: voltage conversion, voltage detection□ photovoltaic power generation and power supply switching circuit.

- **Voltage conversion circuit**

  The monitoring node is powered by a 3.7V rechargeable lithium battery, while the operating voltage of the node's MCU, sensors and other devices is 3.3V, and the operating voltage of the LoRa communication module is 5V. The high-precision, low-power, and small-volume HT7833 chip and MAX856ESA chip are used to achieve 3.3V and 5V power supply respectively. The voltage conversion circuit is shown in figure 3.12.

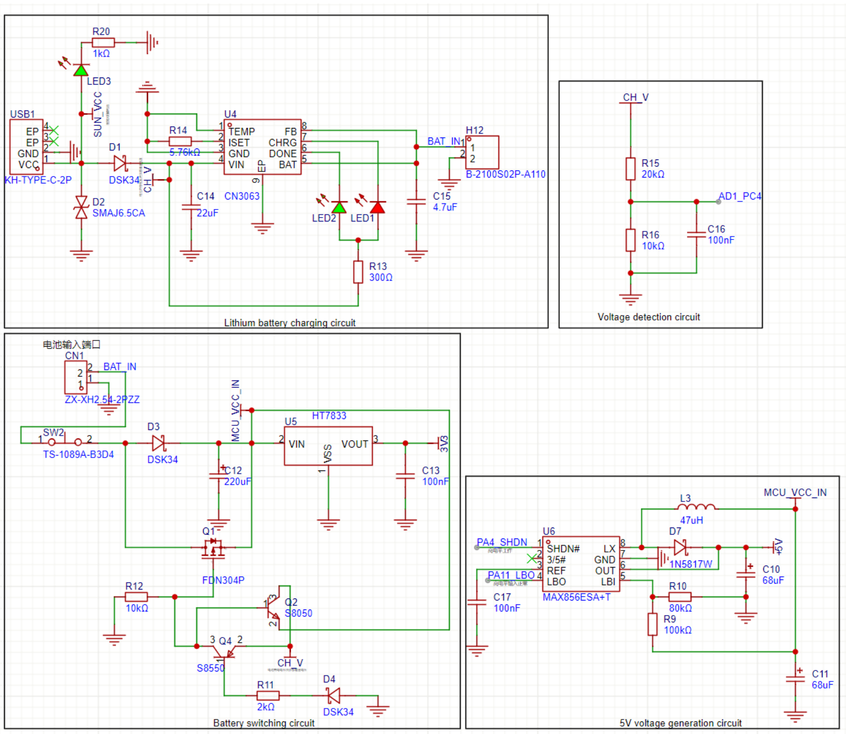


Figure 4.5: Power management module

- **Voltage detection circuit**

  The monitoring node is powered by lithium batteries. In order to monitor the charging status and battery power of the photovoltaic power generation circuit, a voltage detection circuit needs to be designed. This circuit uses the 12-bit ADC inside the microcontroller. The voltage detection circuit is shown in figure 4.5.

- **Photovoltaic power generation circuit**

  Photovoltaic power generation is a widely used clean power generation technology. Combining it with a sensor network can effectively improve the reliability of sensor networking. The photovoltaic power generation circuit uses the CN3063 chip. The CN3063 charging circuit is shown in Figure 4.5.

  In this circuit, FB and BAT of CN3063 are connected in parallel to charge a 3.7V lithium battery. When the voltage on the FB pin is lower than 3V, the charging circuit is in the pre-charging state; when the voltage on the FB pin rises above 3V, it enters the constant current mode and charges at 265 mA. In the constant current mode, the charging current is set by the resistor at ISET, see formula 4.1.

$$ICH = 1800V/R_{IEST} \tag{4.1}$$

ICH is the charging current in amperes; R_{ISET} is the resistance between the ISET pin and GND in ohms. In this circuit, RISET is 6.8kΩ. When the battery is close to 4.2V, the charging current decreases, and CN3063 enters constant voltage mode. When the current drops to 50 mA, charging is complete and CN3063 enters sleep mode.

- **Power supply switching circuit**

  The power supply switching circuit is responsible for completing the switching of photovoltaic power generation and lithium battery power supply to the node circuit. When the photovoltaic panel voltage is greater than the lithium battery voltage, the photovoltaic panel supplies power to the node. When the photovoltaic panel voltage is lower than the lithium battery voltage, the lithium battery directly supplies power to the node. This part of the circuit is shown in Figure 4.5.

  In this circuit, when the lithium battery voltage is greater than the photovoltaic panel voltage, Q1 is turned on and the lithium battery supplies power to the node; when the lithium battery voltage is lower than the photovoltaic panel voltage, Q2 and Q4 are turned on, Q1 is not turned on, and the voltage at MCU_VCC_IN is the photovoltaic panel output voltage, while the front-end voltage of MCU_VCC_IN is the lithium battery voltage. Since the lithium battery voltage is lower than the photovoltaic panel voltage, the lithium battery cannot supply power to the node.

4.2.2 LoRa Management Module

In the proposed buoy system, the monitoring node periodically transmits collected data to the LoRa concentrator using a LoRa communication module. The E22-400T22D module, which is based on the SX1262 chip, is adopted to implement reliable data transmission.

The E22-400T22D is a new-generation LoRa wireless module based on the SX1262 RF chip developed by Semtech. It is a UART wireless serial communication module that supports multiple transmission modes and operates in the 410.125–493.125 MHz frequency range (default: 433.125 MHz). Utilizing LoRa spread spectrum technology, it features TTL-level output and is compatible with both 3.3V and 5V I/O voltages.The recommended connection diagram between the module and the MCU is shown in Figure 4.6, while the interface circuit with the STM32F103ZET6 is illustrated in Figure 4.7.

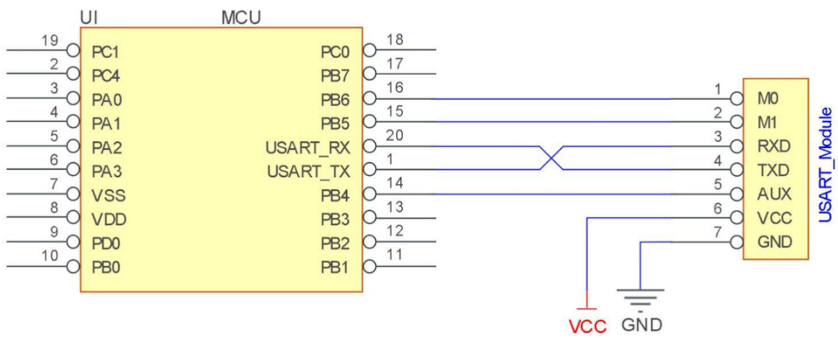


Figure 4.6: LoRa module and MCU connection diagram

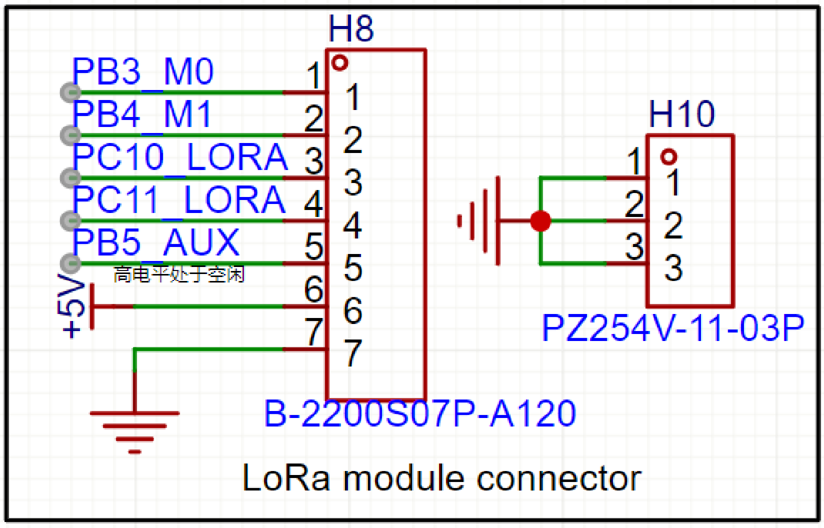
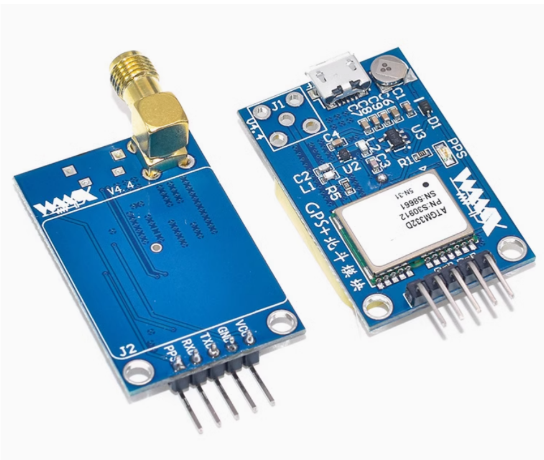


Figure 4.7: LoRa module connector

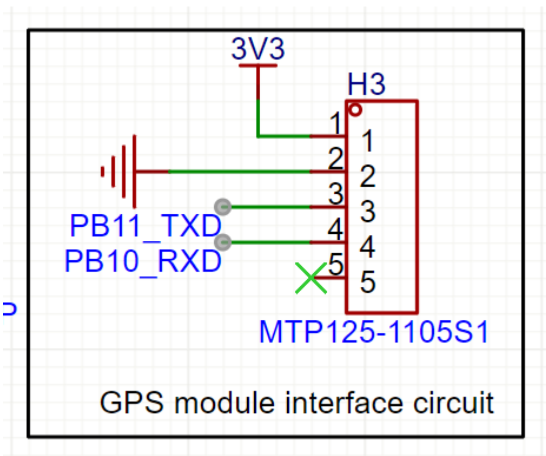
4.2.3 GPS Positioning Module

The GPS positioning module is used to locate the three-dimensional geographic coordinates, namely longitude, latitude and altitude. This design uses the WF-NEO-7M GPS positioning module shown in Figure 4.8(a), which has the characteristics of high performance and low power consumption[17].

The interface circuit of the GPS module is shown in Figure 4.8(b). The GPS module outputs GPS positioning information to the MCU of the monitoring node through serial port 3, and the module's TXD and RXD are connected to PB11 and PB10 of the MCU respectively.



(a) GPS positioning module physical picture



(b) GPS module interface circuit

Figure 4.8: GPS object and interface circuit

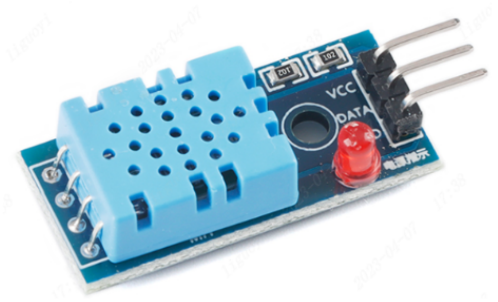
4.2.4 Temperature and Humidity Sensor Module

The temperature and humidity sensor mainly collects air temperature and relative humidity. This design uses the AM2302 digital temperature and humidity sensor shown in Figure 4.9 (a). It is a temperature and humidity composite sensor with calibrated digital signal output. It combines dedicated digital module acquisition technology with temperature and humidity sensing technology to ensure the product's excellent stability and manageability. The performance parameters of AM2302 are shown in Table 4.2.

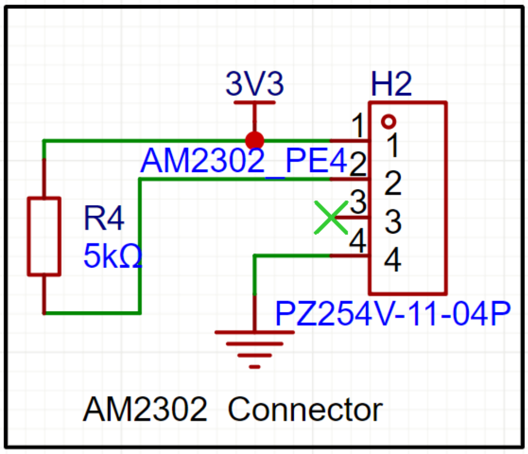
Table 4.2: AM2302 parameters

Model	Temperature range	Humidity range	Temperature measurement accuracy	Humidity measurement accuracy
AM2302	-40-80°C	0-100%RH	±0.5°C	±2%RH

AM2302 uses a single bus communication. When designing the circuit, a 5K pull-up resistor is used as shown in Figure 4.9(b), so that the data line is high enough at a high level to facilitate accurate data acquisition.



(a) Temperature and humidity sensor



(b) AM2302 module interface circuit

Figure 4.9: AM2302 object and interface circuit

4.2.5 Barometric Pressure Sensor Module

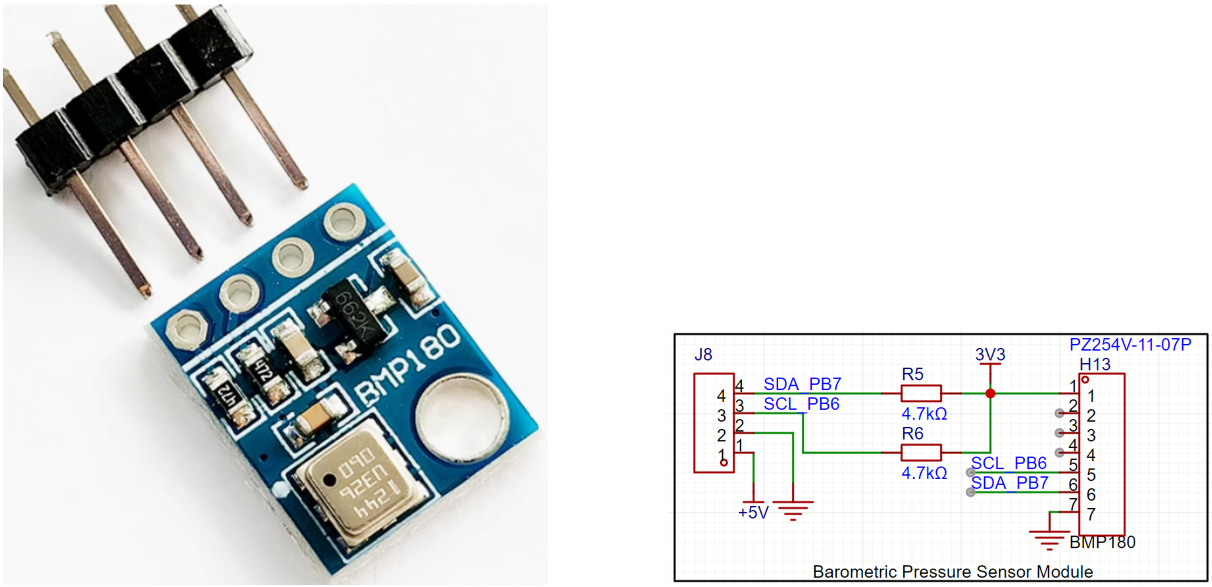
Barometric pressure sensor is mainly used to collect atmospheric pressure values. This design uses a high-precision digital pressure sensor BMP180 as shown in Figure 4.10 (a). It contains four parts: piezoresistive sensor unit, ADC converter unit, control unit and E2PROM. E2PROM stores 11 16-byte calibration coefficients. The pressure and temperature values measured by the sensor can use their internal data to perform compensation operations such as correction offset and temperature dependence, thereby reducing errors caused by environmental changes. The performance parameters of BMP180 are shown in Table 4.3.

The BMP180 barometric pressure sensor communicates with the MCU on the monitoring node board via the I2C bus. The internal measurement unit of the sensor measures the current atmospheric pressure, and the acquired data is converted into a digital signal through an ADC and then corrected. The corrected result is transmitted to the MCU via the I2C data bus. As shown in the pin connection diagram in Figure

Table 4.3: BMP180 parameters

Model	Pressure measuring range	Measurement accuracy	Power consumption	Output signal type	Resolution
BMP180	300-1100hPa	0.03hPa	5uA	I2C	0.03hPa

4.10(b), the sensor's clock line (SCL) and data line (SDA) are connected to the MCU's PB6 and PB7 pins, respectively. In this design, a 4.7kΩ pull-up resistor is used to reduce power consumption.



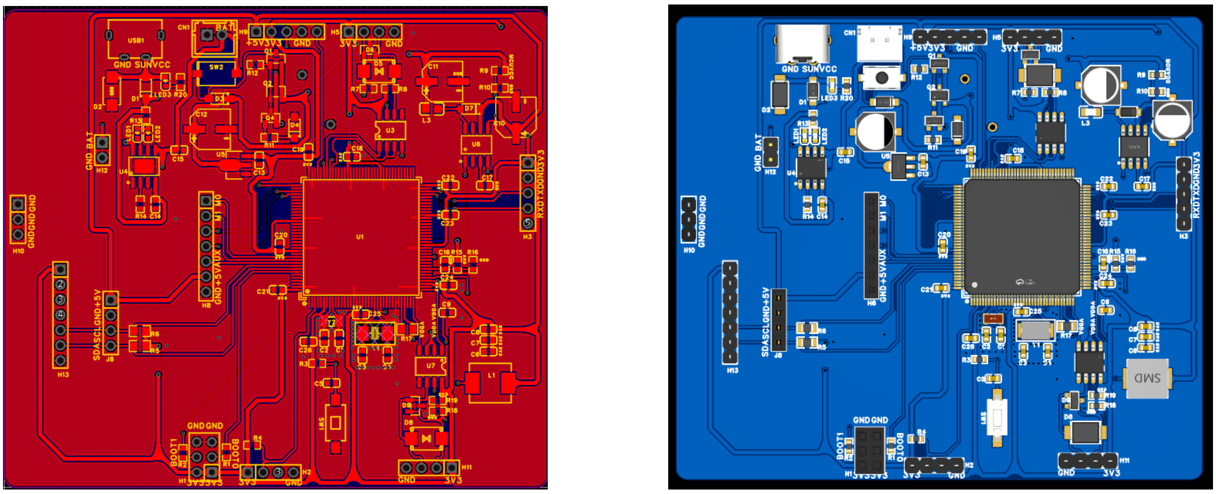
(a) Barometric pressure sensor

(b) Barometric pressure sensor interface circuit

Figure 4.10: BMP180 object and interface circuit

4.2.6 Collection and transmission circuit board

Based on the aforementioned power circuit, various sensor interface circuits, and the LoRa communication module interface circuit, the PCB layout of the data acquisition and transmission board was designed using JLCEDA circuit design software, as shown in Figure 4.11(a). During the PCB layout process, efforts were made to minimize circuit interference, reduce the overall board area as much as possible, and lower costs. The final design of the acquisition and transmission board circuit is shown in Figure 4.11(b).



(a) PCB board (b) photograph of the actual device

Figure 4.11: PCB layout and physical photograph of the monitoring node

4.3 Monitoring Node Software Design

4.3.1 Functional Requirements

The monitoring node is required to fulfill the following functions:

- The data acquisition and transmission board communicates with the LoRa module via UART4, establishing a connection with the LoRa concentrator.
- The temperature and humidity sensor, barometric pressure sensor, and GPS positioning module transmit the collected data to the slave controller via a one-wire interface, an I2C interface, and UART3, respectively.
- After acquiring the raw data, the monitoring node performs quality control. By integrating data processing algorithms into the software, errors caused by hardware limitations in various measurement stages—including those from the sensors themselves—are mitigated, thereby improving overall system performance[18].

4.3.2 Software Process

The monitoring node board is a crucial component of the marine buoy system, functioning as a controllable probe for environmental monitoring instruments. Its primary role is to collect and process meteorological and geographic coordinate data from the sea surface and transmit the results to the LoRa concentrator. The software workflow of the monitoring node is illustrated in Figure 4.12, and its main functions include parameter monitoring, data processing, and data transmission.

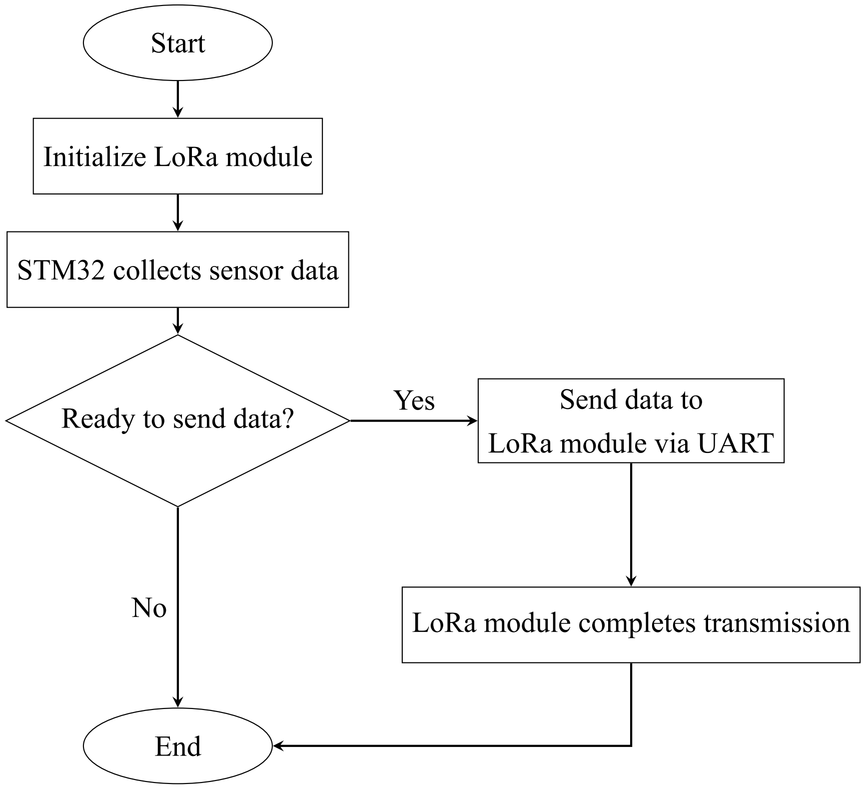


Figure 4.12: Data acquisition and transmission flowchart of the LoRa module

After the hardware system of the monitoring platform is powered on, it first performs system configuration and module initialization, and establishes communication with the remote LoRa concentrator. The system then enters a timed acquisition and transmission state, in which sensor data is automatically collected ten times every five minutes and averaged to ensure stable and reliable data acquisition and automatic transmission.

The acquisition and transmission unit primarily collects five types of environmental parameters, including three meteorological factors—temperature, humidity, and barometric pressure—as well as three geographic location parameters—longitude, latitude, and altitude. The raw data is processed using a built-in arithmetic averaging algorithm for quality control and is then transmitted to the LoRa module via a serial interface for remote delivery.

The system configuration includes system clock initialization, interrupt setup, timer configuration, initialization of various sensor modules, and configuration of communication interfaces. The communication interfaces used include a one-wire interface, UART3, UART4, ADC, and I2C, which are responsible for connecting temperature and humidity sensors, pressure sensors, the GPS module, and the LoRa communication module.

After the system configuration is completed, the acquisition and transmission unit enters the data acquisition process. The system communicates with the LoRa wireless module via UART4 and establishes a point-to-point data transmission link with the LoRa concentrator. Once the data collection and processing are completed, the system sends commands or data packets through the serial port to trigger the LoRa module to transmit the information to the receiver, thereby enabling remote transmission of monitoring data[19][20].

4.3.3 Core Code Functions

- **LoRa communication module program**

  The LoRa wireless communication module in this design is primarily responsible for remote data transmission. As a low-power and long-range communication device, the LoRa module is connected to the MCU of the monitoring node via UART4 and is used to transmit collected data to the LoRa concentrator, thereby enabling point-to-point data communication. The MCU of the monitoring node sends data frames through the serial port to trigger the LoRa module to perform wireless transmission.

  In this design, the LoRa module operates in transparent transmission mode, which does not require additional command configuration. Data written to the serial buffer is automatically transmitted over the air. The relevant data transmission functions are as follows:

  Lora_Init(); // LoRa module initialization (baud rate, frequency, address, etc.)

  Lora_Send(data_buf); // Write data frame to serial port buffer and trigger wireless transmission

  The Lora_Init() function is responsible for initializing the UART parameters and configuring communication settings such as frequency, transmission power, and node address. The Lora_Send() function sends the processed data frame to the serial buffer, and the LoRa module completes the subsequent wireless transmission automatically, without further intervention from the MCU. This improves the efficiency and reliability of data transmission within the system.

- **GPS Positioning Module**

  In this design, the GPS module WF-NEO-7M is primarily used to provide positioning information, including geographic coordinates such as latitude, longitude, and altitude. The module is connected to the MCU of the monitoring node via UART3. The MCU initializes the module and continuously receives real-time positioning data from GPS satellites.

  The WF-NEO-7M module is based on the u-blox 7 chipset and supports standard NMEA protocol output, with a default baud rate of 9600 bps. The MCU receives the continuous NMEA data stream via the serial interface and parses it to extract valid positioning fields, enabling real-time geographic data acquisition.

  The main functions related to GPS communication are as follows:

  GPS_Init(); // Initialize UART3, configure baud rate, and enable receive interrupt

  GPS_Read(); // Read NMEA data frames from the UART buffer GPS_Parse(); // Parse key fields such as latitude, longitude, and altitude

  The GPS_Init() function configures UART3 and sets up interrupt-driven reception. The GPS_Read() function retrieves raw NMEA sentences from the UART buffer, while the GPS_Parse() function extracts essential geographic information for subsequent data fusion and remote transmission by the system.

- **Temperature and Humidity Sensor Module**

The temperature and humidity sensor module in this design adopts the AM2302 digital sensor, which is responsible for collecting ambient temperature and relative humidity data. The sensor is connected to the MCU of the monitoring node via a one-wire interface. The MCU periodically initiates data acquisition requests, receives the digital data stream transmitted by the sensor, and then performs decoding and validation.

The AM2302 sensor uses a single-bus communication protocol and transmits data in a 40-bit frame containing temperature, humidity, and checksum information. Communication is initiated by the MCU pulling the data line low for a specific duration. After receiving the response signal, the MCU reads the transmitted data bit by bit based on timing analysis.

The main functions related to sensor communication are as follows:

AM2302_Init(); // Initialize the GPIO and timing parameters

AM2302_Read(); // Trigger data acquisition and receive 40-bit data frame

AM2302_Parse(); // Extract temperature and humidity values from raw data

The AM2302_Init() function is responsible for configuring the data pin and preparing the GPIO timing environment. The AM2302_Read() function handles the signal-level interaction between the MCU and the sensor to complete one acquisition cycle. The AM2302_Parse() function decodes the received 40-bit data and verifies the checksum to ensure accuracy, providing valid temperature and humidity readings to the system.

- **Barometric Pressure Sensor Module**

The barometric pressure sensor module in this design adopts the BMP180 digital sensor, which is mainly used to measure atmospheric pressure and can also assist in calculating altitude information. The sensor is connected to the MCU of the monitoring node via the I2C interface. The MCU initiates communication to read raw pressure and temperature data, and compensates the output using the built-in calibration coefficients stored in the sensor.

BMP180 supports standard I2C protocol, featuring a fixed address, well-defined data format, and high precision. After initialization, the MCU first reads the calibration parameters, then acquires raw temperature and pressure values during each acquisition cycle. These values are processed through a compensation algorithm to produce accurate barometric pressure measurements.

The main functions related to BMP180 communication are as follows:

BMP180_Init(); // Initialize I2C interface and read calibration data

BMP180_ReadRaw(); // Read raw temperature and pressure values

BMP180_Calculate(); // Calculate compensated pressure value using algorithm

The BMP180_Init() function sets up the I2C communication and retrieves the sensor's internal EEPROM-stored calibration data. The BMP180_ReadRaw() function collects the uncompensated temperature and pressure readings, while the BMP180_Calculate() function applies the official Bosch compensation algorithm to compute the final output value suitable for display or transmission.

4.4 Summary

This chapter presents the design of a monitoring node used for marine environmental data acquisition. The system is composed of three main components: the platform structure (carrier), the data acquisition and transmission unit, and the battery management system. The research focuses on the hardware and software design of the STM32 microcontroller, the interface circuits for various sensors (including temperature and humidity, barometric pressure, and GPS), and the data transmission process using the LoRa communication module. In the software design, sensor data is calibrated, filtered, and processed using scheduled acquisition and averaging-based quality control algorithms, which improves the accuracy and reliability of the collected data, ensuring the effectiveness of remote environmental monitoring.

5 Design of the LoRa Concentrator and Cloud Platform

5.1 LoRa Concentrator Hardware Development

The LoRa concentrator needs to have the ability to form a LoRa network and interact with the monitoring platform. According to the functional requirements, the hardware design of the LoRa concentrator is divided into four parts: power supply circuit, LoRa module circuit, microcontroller circuit and 4G module circuit[21]. The overall structure of the concentrator is shown in Figure 5.1:

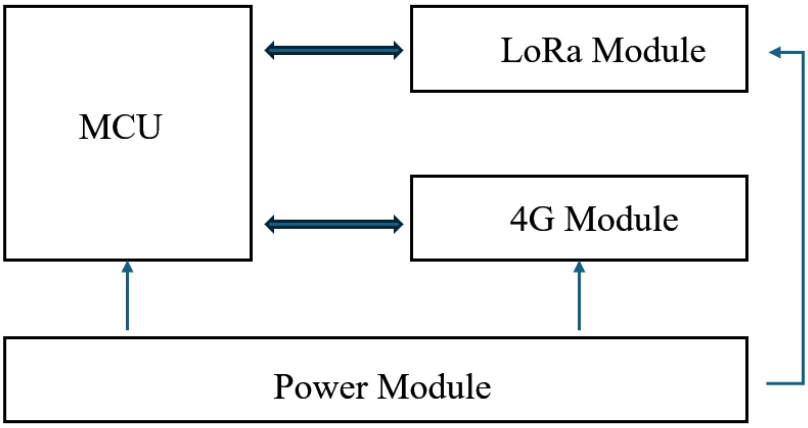


Figure 5.1: LoRa concentrator overall structure

(1) Power Supply Module: Provides a stable and reliable current for system operation. A reliable power supply ensures effective communication between the 4G module and the LoRa module, which facilitates the establishment of a connection between the 4G module and the monitoring platform, thereby reducing system packet loss rate.

(2) LoRa Communication Module: Responsible for modulation and demodulation of the LoRa signal, as well as the transmission and reception of data from the microcontroller and the temperature monitoring node.

(3) Microcontroller Module: Serves as the control core of the concentrator. The microcontroller circuit handles the overall logical control of the concentrator's functions.

(4) 4G Communication: Acts as a bridge for data interaction between the microcontroller and the monitoring platform, enabling the uploading of node data to the platform and receiving commands issued by the platform.

The hardware design of the LoRa concentrator uses JLCEDA circuit design software to design the circuit diagram shown in Figure 5.2. The circuits are interconnected through network labels, and the entire circuit is intuitive and clear with strong readability.

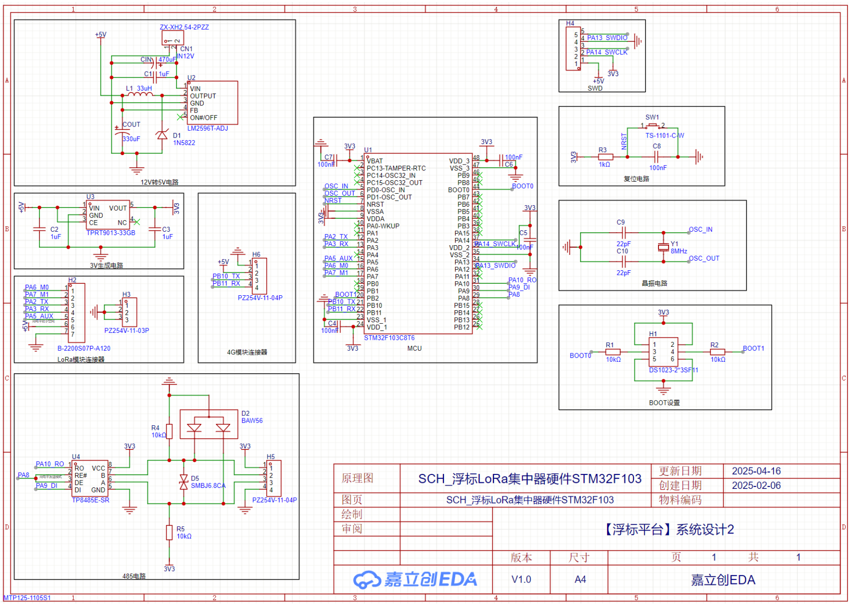


Figure 5.2: LoRa concentrator schematic diagram

5.1.1 Microcontroller Module

The microcontroller of the concentrator is responsible for completing LoRa networking, node data parsing, and 4G communication functions. The STM32F103 series microcontroller is selected as the core controller of the concentrator, which fully meets the functional requirements of the system. Specifically, the STM32F103C8T6 chip is used as the main control unit of the concentrator.

The STM32F103 is based on the ARM Cortex-M3 core and is manufactured using a 90 nm process combined with a dedicated low-leakage technology. Its main parameters are shown in Table 5.1.

Table 5.1: Main control chip parameters

MCU Name	STM32F103C8T6
Typical voltage value	3.3V
SRAM	20K
FLASH	64KB
IIC	2
USART	3
Operating frequency	Maximum frequency： 72MHz
Encapsulation	48-LQFP
Number of input and output pins	37

5.1.2 Power Module

The power supply circuit of the concentrator is required to provide power to the MCU, LoRa module, and 4G module. Since wireless communication modules typically demand relatively high supply current, insufficient current may lead to issues such as network formation failures, difficulty in accessing the network, and increased packet loss rate. Therefore, a stable and reliable power supply is essential for the normal operation of the concentrator.Considering the different operating voltages required by various modules, the system needs to supply 12V, 5V, and 3.3V. The 12V voltage can be provided by a 12V power adapter or a 12V battery. The LM2596T-ADJ chip is used to convert 12V into 5V for peripheral circuits, and the RT9013-33 chip is used to further convert 5V into 3.3V.

The LM2596T-ADJ is a typical adjustable step-down DC/DC regulator chip that supports a wide input voltage range (4V–40V) and provides an output current of up to 3A. It features high efficiency, low ripple, and a simple circuit structure, making it suitable for 12V-to-5V voltage regulation in the concentrator system. The output voltage of the LM2596T-ADJ can be adjusted through external feedback resistors, and its output voltage is calculated using the following formula (5.1):

$$V_{\mathrm{OUT}} = 1.23 \times \left(1 + \frac{R_1}{R_2}\right) \tag{5.1}$$

When the feedback resistor values are set to $R_1 = 3.3\,\mathrm{k}\Omega$ and $R_2 = 1.2\,\mathrm{k}\Omega$, the output voltage is $\mathrm{V}_{OUT} = 4.62V$.

RT9013-33 is a 500 mA wide voltage (2.2V-5.5V) input LDO regulator with excellent performance in fast turn-on, output accuracy, current limiting protection, and high ripple suppression. The voltage conversion circuit principle is shown in Figure 5.3 below.

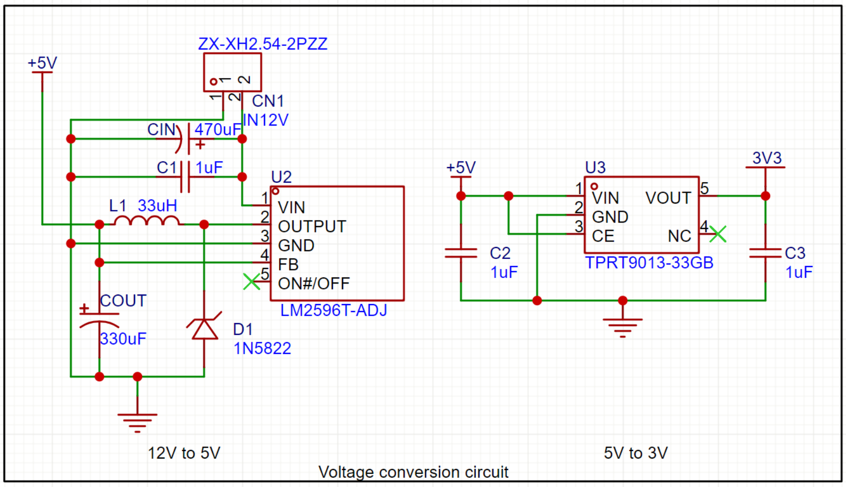


Figure 5.3: Voltage conversion circuit

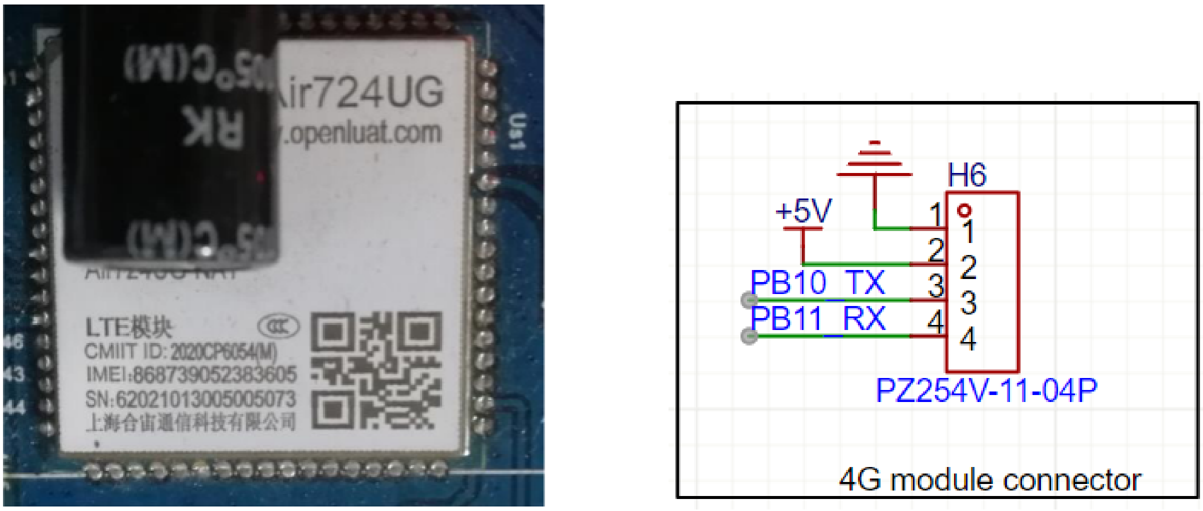
As shown in the figure above, the circuit implements 12V to 5V step-down conversion through the LM2596T-ADJ chip. The output side is equipped with a COUT filter capacitor to reduce output voltage ripple. The inductor L1 and the Schottky diode D1 (1N5822) form a complete buck topology, providing freewheeling and protection functions. On the input side, capacitors CIN (470µF) and C1 (1µF) are used to filter the input voltage and suppress high-frequency interference.

The 5V output is further regulated to 3.3V using the RT9013-33 voltage regulator. Capacitors C2 and C3 (both 1µF) are placed at the input and output terminals of the regulator to filter noise and improve power quality. This ensures that components such as the MCU and sensors receive clean and stable low-voltage power.

5.1.3 4G Communication Module

The 4G communication module is a critical component of the concentrator, which transmits data to the monitoring platform via the AIR724UG module. The AIR724UG is a full-network 4G CAT1 module developed by Ai-Thinker, supporting multiple network protocols including TCP, UDP, LwM2M, and MQTT. The power supply circuit, serial communication circuit, and SIM card circuit constitute the key parts of the 4G module circuitry.

There are two types of IoT SIM cards: embedded (chip-mounted) and removable (plug-in) forms. Compared to removable IoT SIM cards, embedded SIM cards offer advantages such as smaller size, better shock resistance, higher temperature tolerance, and longer lifespan. Therefore, this system adopts an embedded IoT SIM card. The physical view of the 4G module is shown in Figure 5.4(a), and the corresponding partial circuit of the 4G module is shown in Figure 5.4(b).



(a) 4G module physical object

(b) 4G module connector

Figure 5.4: AM2302 object and interface circuit

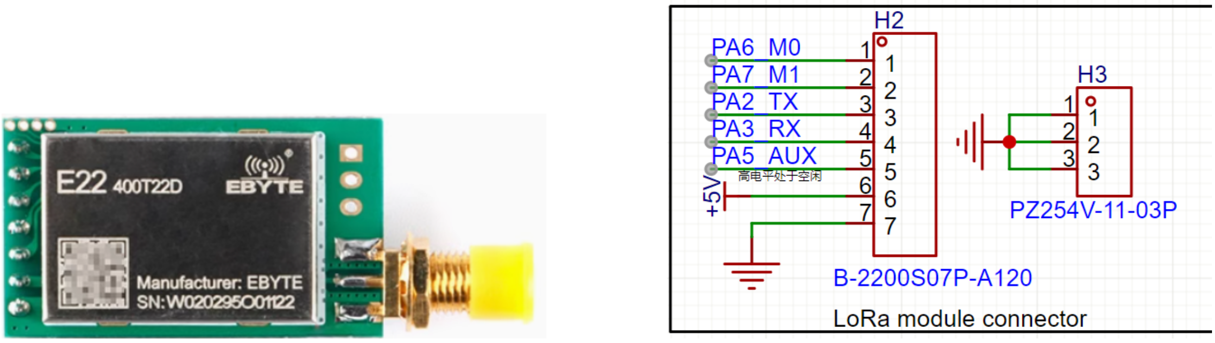
5.1.4 LoRa Communication Module

This system adopts the E22-400T22D LoRa module developed by EBYTE, which internally integrates the SX1268 chip along with its necessary peripherals. Compared to using the SX1268 chip alone, the standardized and integrated design of the module ensures more reliable performance. Furthermore, compared to modules based on the SX1278 chip, the SX1268-based solution offers greater advantages in terms of communication range and low power consumption.

The module supports a wide input voltage range from 3.3V to 5.5V and provides a communication distance of up to 5 km. It also supports transmission encryption, LBT (Listen Before Talk), and fixed-point transmission, enhancing communication security.

The operating mode is configured through the M0 and M1 pins, while data communication with the MCU is achieved through the RXD and TXD pins. The physical view of the module is shown in Figure

5.5(a), and the interface circuit design is illustrated in Figure 5.5(b).



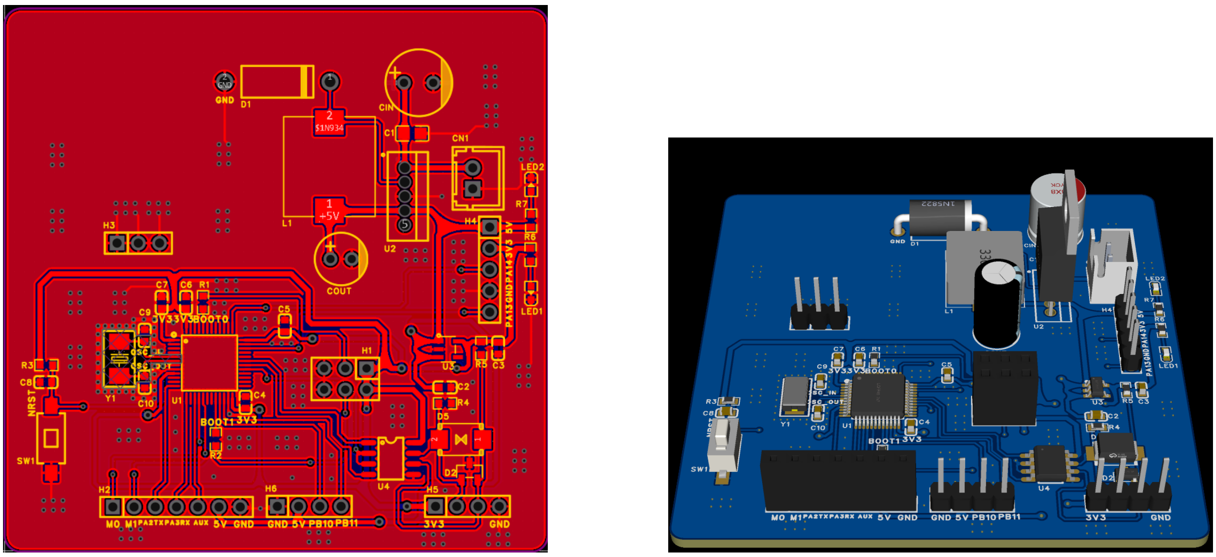
(a) LoRa module physical object

(b) LoRa module connector

Figure 5.5: LoRa module object and interface circuit

5.1.5 LoRa Concentrator PCB and Physical Object

The LoRa concentrator adopts a double-layer board design, with both the top and bottom layers being GND. The LoRa concentrator PCB is shown in Figure 5.6 (a), and the actual image is shown in Figure 5.6 (b).



(a) LoRa concentrator PCB

(b) LoRa concentrator physical picture

Figure 5.6: LoRa module object and interface circuit

5.2 LoRa Concentrator Software Development

The LoRa concentrator has the largest data processing capacity. The transfer, analysis and time slot allocation of all system data are completed in the concentrator. The software design of the concentrator will seriously affect the robustness of the system. The concentrator collects node data through the mixed allocation TDMA protocol to effectively reduce the possibility of sending collisions when nodes upload data. 4G communication uploads the collected data to the monitoring platform through the MQTT network protocol[22][23]. As an application layer protocol built on the TCP transport layer protocol, the MQTT protocol is widely used in low-bandwidth networks and low-computing devices. It has the long connection characteristics of the TCP protocol, a feedback mechanism for data reception and transmission, and high data transmission reliability. The software flow of the LoRa concentrator is shown in Figure 5.7.

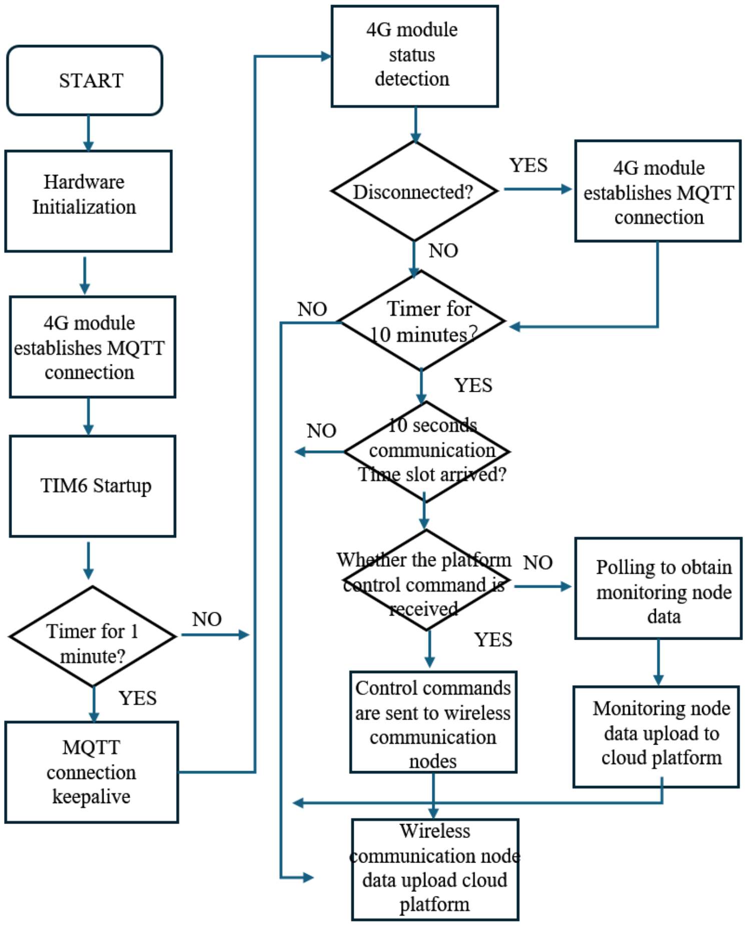


Figure 5.7: Concentrator software flow chart

As can be seen from the figure above, after the concentrator completes hardware initialization, it connects to the monitoring platform via the MQTT protocol. The timer is used to keep the MQTT connection alive once a minute and poll all nodes once every ten minutes. The communication time slot of each node is 10 seconds. After receiving the node data, the data is uploaded to the monitoring platform[15].

5.2.1 4G Communication

The 4G module Air724UG used in this system supports the AT instruction set. The microcontroller of the concentrator can send AT instructions through the serial port to connect the 4G module to the monitoring platform. The MCU uses the UART13 interface to interact with the 4G module, and completes the processing of the module return data and the monitoring platform downlink data through the UART3 receiving interrupt. The software design of the 4G module configuration uses state machine programming.

State machine programming requires a series of event processing functions to be designed according to system requirements to handle events. State machine programming has the advantages of improving CPU efficiency, complete logic, and clear program structure. See Figure 5.8 for detailed status signs.

```
enum
{
    AT_RESET_sta,
    AT_sta,
    ATE0_sta,
    AT_CGSN_sta,
    AT_CCID_sta,
    AT_CEREG_sta,
    AT_CGATT_sta,
    AT_CSQ_sta,
    AT_MCONFIG_sta,
    AT_MIPSTART_sta,
    AT_MCONNECT_sta,
    AT_MSUB_sta,
    AT_MPUB_sta,
} MQTT_CONNECT_STAGE ;
```

Figure 5.8: 4G communication status symbol

The 4G communication task switches between different states to achieve MQTT communication of the 4G module. The detailed process is as follows:

- When the 4G network access program is called for the first time, it first enters the AT_RESET_sta state. The MCU first sends a reset command to the module and then enters the AT_sta state.
- Enter the AT_sta state, complete the module response test, and if the test passes, complete the six tasks related to module initialization, namely ATE0_sta, AT_CGSN_sta, AT_CCID_sta, AT_CEREG_sta, AT_CGATT_sta, and AT_CSQ_sta.
- After the module initialization instruction configuration is completed, it enters the AT_MCONFIG_sta state and starts to set the triplet for MQTT network access. After the setting is completed, it enters the AT_MIPSTART_sta state.
- In the AT_MIPSTART_sta state, the module completes the connection to the server using the TCP protocol, and then establishes a session connection in the AT_MCONNECT_sta state. After the connection is successful, the concentrator can implement topic publishing and subscription of the MQTT protocol by entering AT_MSUB_sta and AT_MPUB_sta, thereby realizing data interaction with the monitoring platform.

The 4G module realizes data interaction between the concentrator and the monitoring platform through the MQTT protocol, uploads monitoring data to the monitoring platform through topic publishing, and receives control commands through topic subscription, and both publishing and subscribing topics use the JSON data format. JSON is a lightweight data exchange format that is easy to read, write and parse, and is suitable for sensor data and control command transmission of IoT systems based on the

MQTT protocol.

The MQTT protocol of this system is used to publish the topics and data formats used by sensor data, as shown in Figure 5.9:

```
TOPIC:
/LoRa/{deviceNum}/property/post

Data format(数据格式):
[{
  "Type": "temperature",
  "Value": "28.8"
}, {
  "Type": "humidity",
  "Value": "38.6"
}]
```

Figure 5.9: Topics and data formats used to publish sensor data

Among them, deviceNum is the device number; Type is the identifier, which is the physical model attribute of the monitoring data. There are 6 types in total, namely Air temperature, humidity, Barometric Pressure, longitude, latitude and altitude; Value is the data, which stores the data of the physical model attribute.

5.2.2 LoRa Networking

The LoRa networking of this system adopts a low-power networking method that combines a mixed allocation TDMA protocol with LBT. This system assigns a unique device ID to all LoRa nodes. After the LoRa node is powered on, the hardware initialization and device ID configuration will be completed. After the configuration is completed, the system enters the stop mode and waits for the concentrator to wake up the command[24]. After receiving the wake-up command, the node MCU will compare the received device number with its own device number. If the authentication is successful, the node collects data and transmits it to the concentrator. After the transmission is completed, the node enters the stop mode again; if the authentication fails, the node enters the stop mode again. The LoRa module of the concentrator turns on the LBT function and performs LBT detection at the beginning of each time slot when the LoRa transmission is performed. If the channel is busy, it will back off. If the back off time exceeds 2 seconds, the module will force the data to be sent[25].

The use of the mixed allocation TDMA protocol can effectively solve the co-channel interference problem in the LoRa network and enhance the communication reliability; the channel status is detected each time data is sent, and the channel is backed off when it is busy, and data is sent when the channel is idle, which is conducive to reducing data collisions; the low-power wake-up function is effective in reducing the power consumption of the LoRa node. The node is in stop mode when the concentrator does not poll the node. When the node is polled, it can complete the data uplink in its own time slot.

This system adopts a networking method that combines a hybrid allocation TDMA protocol with LBT. Among them, the monitoring nodes adopt a fixed allocation method, and poll each monitoring node in turn in each data collection cycle; because the wireless communication node is responsible for receiving greenhouse control commands irregularly and cannot perform fixed periodic LoRa communication, the communication time slot of the wireless communication node adopts a dynamic allocation method. If the concentrator receives a greenhouse control command when polling and collecting monitoring data, the concentrator inserts the communication time slot of the wireless communication node after completing the data collection of the current time slot. The LoRa networking process is shown in Figure 5.10.

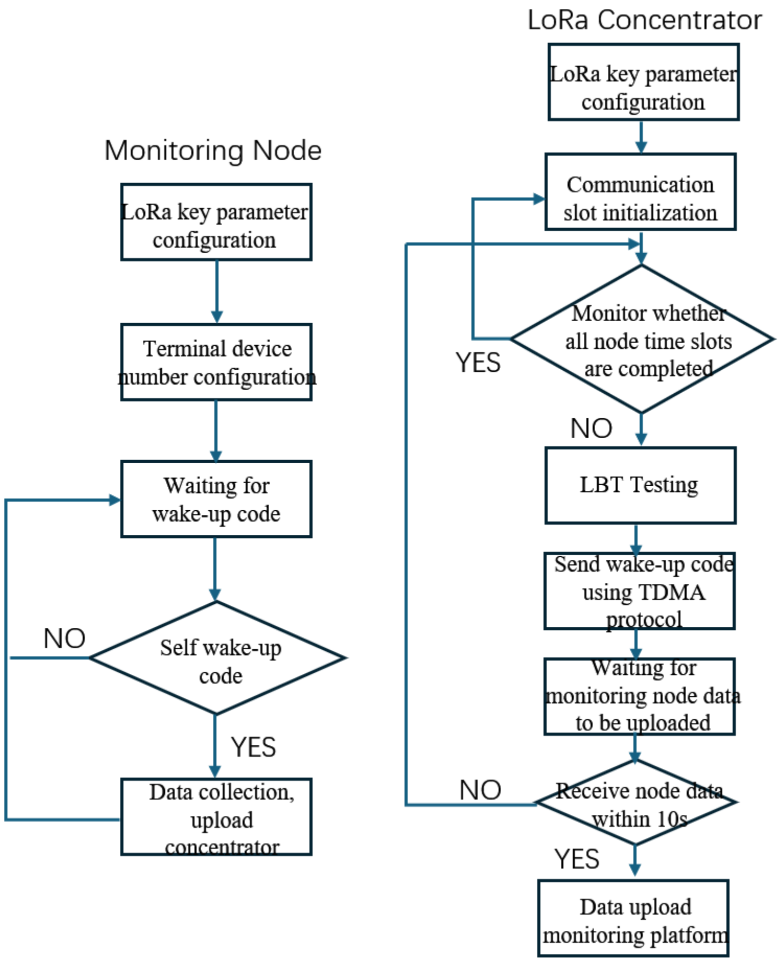


Figure 5.10: LoRa Networking Process

5.2.3 Sensor Data Analysis

The sensor data parsing task implements the parsing of data uploaded by monitoring nodes and uploads it to the monitoring platform. This task parses the data uploaded by the greenhouse monitoring node by reading the sensor_uart_buf connected to the UART2 port of the LoRa module. First, perform CRC16 verification on the data frame reported by the greenhouse monitoring node. After the verification passes, the sensor data is taken out and the data is combined into different JSON data packages according to different sensor types. Then, the 4G network access task is called to upload the data to the monitoring platform in the AT_MPUB_sta state[26][27][28]. The sensor data analysis task flow chart is shown in Figure 5.11.

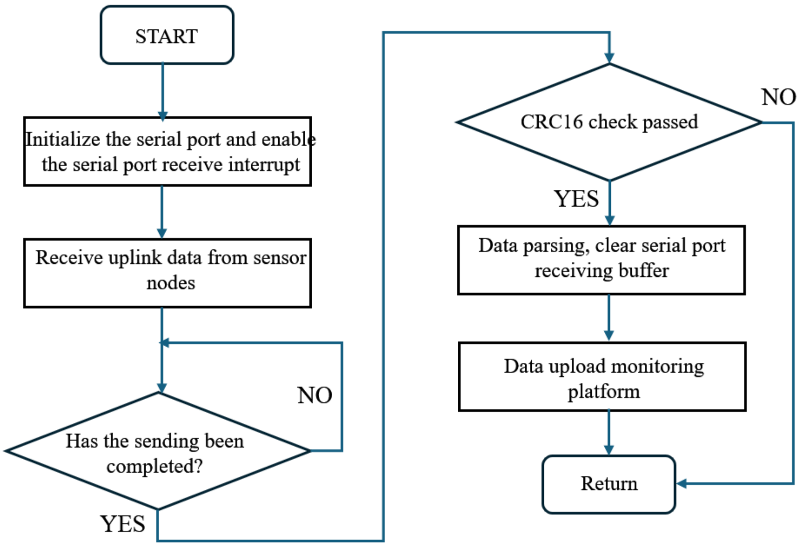


Figure 5.11: Data analysis flow chart

5.3 Design of Cloud Platform

The monitoring cloud platform can display the environmental information uploaded by the monitoring node in real time and remotely control the monitoring node sensors and other equipment. The specific functions include real-time data query, historical data visualization, device management and command issuance[29].

5.3.1 OneNet Cloud Platform

OneNET - China Mobile IoT Open Platform is a PaaS-based IoT open platform developed by China Mobile. It helps developers easily achieve device access and connection, providing comprehensive IoT solutions for data acquisition, data storage, and data visualization of IoT devices[30].The OneNet resource model is shown in Figure 5.12.

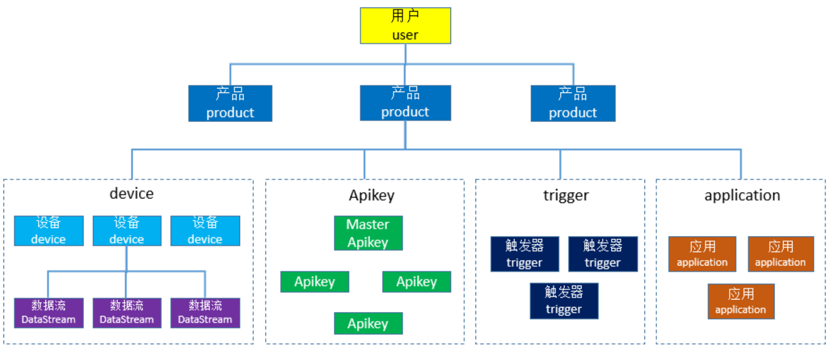


Figure 5.12: OneNet resource model diagram

- Product: A product in the OneNET platform serves as the largest resource unit for users. A product can include multiple resources such as devices, device data, device permissions, data trigger services, and applications based on device data. Users can create multiple products to facilitate resource classification, management, and application development.
- Device: A device refers to the mapping of a real-world terminal device on the OneNET platform. When a physical terminal connects to the platform, it must establish a one-to-one correspondence with a device entry. The data uploaded by the terminal device is stored in the corresponding data streams. A single device can have one or more associated data streams, supporting multi-dimensional data collection.
- Data Streams and Data Points: Data streams are used to store a specific category of attribute data from devices, such as temperature, humidity, or location information. The platform requires that data uploaded by devices must follow a key-value structure, where the key represents the name of the data stream and the value represents the actual stored data. The value supports multiple formats, including int, float, string, and json, providing strong flexibility and scalability.
- APIkey: The APIkey is the credential required for users to access OneNET product resources via API calls. Each product directory generates a unique APIkey to authenticate and authorize data access and operations, ensuring security and integrity.
- Trigger: A trigger is a messaging service under the product directory. It allows simple logic judgments based on data stream changes, and can trigger HTTP requests or send email notifications when preset conditions are met, enabling intelligent data processing and event-driven responses.
- Application: The application editing service enables users to build web-based applications by dragging and dropping widgets, which can be linked to device data streams. This low-code approach allows users to easily create interactive data visualization applications without requiring complex programming skills, thus improving development efficiency.

5.3.2 Product and Equipment Management Process

To achieve data acquisition and cloud management of IoT terminal devices, it is necessary to complete the creation and configuration of products, devices, and data streams on the OneNET cloud platform. Proper resource management facilitates device access, data storage, and visualization. This section elaborates on the processes of product creation, device registration, and configuration of data stream templates.

- Creation of Products

  In the OneNet platform, a product serves as the fundamental unit for resource management, grouping devices, and related services under a unified framework. A product defines core attributes such as device models, data templates, and communication protocols, laying the foundation for large-scale device access and data processing.

  Typically, the process of creating a product begins by logging into the OneNet cloud management interface and navigating to the product management module. Users can create a new product by filling in essential information, including the product name, industry type, node type (such as direct connection or gateway sub-device), and communication protocol (e.g., MQTT). Depending on the application scenario, users may also enable features such as transparent data transmission or data templates. Upon saving, the platform automatically assigns a unique product ID, which serves as a critical reference for device authentication and connection. Once the product creation is completed, users can proceed with device registration and data structure configuration under this product. The created product is named ”Buoy Monitoring Platform” as shown in Figure 5.13

- Device registration

  Devices act as virtual representations of physical terminals within the cloud platform and must be registered under their corresponding products. During device registration, users access the device management module under the selected product, initiate the ”Add Device” process, and fill in basic device information, including the device name, device ID (either user-defined or system-generated), and a description.

  Furthermore, an authentication method must be selected, such as authentication based on product key, individual device keys, or APIKey, to ensure secure communication. Upon successful registration, each device is assigned a unique device ID and AccessKey, which are essential for subsequent device authentication and connection processes. Initially, newly registered devices appear with a ”Not Activated” status, which automatically updates to ”Activated” after the device successfully connects to the platform and reports its first data payload.The created device name is ”FBPT” as shown in Figure 5.14

Figure 5.13: Product creation

Figure 5.14: Device creation

- Configuration of data stream templates

  To standardize the structure and format of data uploaded by devices, the OneNET platform supports the creation of unified data stream templates at the product level. Through data stream templates, users can pre-define device attributes and clearly specify the types and formats of uploaded data, facilitating efficient parsing, storage, and visualization.

Within the product details page, users can navigate to the ”Data Template” module to create a new template. During the template setup, the name of each data stream (such as temperature, humidity, GPS location), data type (such as int, float, string, or json) and reporting method (single or batch upload) are specified. Additional metadata, such as measurement units and field descriptions, can be added to enhance data readability and maintainability. The data flow template is shown in Figure 5.15.

Once the data template is established, devices are expected to format their uploaded data according to the predefined key-value structure. This standardized approach significantly improves the consistency of data management throughout the system and provides a solid foundation for the subsequent visualization of data and the development of applications.

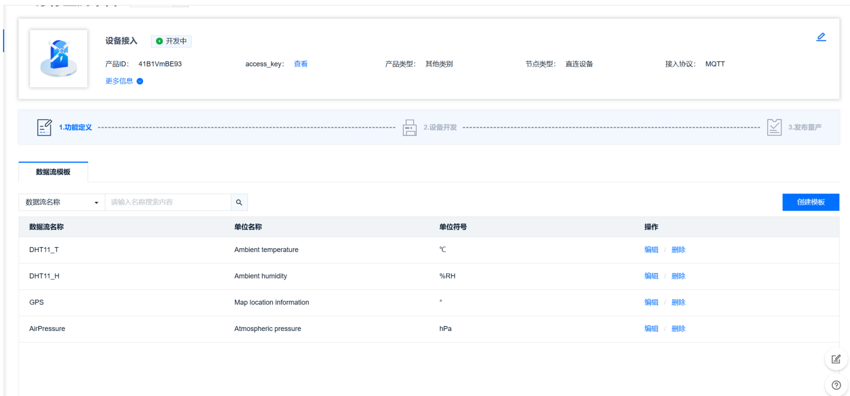


Figure 5.15: Data flow

5.3.3 MQTTX Tool Login Test

MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol based on the publish/subscribe model, widely applied in the field of the Internet of Things (IoT). Its communication method centers on topics, where publishers send messages to specific topics, and subscribers receive relevant data by subscribing to topics of interest, thus achieving loosely coupled communication between devices. Topics are organized in a hierarchical string format and support wildcard matching, which enhances the flexibility of data transmission and the efficient use of system resources. By forwarding messages through an intermediate broker, MQTT eliminates the need for direct connections between publishers and subscribers, thereby significantly improving system scalability and reliability.

In practical IoT applications, MQTT connections often adopt a triple authentication mechanism to ensure secure device access and reliable data transmission. The ”triple credentials” consist of a Product ID, Device Name, and Device Secret, which are used to identify the product category, uniquely distinguish each device, and authenticate the device identity, respectively. When connecting to the platform, the device uses the Device Name as the Client ID, the Product ID as the username, and a credential generated based on the Device Secret for authentication. This mechanism effectively enhances the security of device access and standardizes platform management, making it a widely adopted standard authentication method across mainstream IoT cloud platforms.

- Simulating Device Login

  During the device access and data upload verification process, the MQTTX client tool is used to simulate communication between terminal devices and the cloud platform. MQTTX enables convenient simulation of device login, topic subscription, and message publishing operations, thereby facilitating quick testing of device-side functionalities.

  Initially, according to the input prompts provided by the MQTTX interface, necessary connection parameters such as server address, port number, client ID, username, and password are entered. Typically, the client ID, username, and password are generated based on the device's triple credentials, namely the Product ID, Device Name, and Device Secret. After completing the parameter configuration, the device can initiate a connection and subscribe to designated topics as required. Subsequently, by publishing correctly formatted messages to the specified topics using MQTTX, the data reporting process of the device can be effectively simulated, achieving preliminary validation of the data communication link. As shown in Figure 5.16.

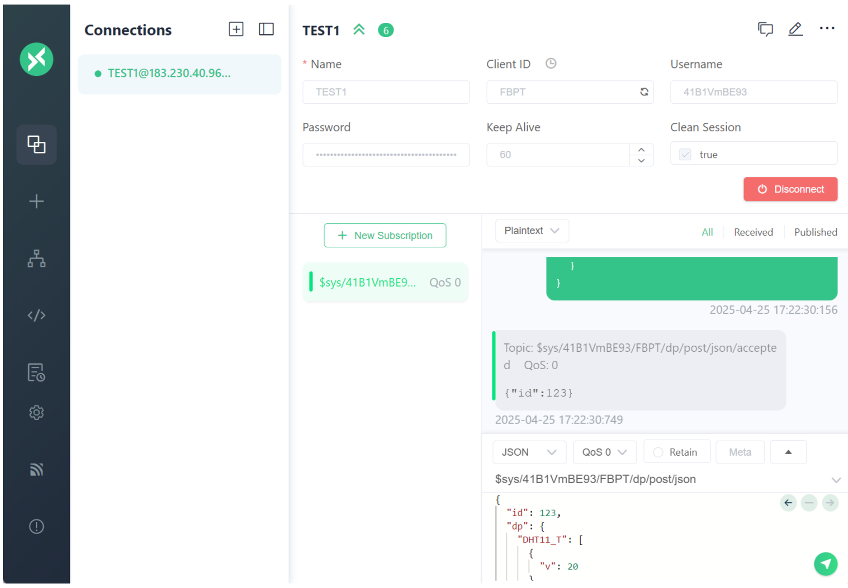


Figure 5.16: MQTTX client login

- Logging into the OneNet Console to View Devices

  After completing device login simulation and data publishing, users can log into the OneNet platform's device management console. On the device list page, the device's online status can be viewed in real time, indicating successful connection to the cloud platform. The device status transitions from "Not Activated" to "Activated," confirming the first successful connection and data reporting. As shown in Figure 5.17.

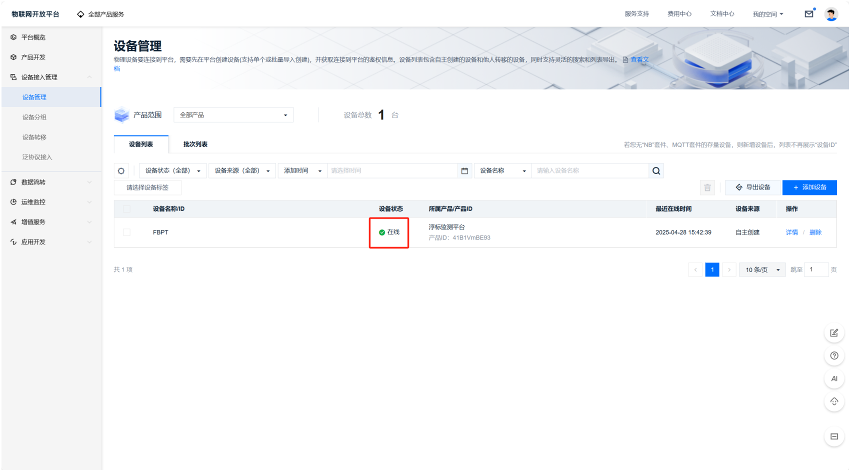


Figure 5.17: OneNet console activation

By further accessing the device details page, users can inspect the data recently uploaded by the device simulator, including temperature, humidity, air pressure, and GPS location information. As shown in Figure 5.18 and Figure 5.19. The visualized data allows intuitive verification of the completeness and correctness of the uploaded information, ensuring alignment with the platform's data parsing logic.This process not only verifies the accuracy of communication between the device and the cloud but also lays a solid foundation for subsequent integration and testing of actual terminal devices.

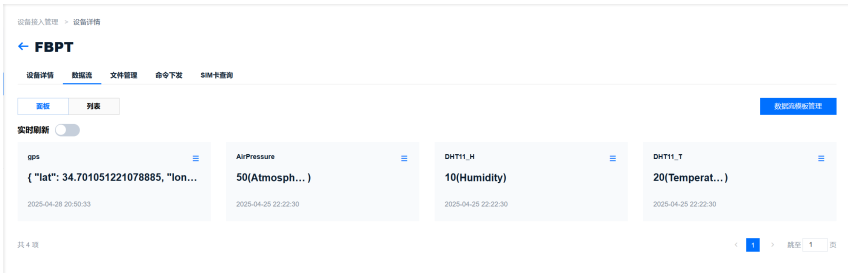


Figure 5.18: Data display

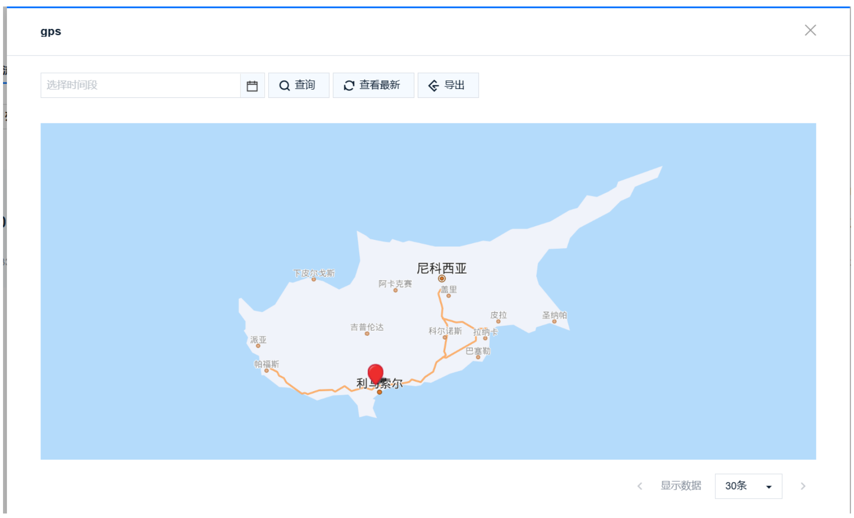


Figure 5.19: View positioning

5.3.4 Visual Interface Design

To enhance the data interaction experience and management efficiency of the IoT system, this project utilizes the application editing features provided by the OneNet platform to design and implement a visualization interface for device data. Through real-time data display and graphical analysis of historical data, users can intuitively monitor the operational status of terminal devices and observe environmental changes, thereby effectively supporting subsequent maintenance and decision-making processes.

During the interface design process, the overall system architecture and business requirements were first analyzed to determine the key content for visualization, including temperature, humidity, air pressure and GPS location information. Different types of data were presented using various visualization components such as tables, line charts, bar graphs, and geographic maps, thereby accommodating the specific characteristics of each data type.

Utilizing the low-code development tools offered by the OneNET platform, a modular layout approach was adopted. Real-time data, historical trends, device status, and alarm information were arranged into different sections to ensure data completeness while enhancing clarity and user experience. In addition, by integrating data triggers and rule engines, dynamic alerts were implemented to promptly notify users of abnormal data, further improving the level of intelligence of the system. As shown in Figure 5.20.

The finalized visualization interface not only achieves intuitive presentation of device data, but also supports multiterminal access, being compatible with both PC and mobile platforms. This significantly improves system accessibility and management convenience. Through the design and deployment of this visualization interface, the overall user-interaction experience has been greatly optimized, providing strong support for the practical application of the platform.

Figure 5.20: Visual interface

5.4 Summury

This chapter introduces the LoRa concentrator section of the buoy monitoring platform based on LoRa communication, with a focus on both hardware and software design aspects. The concentrator is responsible for receiving environmental monitoring data transmitted by the sensing nodes and forwarding the data to the central monitoring platform via a 4G communication module.

On the cloud side, the system utilizes the OneNET platform to receive, store, and display the uploaded data in real time. A visualization interface was designed using OneNET's application tools, enabling intuitive monitoring of key environmental parameters such as temperature, humidity, air pressure, and GPS location. The interface supports both PC and mobile access, and integrates data trigger mechanisms to provide prompt alerts in case of abnormal values. This cloud platform design significantly enhances the usability, accessibility, and intelligence of the monitoring system, providing strong support for remote data management and real-time environmental assessment.

6 Conclusion and Future Work

6.1 Conclusion

This paper presents the design of a low-power, long-range, and scalable buoy-based environmental monitoring platform based on LoRa communication technology. Multiple monitoring nodes are deployed on the sea surface, powered by photovoltaic cells, to periodically collect key parameters such as temperature and humidity, atmospheric pressure, and GPS location information. The collected data is transmitted via LoRa to a concentrator, which then uploads the data to the cloud monitoring platform through a 4G communication module, enabling remote data transmission and command delivery.

In the system design, a complete end-to-end communication link was established by integrating LoRa-based wireless transmission and the concentrator module. The MQTT protocol was adopted to ensure reliable data publishing and command exchange between the device and the cloud. The cloud-side visualization platform was developed using OneNET, allowing real-time data display, historical trend analysis, and alarm functionalities, thereby enhancing the user experience. The entire system adopts a modular design with high integration, low power consumption, strong adaptability, and excellent scalability.

The main contributions of this work are summarized as follows: (1) A set of LoRa-based environmental monitoring nodes was constructed to collect and transmit key parameters such as temperature, humidity, atmospheric pressure, and GPS location. Solar power ensures the independent operation of each node. (2) A concentrator combining LoRa and 4G communication was designed to enable bidirectional communication between field nodes and the cloud platform. (3) An MQTT-based data communication mechanism was implemented to enhance the reliability and real-time performance of the system. (4) A OneNET-based visualization cloud platform was built to support remote monitoring, alarm triggering, and data management.

6.2 Future Work

In future research and system optimization, efforts will focus on improving overall performance and application reliability. Specific plans include: conducting LoRa communication range and networking tests to evaluate the stability and effective coverage of communication under different environmental conditions; analyzing overall system communication performance, including key indicators such as end-to-end transmission delay and packet loss rate; performing field tests on the photovoltaic power generation and energy consumption of the monitoring nodes to verify their long-term stability under marine operation conditions; and refining data acquisition accuracy to enhance the precision and consistency of environmental monitoring.

In addition, the visualization interface and alert mechanisms on the cloud platform will be further optimized based on diverse application scenarios, aiming to improve user interaction experience and platform intelligence. Through these tests and enhancements, the system is expected to evolve into a stable, low-power, and highly adaptive water environment monitoring solution, providing strong technical support for future deployment and large-scale application.

After successful validation of the current system, additional monitoring nodes will be integrated to extend the system's sensing capabilities. These nodes will be designed to collect a wider range of marine environmental parameters, including wind speed and direction, wave height, wave period, wave direction, as well as ocean current velocity and flow direction. This expansion will enable more comprehensive environmental perception and support advanced oceanographic research and maritime applications.

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APPENDICES

APPENDIX I

Title of Appendix

If you have material that cannot be included within your document, you must include an appendix. You may include one appendix or a number of appendices. If you have more than one appendix, you would number each accordingly (i.e., Appendix I, Appendix II, etc.). Write your appendix headings in the same manner as your chapter headings.