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Research Article

Research and Design of Distributed IoT Water Environment Monitoring System Based on LoRa

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In order to solve the problems of high labor cost, long detection period, and low degree of information in current water environment monitoring, this paper proposes a lake water environment monitoring system based on LoRa and Internet of Things technology. The system realizes remote collection, data storage, dynamic monitoring, and pollution alarm for the distributed deployment of multisensor node information (water temperature, pH, turbidity, conductivity, and other water quality parameters). Moreover, the system uses STM32L151C8T6 microprocessor and multiple types of water quality sensors to collect water quality parameters in real time, and the data is packaged and sent to the LoRa gateway remotely by LoRa technology. Then, the gateway completes the bridging of LoRa link to IP link and forwards the water quality information to the Alibaba Cloud server. Finally, end users can realize the water quality control of monitored water area by monitoring management platform. The experimental results show that the system has a good performance in terms of real-time data acquisition accuracy, data transmission reliability, and pollution alarm success rate. The average relative errors of water temperature, pH, turbidity, and conductivity are 0.31%, 0.28%, 3.96%, and 0.71%, respectively. In addition, the signal reception strength of the system within 2 km is better than -81 dBm, and the average packet loss rate is only 94%. In short, the system's high accuracy, high reliability, and long distance characteristics meet the needs of large area water quality monitoring.

1. Introduction

With the increasingly frequent human social and economic activities, lakes in many cities are facing serious surface water pollution [1]. The water quality of urban watersheds is extremely important for the production, life, health, and sustainable development of residents in the surrounding areas. Among them, the use of polluted water to irrigate farmland will damage the soil, affect the growth of crops, and cause loss of production in agricultural production. In fish farming, water pollution will endanger the growth and reproduction of aquatic organisms. In addition to economic losses, fish carrying heavy metal pollution elements will spread to consumers by food chain and cause various difficult-to-treat diseases [2, 3]. In order to improve urban water quality, the Chinese central government has promulgated an innovative water quality management policy, River Chief Policy [4, 5], and actively advocates the development of informatized water pollution prevention and control [6]. It can be seen that obtaining water quality information of urban lakes in a timely manner to drive managers to make rapid and accurate pollution prevention and control strategies has very important research significance.

At present, people have obtained many research results in the water quality monitoring field. Jiang et al. (2018) deployed a WSN system for drinking water monitoring [7]. Ruan and Tang (2012) combined solar charging and wireless sensor network technology to design an energy-saving and low-carbon water quality monitoring system [8]. Nam et al. (2015) designed a wireless sensor network system based on CDMA (code division multiple access) and ZigBee technology when monitoring the water environment where coastal fish live [9]. Raul et al. (2013) designed a set of remote water quality analyzer based on GPRS (General Packet Radio Service), which used National Instruments' LABVIEW for visual analysis [10]. Wiebke et al. (2017) deployed a wireless sensor network in coastal fishing grounds with low-cost compact buoys equipped with water quality monitoring sensors to analyze the impact of water quality parameters on aquaculture [11]. The above studies have provided unique water quality monitoring methods. However, with the development of Internet of Things (IoT) technology, a LoRa communication technology (Lavric et al. 2016) with the characteristics of long distance, low power consumption, low cost, and standardization has been favored by more researchers [12]. Rachmani and Zulkifli (2018) deployed a LoRa-based and IoT monitoring system in a carambola plantation in Indonesia [13]. The monitoring system obtained a reliable transmission range of 700 meters in dense carambola forest, and the average response effect of monitoring system was 0.408 seconds. Ayele et al. (2018) used LoRa technology in outdoor population research to achieve sustainable wildlife monitoring [14]. Deng et al. (2020) collected information from radio frequency identification (RFID) sensors deployed in the soil by patrol vehicles and communicated with the monitoring center by LoRa [15]. The new soil environment monitoring system has a coverage area of 10 square kilometers, and the communication success rate is as high as 90%. Waseem et al. (2020) combined acoustic telemetry and LoRa technology to develop and test a new concept-Internet of Fish (IOF) [16], which is used to help fishermen obtain behavioral data of fish in fishing grounds. After testing, the service quality of all nodes in the system has reached more than 90%.

Looking at the above research results, it can be seen that LoRa technology has played an effective and reliable role in multiscene monitoring applications. Besides, compared to short-range communication technology, it is more suitable for field application scenarios such as agriculture and aquaculture monitoring [17, 18]. Because most of the waters to be monitored are often in the field where power is not easily available, the monitoring distance and low-power operation of the water quality monitoring system is very important. However, the above water quality monitoring solutions cannot achieve both long distance and low power requirements, this paper is based on the LoRa technology of low power cosnsumption and long distance characteristics [19, 20] and designed a distributed water environment system for the field complex environment.

The system is based on a star topology network. The terminal node uses STM32L151C8T6 chip and a variety of water quality sensors to obtain and package the water quality information of target water body in real time and then upload data packet to the gateway by LoRa technology. The SX1301 baseband chip commonly used in LoRa gateways has only one downlink channel, which is not enough to support the concurrent upload of large-scale water quality monitoring nodes [21, 22]. Therefore, this research has expanded multiple SX1278 baseband chips in the gateway to replace the original downlink channel to alleviate the high concurrent access problem of data. In addition, the cloud server receives data from gateway, analyzes and stores the data for the user monitoring platform to query and analyze water quality data and another node information.

The rest of this paper is organized as follows. Section 2 introduces the overall architecture of distributed water environment monitoring system and its functions. Section 3 introduces the hardware design of the water quality monitoring node and its embedded software design in detail. In Section 4, the network topology and data interaction of transport layer are introduced, and the gateway is improved to alleviate the congestion of high concurrent upload of large amounts of data. Section 5 discusses the software design of the application layer. Section 6 presents the monitoring results and data and evaluates the system reliability. Finally, the paper is summarized in Section 7.

2. Architecture Design

The lake water quality monitoring system proposed by this research consists of four parts: perception layer, transmission layer, platform layer, and application layer. The system mainly realizes the functions for distributed collection of water quality data, node positioning, remote transmission, data storage, and remote monitoring. The system architecture diagram is shown in Figure 1.

The water quality monitoring node in this system is based on LoRa technology. The node is distributed in the target water area and consists of a control unit, a water temperature-pH composite sensor, a turbidity sensor, a conductivity sensor, a global positioning module, a power management module, and a LoRa Radio Frequency (RF) transceiver module. On the one hand, the LoRa node collects various water quality parameters such as water temperature, pH, turbidity, and conductivity by sensors, and on the other hand, obtains its own longitude and latitude information by the global positioning system. Finally, the information is packaged and sent to the transport layer by the LoRa communication module. In the transport layer, in order to cope with high PLR (packet loss rate) that may be caused by the data access of large-scale nodes, this research has extended eight SX1278 baseband chips for the SX1301 baseband chip of the LoRa gateway. In this way, the symmetry of uplink and downlink eight channels is realized, and a reliable transmission link is provided for user data. The third layer is the platform layer, which is responsible for aggregating terminal data forwarded by the LoRa gateway. And according to the different data types, it is stored in the MySQL database in an orderly manner and provides support for the monitoring application system to realize specific business functions. The application layer is the fourth layer. The monitoring system completes data analysis, query, visualization, local storage, node positioning, pollution alarm, and other functions by calling the data processing interface provided by the cloud platform.

The system has a clear hierarchy from bottom to top. The terminal node of the perception layer obtains detailed data. The transport layer puts forward countermeasures in the face of the large-scale data access problem of distributed nodes. The platform layer provides reliable support for user

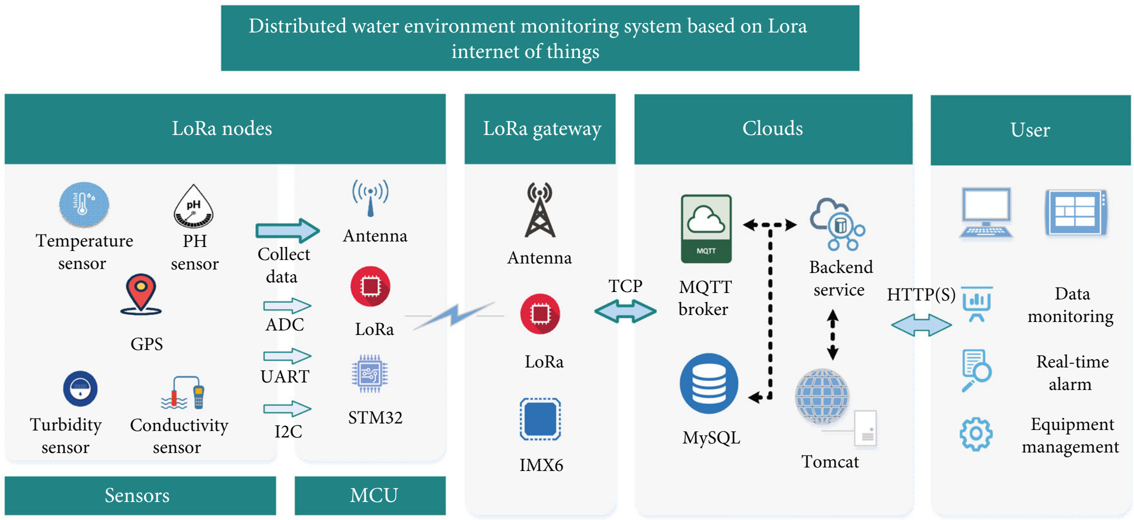

Figure 1: System architecture diagram.

applications. The monitoring system at the application layer is fully functional.

3. Perception Layer Node Design

The water quality monitoring node is located in the sensing layer of monitoring system and is distributed in the monitoring target water area. Each node has its unique ID number and communicates with the gateway by different channels. It can be divided into five parts for design: main control board design, LoRa RF unit selection, power management module design, and data frame format design. Among them, the design of the main control board and LoRa RF unit is the most critical, and main control board dispatches water quality sensor for data collection. LoRa RF unit is responsible for data interaction with the gateway.

3.1. Main Control Board Design. The frame diagram of the main control board design is shown in Figure 2. Considering the complex water quality environment, multidimensional water quality data is collected for comprehensive analysis. For this reason, temperature sensor DHT12, pH composite electrode E-201-C, turbidity sensor TSW-30, conductivity electrode DJS-1, and TDS sensor are selected to obtain the water temperature, pH value, turbidity, conductivity, and solids of the target water area. The main control chip adopts STM32F103C8T6 produced by STMicroelectronics. This chip has rich peripheral interfaces such as timers, UART, ADC, I2C, GPIO, and SPI. And the built-in 64 kBytes Flash and 32 kBytes RAM can meet the access requirements of sensors and LoRa communication modules. In addition, the chip is based on ARM Cortex-M3 architecture, which has low power consumption and is suitable for long-term monitoring needs. The chip mainly completes data collection, processing, and storage and sends and receives data packets by the SX1278 RF unit. The data collection period of nodes is set to 30 min by the timer.

3.2. Water Quality Sensor and GPS Module Selection. This research conducted a more comprehensive analysis of water quality parameters such as water temperature, pH, turbidity, and conductivity. The selected sensor modules are shown in Figure 3. Among them, in water temperature-pH composite sensor, we use BNC interface and E-201-C type pH composite electrode. In addition, the sensor has expanded DS18B20 temperature sensor interface. On the one hand, it can read the water temperature parameters, and on the other hand, it can compensate pH detection value to improve the accuracy. The sensor uses 5 V working voltage and analog output. The working temperature is between 0-60°C, the measuring range is 0-14PH, and the response time is less than or equal to 1 minute.

The model of turbidity sensor selected in this study is TSW-30. The sensor comprehensively judges the turbidity by light transmittance and scattering rate in the target solution. The sensor can output both analog and digital signals at the same time, and the working voltage is 5 V. The standard operating temperature is between -20°C and 90°C, and the detection response time is less than 500 ms.

Conductivity reflects the electrolyte concentration of the measured solution and is an important parameter to measure the water quality. DJS-1 conductivity electrode in conductivity sensor is used for water quality monitoring. The sensor uses a 5 V supply voltage and a 0 ~ 3.4 V analog output. The working temperature is between 0 and 40°C, and the supported measurement range is 0-20 mS/cm.

GPS module model ATK-NEO-6 M is used in order to obtain the location of water quality monitoring node. The module comes with a ceramic antenna and MAXIM's 20.5 dB high-gain LNA chip, compatible with 3.3 V and 5 V power supply voltages. The working temperature range is -40°C ~ 85°C, the positioning accuracy is high, and it is easy to use.

3.3. Communication Module Circuit Design. The LoRa RF module is responsible for receiving and forwarding water quality data and works in 480-510 MHz unlicensed ISM

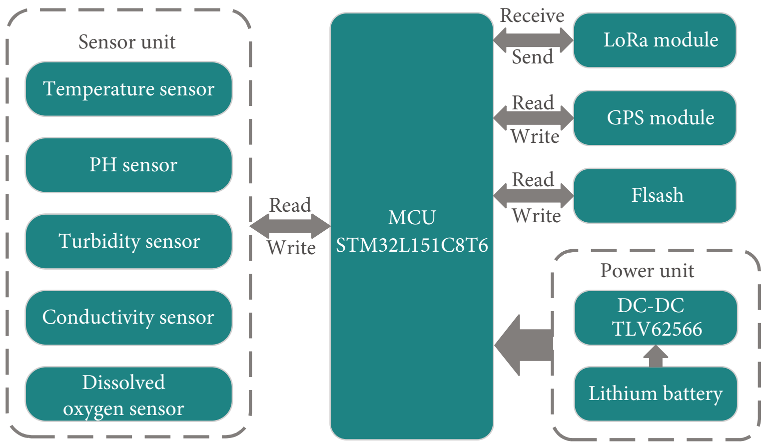

FIGURE 2: Frame diagram of node main control board.

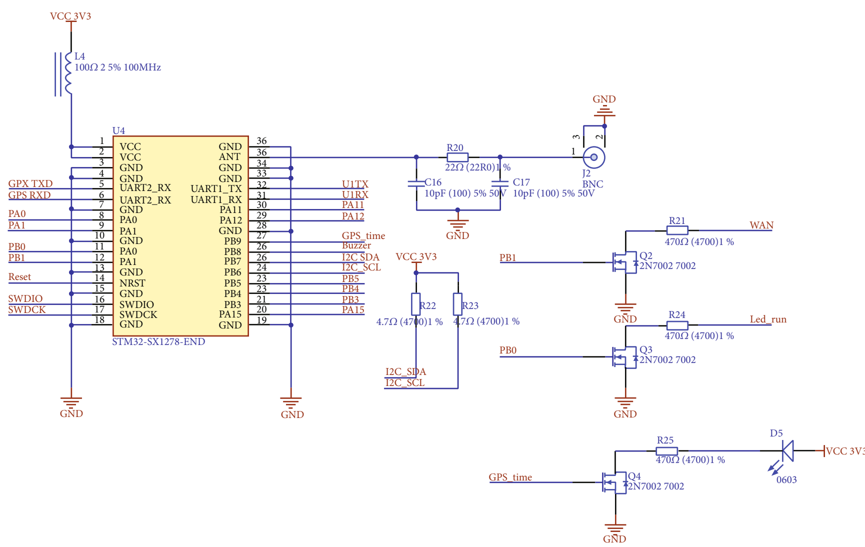

FIGURE 3: Schematic diagram of LoRa RF module.

frequency band in China [23, 24]. Main Control Unit (MCU) is programed to control the LoRa module and send information by the module after encoding. This design uses SX1278 baseband chip of Semtech Company. The chip uses LoRa chirp spread spectrum (CSS) technology to send data [8, 9]. This technology can effectively reduce noise and interference and cover a large distance. Through an integrated +20 dBm power amplifier, it can ensure long-distance wireless communication under the condition of sensitivity as low as -148 dBm. Moreover, the chip only costs about $1-2, which greatly reduces the design cost. Its super high-cost performance meets the management needs of equipment networking for remote water quality monitoring.

The circuit principle diagram of the LoRa communication module is shown in Figure 3. The communication module sx1278 is a RF module, which exchanges data with the stm32, and RF antenna sma connector packs the data and sends it to LoRa gateway. In order to ensure a better power supply performance, a magnetic bead is connected in parallel near the power supply of the sx1278 module. In the circuit design of RF antenna, use si9000 simulation calculation tool for PCB trace to control 50 Ω impedance of RF signal line. A π-type matching circuit is reserved to facilitate RF adjustment and ensure reliability.

3.4. Power Management Module Design. The power management module is responsible for the power supply requirements of water quality monitoring node, and it is composed of a lithium battery and a step-down circuit. The power supply requirement of LoRa module is 3.3 V [25, 26], and the power supply voltage of MCU and water quality sensor is 5 V. Thus, TLV62565 step-down circuit is selected to reduce DC 5 V voltage of lithium battery to 3.3 V required by MCU. The schematic diagram of power management module is shown in Figure 4.

The TLV62565 buck converter integrates a switch capable of delivering up to 1.5 A of output current. This device uses valley current mode control system configuration to work according to adaptive on-time. The typical operating frequency at medium or heavy load is 1.5 MHz. During light

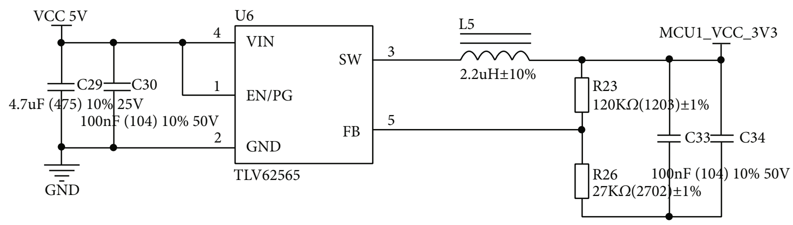

Figure 4: Schematic diagram of power management module.

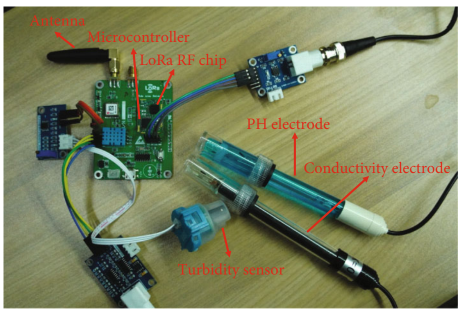

Figure 5: Physical diagram of water quality monitoring node.

load, TLV62565/6 automatically enters the power-saving mode at the lowest quiescent current (typical value 50 μA) to maintain high efficiency over the entire load current range. When shutting down, the current consumption is reduced to less than 1 μA.

In summary, the above hardware modules constitute a water quality monitoring node. The actual node is shown in Figure 5.

3.5. Node Embedded Software and Data Frame Design. This research uses Keil integrated development environment to design the control program of the STM32 single-chip microcomputer. After compilation, simulation, and debugging, the program is finally burned to MCU to complete the development. The program mainly completes the functions of collecting data, signal conversion, and uploading data. The node program flow is shown in Figure 6, and part of program code is as follows:

(1) float DS18B20_Get_Temp (void)//Get temperature value

(2) pH_VALUE = pH_VALUE ∗(3.3/4096); //PH electrode voltage acquisition

(3) ph_result = −5.7541 ∗PH_VALUE +16.654; //PH value ADC conversion

(4) float getTurbidityvalue (void)//Get Turbidity value

(5) tu_result = −865.68 ∗TU_VALUE +3291.3; //Turbidity value ADC conversion

(6) void EC_Value_Conversion(void)//Conductivity value acquisition

(7) EC_value = EC_value/(1.0 + 0.0185 ∗ ((temp_data/10) − 25.0))//conductivity ADC conversion

In order to facilitate subsequent data analysis and processing and improve data security, this design stores sensor information in encrypted MAC layer FRMPayload and uses a frame structure to reduce the error rate of data packet transmission process. The data that the node needs to monitor mainly include water temperature, pH, turbidity, conductivity, and geographic information of the location of nodes. They are arranged in a predetermined format, and the frame format is shown in Table 1. After the server receives it, it will set points according to the preset byte size of each field, and the specific section breaks and other standards are resolved in turn. And they are stored in the relational database MySQL, which provides a data basis for subsequent water quality monitoring platform.

4. Transport Layer Design

The transmission layer design of this system includes communication networking architecture and LoRa gateway. The communication networking architecture of this research chooses the star networking mode, and the network topology is shown in Figure 7. The star network is the simplest network structure with the lowest latency.

LoRa gateways can be built by themselves without relying on operators. LoRa gateway is arranged in the water quality monitoring system. It is at the core of LoRa star network and is an information exchange bridge between data terminals and servers. The gateway and cloud server are connected by standard IP. At the same time, it also supports functions such as node access control, node upload data packet analysis, uplink and downlink resource allocation and scheduling, user data encrypted transmission, and software remote upgrades.

4.1. LoRa Gateway Hardware Design. The embedded gateway designed by this research is composed of an industrial control core board, a LoRa gateway module, and a 4G Long Term Evolution (LTE) mobile data board, as shown in Figure 8.

The industrial control core board is based on i.MX6ULtraLite application processor with ARM Cortex-A7 core. This processor has a main frequency of up to 528 MHz, built-in 256 MB DDR3 memory, and 256 MB NAND FLASH. The board also integrates peripheral interfaces such as USB, ADC, UART, I2C, SPI, and GPIO, which can be widely used in various IoT scenarios. This industrial control core board is connected to LoRa gateway module by MiniPCI-E interface to provide relevant LoRa modem and processing functions.

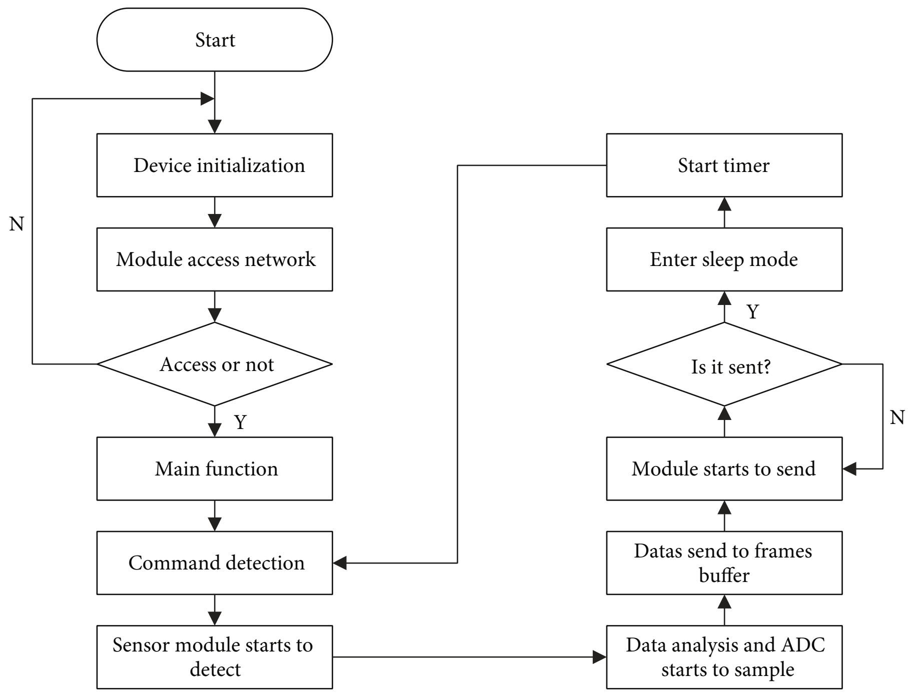

Figure 6: Program flow diagram of perception layer node.

Table 1: Data frame protocol.

Byte	Character	Meaning
Byte[0]	0x40	Data frame header
Byte [1]	ID	LoRa node ID
Byte [2]	Data	7-4 bit: integer part of water temperature; 3-0 bit: decimal part of water temperature
Byte [3]	Data	7-4 bit: pH integer part; 3-0bit: pH decimal part
Byte [4]	Data	7-4 bit: integer part of turbidity; 3-0 bit: decimal part of turbidity
Byte [5]	Data	7-4 bit: integer part of conductivity; 3-0 bit: decimal part of conductivity
Byte [6]	Data	7-4 bit: integer part of longitude; 3-0 bit: decimal part of longitude
Byte [7]	Data	7-4 bit: integer part of latitude; 3-0 bit: decimal part of latitude
Byte [8]	0x35	Data frame tail

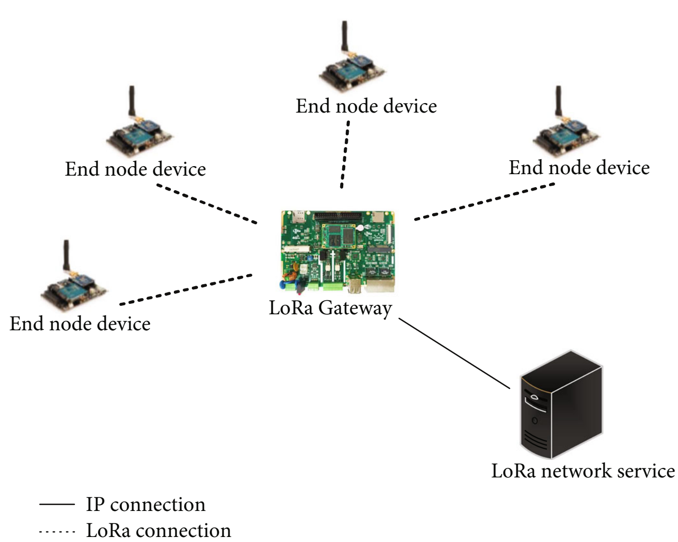

Figure 7: LoRa star networking architecture.

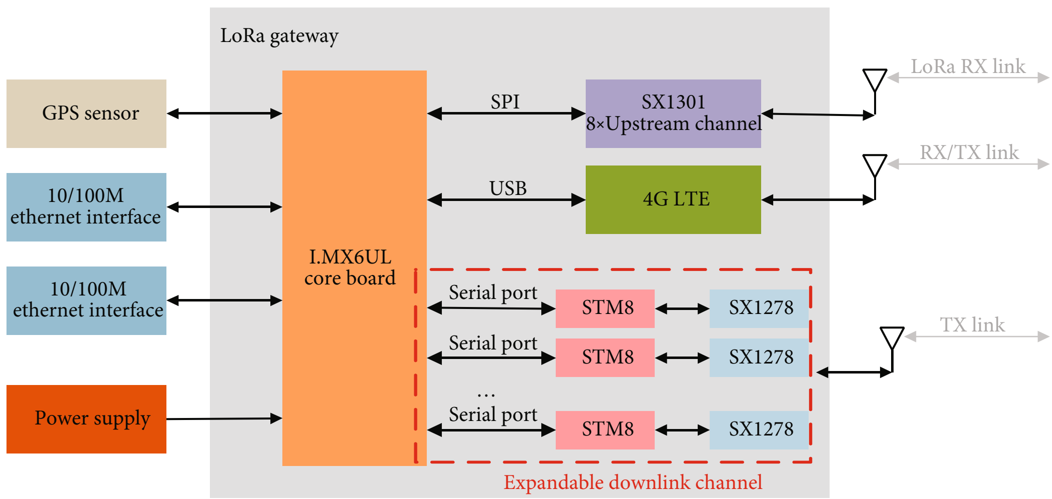

Figure 8: Gateway hardware architecture.

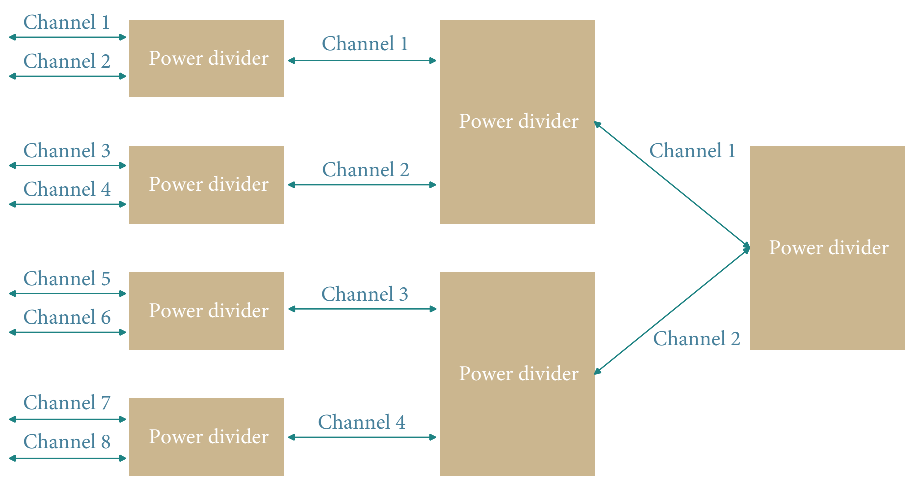

Figure 9: Schematic diagram of symmetrical channel design.

In addition, analyzing the current needs of water quality monitoring, monitoring results for a small number of nodes are not representative. In order to cope with large-scale distributed monitoring scenarios, it is necessary to extend the downlink channel of gateway. Symmetrical channel processor refers to the coexistence of multiple SX1278s by combiners based on communication channel provided by the existing SX1278 RF chip and makes the frequency band of each SX1278 signal different and independent of each other. Connect the module with the serial port of LoRa gateway, and control frequency band, power, spreading factor, and other RF parameters of each channel by application program to operate the serial port, and all channels of modules are fixed as downlink channels. This makes up for the lack of one downlink channel of existing LoRa gateway and realizes a LoRa gateway structure under multichannel symmetrical channel, which can alleviate transmission congestion and packet loss caused by large-scale data access. The design principle diagram of LoRa gateway is shown in Figure 9.

In the symmetrical channel circuit design, the output pin of the SX1278 RF chip is first filtered by HDF6566 communication filter, and then the signal is sent to RF input pin of RFPA0133 amplifier for signal gain amplification. The eight channels of signals (CH0 ~ CH7) after gain amplification will pass by power divider (PD0409J5050S2HF) chip to divide the signals twice in a way of two inputs and one output. The signal after power division is coupled to RFPA0133 signal amplifier by HDF6566 chip and resistor capacitance (RC) series circuit. Finally, amplified signal is filtered by LP15A500 low-pass filter chip. Pass the required signal and block unwanted channel. Through the above design, the frequency band of each signal cannot affect each other under the premise of normal work. Finally, the gateway is connected to the LoRa module by serial port to realize the control and use of eight extended channels.

4.2. LoRa Gateway Software Design. The workflow of gateway in this paper is shown in Figure 10. The gateway passively accepts data packets from nodes in this system. When LoRa gateway receives data packet of LoRa node in the perception layer, it parses the hidden information in data packet, including cyclic redundancy check (CRC) check bit, the node ID that sent data packet, the destination addresses

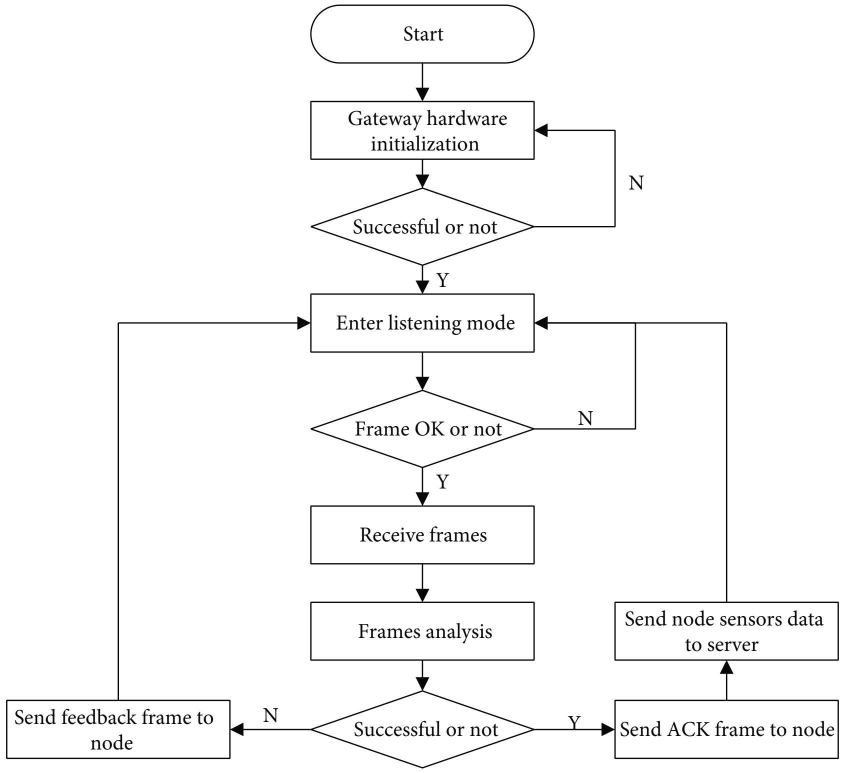

Figure 10: Program flow chart of the gateway.

of data packet, the data collected by sensors and GPS, and RSSI value of packets.

After the gateway receives data packet sent from nodes, it first stores the data in a 16-byte data buffer. For the data packet stored in data buffer, CRC check is performed first, if the check is successful. Then, analyze data packet according to the preset protocol and discard data packet if CRC check fails.

5. Platform Layer and Application Layer Design

The platform layer of this research is supported by China Mobile Internet of Things Open Cloud Platform (OneNET), which reduces hardware costs while achieving high availability and data security. The remote monitoring system of application layer communicates with cloud platform by HTTP protocol to obtain the data of underlying equipment and realize data real-time monitoring, equipment management, water quality alarm, historical data viewing, and other functions. As shown in Figure 11, the user water quality monitoring system searches by node ID number and sensor name and can monitor the real-time data collected by sensors under each node. Moreover, it can view the historical data curve collected by nodes. The water quality monitoring alarm is mainly realized by triggers in the application software. When the trigger detects that node collection value exceeds the threshold range preset by administrator, it will send out an alarm message. The alarm information contains abnormal node ID, the geographic location of nodes, and the name of abnormal water quality parameter, which is convenient for users to accurately locate the location of abnormal

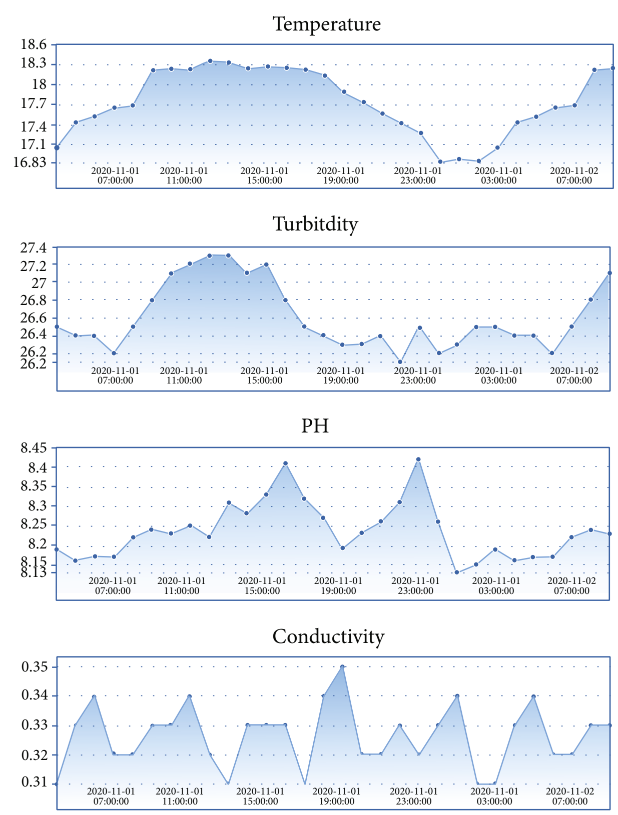

Figure 11: Historical data curve of remote monitoring platform.

Table 2: Node monitoring results on November 8, 2019 (clear weather).

Monitoring time	Water quality parameter	Standard value	Node actual value	Relative error (%)
00 : 00	Water temperature (°C)	17.85	17.83	-0.11
	pH	8.31	8.32	0.12
	Conductivity (mS/cm)	0.34	0.33	-2.94
	Turbidity (NTU)	26.5	26.4	-0.38
08 : 00	Water temperature (°C)	18.90	18.94	+0.21
	pH	7.88	7.86	-0.25
	Conductivity (mS/cm)	0.35	0.36	+2.86
	Turbidity (NTU)	26.6	26.6	0
16 : 00	Water temperature (°C)	18.78	18.81	+0.15
	pH	8.33	8.41	+0.96
	Conductivity (mS/cm)	0.33	0.35	+6.06
	Turbidity (NTU)	26.9	27.1	+0.74

water quality. In addition, the alarm information is divided into three states: unprocessed, processed, and marked. The system administrator classifies alarm information according to the current processing situation.

6. Experimental Results and Analysis

6.1. Data Collection Accuracy Experiment. In order to verify the system accuracy of data monitoring, we chose to conduct field tests in Tianyin Lake of Nanjing Institute of Technology. The lake covers an area of about 0.3 square kilometers, and there are a large number of egrets on the island in the lake center. It has the functions of receiving rainwater, aquaculture, and landscape ecology and has great water environmental protection value.

In the experiment, 7 nodes are distributed to different locations in Tianyin Lake to obtain multiple types of water quality parameters in real time. In order to verify the all-weather monitoring ability of system under various meteorological conditions, we selected three typical time periods (08 : 00, 16 : 00, 00 : 00) under three weather conditions: sunny, overcast, and rainy, as well as morning, noon, and night. Measure and read out three sets of data in order to test the sensitivity and accuracy of water quality monitoring node to the changes of water environment parameters. At the same time, this study used parameters measured by OTT Quanta portable multiparameter water quality detector produced by HACH in United States as the standard values for control experiments. The water quality monitor can read water temperature, pH, conductivity, turbidity, etc. at the same time, and the accuracy can reach within 1%. The experiment takes the result data measured by one of nodes as an example, and the following experimental data from Tables 2–4 is obtained. These tables contain the standard values of various parameters measured by instrument and actual values measured by system.

The experiment is implemented in November 2019. In order to observe the measurement results of system under different meteorological conditions, the experiment results on the 8th (clear), 11th (cloudy), and 17th (light rain) of the month are selected for analysis. Judging from the three sets of data, the water temperature on the three days was basically stable at 17~19 °C, and the water temperature dropped slightly under cloudy and light rain. The water temperature monitoring accuracy is maintained at ±0.15°C, and the average relative monitoring error is 0.31%. The pH value of the three days was basically stable between 7.5 and 8.5, and the pH value changed slightly under different weather conditions. The pH value monitoring accuracy is between ±0.08, and the average relative monitoring error is 0.28%. The three-day conductivity is stable between 0.33 and 0.34, and there is no significant change without the external pollution influence. The conductivity monitoring accuracy is within ±0.03 mS/cm, and the average relative monitoring error is 3.96%. The three-day turbidity range is 26.5 ~ 27.5NTU, and there is no significant change under the condition of no pollution. The accuracy of turbidity monitoring is within ±0.5NTU, and the average relative monitoring error is 0.71%.

According to analysis, with the change of meteorological conditions, the system can accurately and dynamically monitor the water temperature change. In the absence of external pollution, pH value, conductivity, and turbidity can be stabilized within a certain range. Compared with the standard value, the relative error of all measured results is very small. It can be seen that the system operates stably under multiple weather conditions and can complete high-precision dynamic monitoring of water environment influencing factors such as water temperature, pH value, conductivity, and turbidity all-weather.

6.2. Communication Quality Experiment. Since the data transmission quality of LoRa communication link will deteriorate with the distance increase, the communication reliability of water quality monitoring system is verified by detecting 0-2 km system RSSI (received signal strength indication) and PLR [27, 28]. The deployment diagram of experiment is shown in Figure 12. In order to test the

Table 3: Node monitoring results on November 11, 2019 (cloudy weather).

Monitoring time	Water quality parameter	Standard value	Node actual value	Relative error (%)
00 : 00	Water temperature (°C)	17.25	17.22	-0.17
	pH	8.13	8.14	+0.12
	Conductivity (mS/cm)	0.35	0.32	-8.57
	Turbidity (NTU)	26.6	26.5	-0.38
08 : 00	Water temperature (°C)	17.97	17.87	-0.56
	pH	7.98	7.96	-0.25
	Conductivity (mS/cm)	0.34	0.35	+2.94
	Turbidity (NTU)	27.3	26.8	-1.83
16 : 00	Water temperature (°C)	18.01	18.06	+0.27
	pH	8.35	8.36	+0.12
	Conductivity (mS/cm)	0.33	0.34	+3.03
	Turbidity (NTU)	27.1	27.2	+0.37

Table 4: Node monitoring results on November 17, 2019 (light rain weather).

Monitoring time	Water quality parameter	Standard value	Node actual value	Relative error (%)
00 : 00	Water temperature (°C)	16.71	16.65	-0.35
	pH	8.13	8.11	-0.24
	Conductivity (mS/cm)	0.31	0.30	-3.23
	Turbidity (NTU)	26.3	26.2	-0.38
08 : 00	Water temperature (°C)	17.05	17.07	+0.12
	pH	7.90	7.87	-0.37
	Conductivity (mS/cm)	0.34	0.33	-2.94
	Turbidity (NTU)	26.1	26.5	+1.53
16 : 00	Water temperature (°C)	17.18	17.33	+0.87
	pH	8.42	8.41	-0.12
	Conductivity (mS/cm)	0.33	0.34	+3.03
	Turbidity (NTU)	26.5	26.7	+0.75

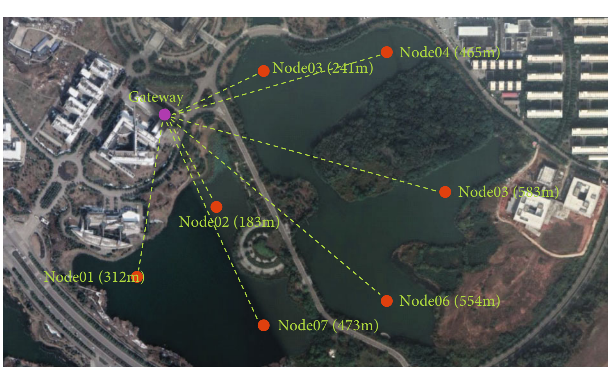

Figure 12: Partial deployment diagram of the experiment.

transmission performance of system at different distances, the test distance is changed by moving the position of the LoRa gateway during the experiment.

In the test of transmission communication distance, in order to test the nodes to be able to communicate normally within the range of 2 km, a node is fixed on the southernmost bank of Tianyin Lake during the experiment. Then LoRa gateway is simulated and tested once every 400 m horizontal distance from the top of an empty building. The relationship between measured RSSI and distance is shown in Figure 13.

From the experiment results, the communication success rate between nodes and gateway is 100% within 1.6 km. The communication success rate is about 94% at 2 km, and signal strength is within the reliable range. It also shows that water quality monitoring node within the diameter of 2 km can normally complete the water area monitoring task. The gateway only needs to upload node data in the range to the equipment management platform to realize distributed remote monitoring of a large area of water.

At the same time, in order to verify system reliability in the data transmission process, PLR of wireless transmission between LoRa water quality monitoring node and LoRa gateway is tested under different transmission distance conditions, and the experimental method is the same as testing WiFi and ZigBee [29, 30]. The size of each packet of data is 9 bytes, using CRC check, and test distance is 0 ~ 2KM. The transmitting power of RF module is 20 dBm, and the

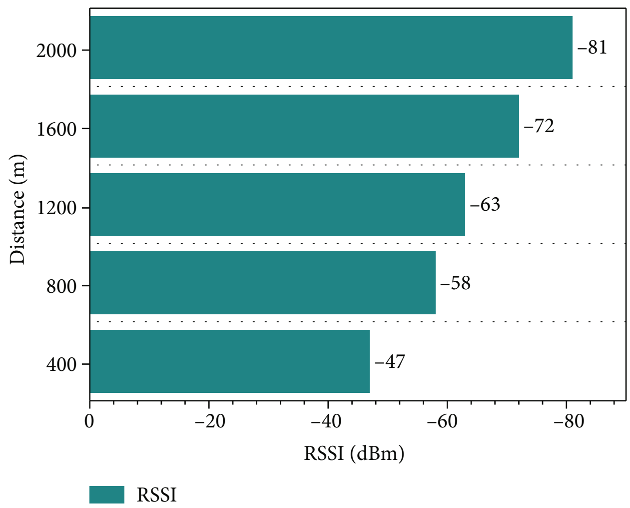

Figure 13: The relationship between transmission distance and RSSI.

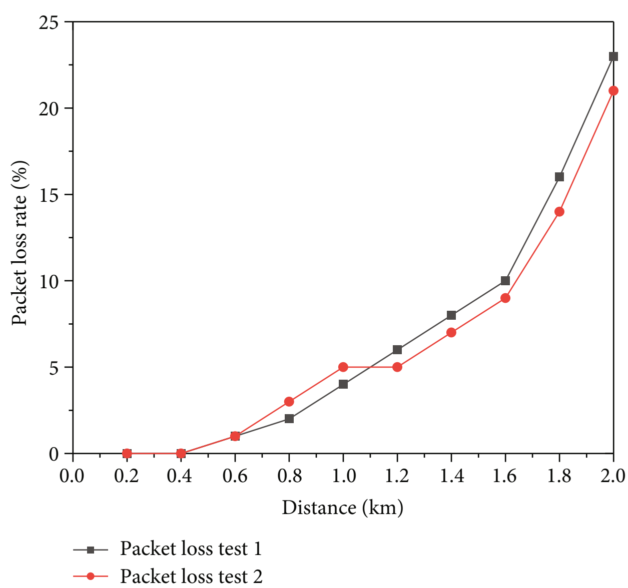

Figure 14: The relationship between transmission distance and PLR.

antenna gain is 3 dbi. 1000 data packets are sent and received for each test distance, and the test is performed twice. After comparing and analyzing data packets at each point, the relationship between transmission distance and PLR is shown in Figure 14.

It can be seen from Figure 14 that in the range of 1.6 km, PLR of the entire network is below 10%, and no packet loss occurs in the test within 400 m. Within the range of 1.6 ~ 2 km, PLR was successfully controlled within 25%, which was within the allowable range of system performance.

After the analysis of the above experiments, it can be concluded that LoRa is able to build a more reliable node network and a longer communication distance in the field

Table 5: The experiment result table of alarm response.

Item (threshold)	Test times	Node number	Alarm response times	Average response time (s)
Water temperature (>21°C)	10	0 × 01	10	9.84
		0 × 02	10	9.23
		0 × 03	10	9.46
		0 × 04	10	9.57
pH (pH < 6 or pH > 9)	10	0 × 01	10	9.71
		0 × 02	10	9.08
		0 × 03	10	9.42
		0 × 04	10	9.53
Turbidity (>50 NTU)	10	0 × 01	10	9.68
		0 × 02	10	9.21
		0 × 03	10	9.39
		0 × 04	10	9.62

in a 2 km range in complex terrain than traditional communication solutions such as ZigBee and WiFi, which are less penetrating and only have an effective communication distance of about 100 m [31, 32].

6.3. Alarm Experiment of Lake Water Quality Monitoring System. In this paper, the monitoring research is mainly carried out for water temperature, pH, conductivity, and turbidity of water area to be measured. Among the four types of parameters measured by this system, water temperature, pH, and turbidity are direct indicators that reflect the water quality of landscape waters. According to the water quality standards for landscape and recreational water of People's Republic of China, the water temperature of landscape water body should not be higher than the average temperature for the month of the past ten years, 4°C, pH value should be in the range of 6.5 ~ 8.5, and the turbidity of ornamental water body should not be higher than 50 NTU.

Based on the above standards and average temperature in Nanjing in the past 10 years (about 17.1°C) in November, this study set the water temperature threshold in the node alarm program to be less than 21°C. The pH threshold reference standard is set to be greater than 6.5 and less than 8.5, and the turbidity threshold reference standard is set to be less than 50 NTU.

The system's response speed and success rate to water pollution alarms are important indicators to measure its reliability. In order to verify the response speed of nodes to severe changes in water quality and the success rate of uploading alarm information, human intervention is used to change water quality parameters of the solution to be tested, performed 10 measurements on four groups of nodes, and calculated the average response time of each group. The experiment results are shown in Table 5.

According to the experimental results in Table 5, when water environment parameters are artificially changed, the system can correctly alarm the abnormal water temperature, pH value, and turbidity and upload the abnormal data to equipment management platform. And the alarm success rate of the four groups can reach 100%, and the response time is less than 10 s. The experimental results show that the system can be sensitive to reflect the deterioration of water quality, helping managers to obtain timely information, so as to further implement the decontamination strategy.

7. Conclusion

In order to conduct all-weather and highly reliable monitoring for a large range of waters, this paper designs a distributed water environment monitoring system based on LoRa and IoT. Specifically, software and hardware such as water quality monitoring nodes embedded LoRa gateways, and remote user monitoring systems are designed and implemented. The whole set of LoRa and IoT system realizes the functions of water quality data collection, remote monitoring, and water environment pollution early warning of target lake. Besides, the field experiments in Tianyin Lake in Nanjing Institute of Technology are conducted.

After experimenting, the water temperature monitoring accuracy system of target water area is maintained at $\pm 0.15^{\circ}$C, and average relative monitoring error is 0.31%. The pH monitoring accuracy is between ± 0.08, and average relative monitoring error is 0.28%. The conductivity monitoring accuracy is within ± 0.03 mS/cm, and average relative monitoring error is 3.96%. The accuracy of turbidity monitoring is within ± 0.5 NTU, and average relative monitoring error is 0.71%. The system can achieve a 100% communication success rate within 1.6 km, and PLR can be controlled within 10%. In addition, the success rate of the water quality alarm response is 100%, and the average response speed is less than 10 s. It can be concluded that distributed water environment monitoring system proposed in this paper can provide accurate data, stable and reliable transmission, and timely alarms for water environment monitoring and management.

The system currently uses battery-powered mode. Moreover, solar power, wind power, and water power can be further adopted considering the saving of manpower for battery replacement and system durability and wide-area considerations.

In addition, this paper currently implements data collection and remote monitoring and alarms. However, intelligent prediction of future water quality changes is more promising in the actual water quality monitoring problem. Therefore, we will organize water quality dataset collected by LoRa water quality node in the follow-up research. Furthermore, machine learning algorithms such as Long and Short-Term Memory network (LSTM) are used to establish water quality prediction model to realize the water quality prediction applications in the monitored water area.

Data Availability

The data included in this paper are available without any restriction.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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