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A ZigBee-based Aquiculture Water Quality Monitoring System

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Abstract

To overcome the issues of many monitoring measurement points, wide range, complex working environment and difficult link in aquaculture monitoring, a low-cost, low-power real-time ZigBee-based water quality monitoring system is presented. The system collects, transmits, displays, queries the water quality parameters (the temperature, dissolved oxygen concentration, pH value, and water level) and controls the increase oxygen machine. The low-power MSP430F149 and CC2530 RF chip are the core of the system which is constituted with the sensor nodes, routing nodes and coordination nodes. The time synchronization algorithm enables all nodes in the network sleep and wake up synchronously to ensure the reliability of data transmission and reduce power consumption. The test results illustrate that the network packet loss rate is 0.83% when the distance between the two nodes is 80 m, which meets the demands of aquiculture. The system runs stably, measures accurately and can automatically regulate the water quality, has certain market value and wide prospects of application.

Keywords: *ZigBee, water quality monitoring, aquiculture monitoring*

1. Introduction

The high-density, industrialized aquaculture results in the deterioration of the water quality environment. The baits and metabolites will pollute the water environment, affect the fish growth, and even cause the mass outbreaks of disease. It is an urgent problem to establish an automatic water environment monitoring system with perfect function, stable performance and medium price. It can accurately measure and adjust the water parameters such as the temperature, dissolved oxygen concentration and pH value to obtain the optimal water environment that is suitable to the growth of fish. Thus, a stable and high yield is earned [1-3].

The traditional water quality monitoring for aquaculture often utilizes the instruments and artificial experience. It has many defects such as time-consuming, incomplete data, scattered monitoring locations and long monitoring period, which can not real-timely and accurately reflect the dynamic changes of the water environment. The water monitoring system using the field bus has issues in difficult routing and construction, vulnerable line, poor flexibility and reliability, high maintenance cost and limited monitoring range. The water quality regulation way, which relies on water changes, boiler heating and aeration, acquires the economic benefits at the expense of depleting resources and destroying environment. The mechanical equipments are manually controlled. It not only causes the waste of human resources, and the control role is limited. The slight mistake easily leads to a large area of fish death due to suffocation. It has become particularly important to establish the automatic water quality parameter measure and control system to save water resource and improve breeding efficiency.

The wireless sensor network consists of inexpensive sensor nodes and forms the network system by a self-organizing way. The node can move freely, without laying lines [4-6]. The operation is simple. It is very suitable to the field of water quality monitoring.

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The short-range wireless networking communication technology based on ZigBee protocol has the advantages of low power, low cost, safety and reliable data transmission, short time-delay, flexible network, robustness, strong fault-tolerance, high node capacity, high security and good compatibility [7-9].

A water quality monitoring and control system based on ZigBee wireless sensor networks is proposed to meet the specific requirements of aquaculture. The water temperature, pH value and dissolved oxygen concentration are real-timely acquired, remotely transmitted by the wireless way, monitored, and automatically controlled. It has little impact on the water environment, covers the wide area and saves the manpower and time. The system is supplied by the battery, without the municipal electric power. The flexible wireless system is realized.

2. System Architecture and Key Technologies

The system consists of the sensor nodes, the routing nodes, the coordinator nodes, the control nodes, the local monitoring center and the remote monitoring center, as shown in Figure 1. The sensor nodes and routing nodes distribute in the various ponds and constitute a tree by the self-organizing networks. The sensor nodes collect the water parameter data, convert into the digital signal and upload to the routing node by the ZigBee wireless communication protocol. The routing nodes receive the data collected by the sensor nodes and process the data. The system can set its own water quality standards. Once the abnormal data (emergency data) are detected, the system will alarm, start the control node to regulate the water quality and immediately upload to the coordinator node. The coordinator node receives the data and alarm information from each routing node, transfers the data to the local monitoring center and receives the commands from the monitoring center to modify the parameters and synchronize the sleep and wake of the nodes to reduce the power consumption. The coordinator node sends the alarm messages to the user's mobile phone via GPRS module or transmits data to a remote monitoring center by accessing the internet. The key technologies are:

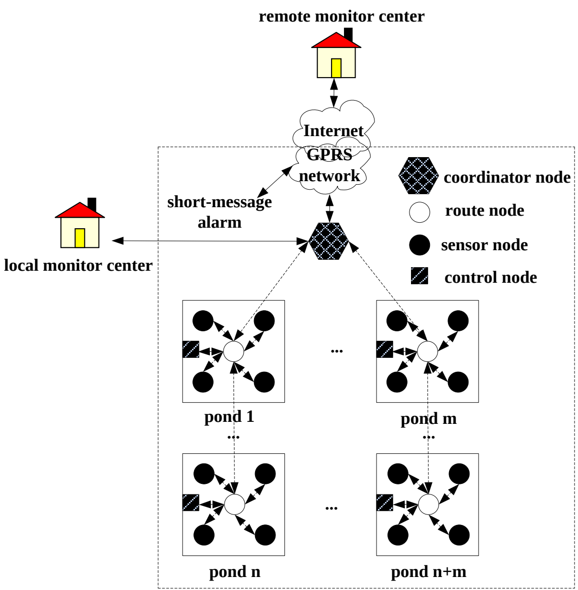

Figure 1. Systematic Entirety Structure

(1)The accuracy of the water quality parameter measure is improved from the sensor selection, signal conditioning circuit design, ADC accuracy, wireless networking and so on. The sensors utilize the high-performance water quality sensors. The signal conditioning circuit adopts the instrument amplifier with high input resistance as the key device to process the weak electrical signals from the sensor. The 12-bit ADC built-in the microcontroller chip is used to meet the requirement of the conversion accuracy. The dynamic networking based on ZigBee wireless communication protocol achieves a wide range of monitoring network coverage.

(2)The stability of the system is improved. The low failure rate and long-term working underwater sensors are chosen to ensure the reliability of data collection and reduce the maintenance costs. The built-in high-performance ADC of the microcontroller chip can reduce the area of the printed circuit board. The fault rate is also decreased. The lightning proof and anti-jamming measures are implemented. The photocouplers are installed in the serial ports, and the lightning protection devices in the communication line. The software is repeatedly tested to clear the troubleshooting. The watchdog timer is reset when the unforeseen circumstances happen.

(3)The flexibility and expansibility are strong. The system has flexible wireless networking. It can increase or decrease the number of network nodes according to the needs. It is easy to maintain and install. The local monitoring center can set the sampling period, modify the water quality standards. The flexibility and operability of the system is stronger.

(4)The power dissipation is low. The sleep cycles of the network nodes are regulated according to the sampling cycle. The nodes are waked up and slept synchronously. If the water quality parameters collected by the sensor nodes do not exceed the limit, they are uploaded to the routing node every 24 hours to reduce power consumption.

3. System Hardware Architecture

Since the large number of nodes in the sensor networks are powered by lithium batteries, the system hardware design needs to consider comprehensively the performance, cost, power consumption and expansibility.

2.1. Hardware Design of the Sensor Node

The sensor nodes are the core element of the network. They complete the field data collection, data preprocessing and data communication to achieve the 24-hour online monitoring of the water parameters in the sampling point. The circuit structure is shown in Figure 2. The sensor nodes collect data once every 30 minutes. The analog output signals are processed via the signal conditioning circuit to filter the interference, amplify and shape, and then fed to the built-in analog-to-digital converter of CC2530 chip to obtain the digital signal. After the pretreatment by the enhanced 8051 processor, it is stored into the EEPROM. After the timer is time out, the stored data are packed into the required format and sent to the routing nodes. If the data exceed the limit, they are marked as urgent data and immediately sent. The sensor nodes can also receive the control commands from the routing nodes to set the parameters and synchronize the time. In order to improve the reliability of communication, the CC2591 chip can be added between the antenna and the CC2530 chip in the routing node.

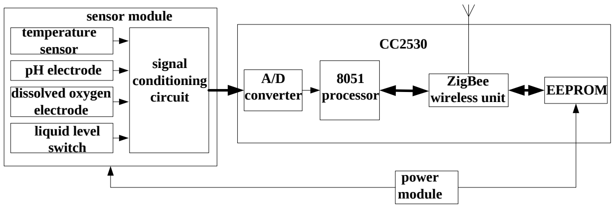

Figure 2. Circuit Block Diagram of the Sensor

2.1.1. CC2530 Wireless Communication Chip: The 2.4GHz RF transceiver CC2530 supporting the IEEE 802.15.4 standard integrates a high-performance and low-power 8051 microcontroller core, 256 KB in-system programmable flash and 8 KB RAM and so on. The sleep current is as low as 1μA. It has 8-channel 12-bit ADC, and can connect to a variety of sensors and control circuits. The external circuit is shown in Figure 3.

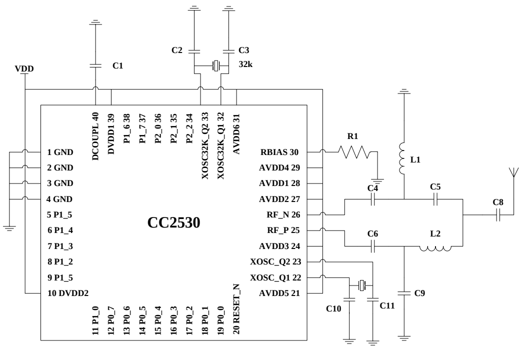

Figure 3. Periphery Circuits of the CC2530

2.1.2. Sensors and Signal Conditioning Circuits: The dissolved oxygen concentration is the oxygen molecules in the water. The aquatic plants and animals survive only in the appropriate oxygen conditions. The weak current output signal of the polarographic-type dissolved oxygen sensor is in uA order, which has a linear relationship with the dissolved oxygen of the measured solution. According to Faraday's law:

$$c = IL / FnAD \tag{1}$$

Where, c is the dissolved oxygen concentration, I is the diffusion current, L is the thickness of the antireflection film, F is the Faraday constant, n is the number of electrons participating in reaction, A is the cathode area, D is the diffusion coefficient of the antireflection film. The output current of the sensor is converted into voltage via the fine current detection device, and then fed to the built-in analog to digital converter of CC2530 to process.

The effect of pH value on aquatic organism is through every stage of its growth. The cathode of pH composite electrode is connected with the reference solution of a known concentration, and the anode is connected with the test solution. When the ion concentration of the tested solution changes, a voltage difference between the cathode and anode is generated. The electric potential difference is proportional to the degree of hydrogen ion activity in solution. The pH value satisfies the Nernst equation:

$$E = E_0 - 2.30259RT\ pH / F = E_0 - kTpH \tag{2}$$

Where, E is the electromotive force of the measured electrode, E_0 is constant, R is the gas constant, T is the absolute temperature of the measured solution, pH is the pH value of the measured solution and F is the Faraday constant. From the above equation, the output electromotive force is affected by the pH value and temperature of the measured solution.

The pH electrodes need to be corrected before using. If the measured solution is alkaline, the standard buffer solutions with the pH value of 6.86 and 9.18 are chosen to correct. If the measured solution is acidic, the standard buffer solutions with the pH value of 4.00 and 6.86 are chosen to correct. When the temperature is t_1, the output electromotive forces at the both standard buffer solutions are as follows:

$$\begin{cases} E_1 = E_0 - K_1 pH_1 \\ E_2 = E_0 - K_1 pH_2 \end{cases} \tag{3}$$

Solving the equations can obtain:

$$E_0 = (E_1 pH_2 - E_2 pH_1) / (pH_2 - pH_1) \tag{4}$$

The temperature coefficient is:

$$K_1 = (E_1 - E_2)/(pH_2 - pH_1) \quad (5)$$

The E_0 and K_1 are stored in EEPROM to compensate the temperature of pH electrode.

The output voltage signal of the mV-level from the pH electrode is amplified and filtered by the signal conditioning circuit, then fed to analog to digital converter of CC2530. The pH electrode has a large resistance, so the operational amplifier INA116 with high input impedance, high precision, wide frequency bandwidth and high common-mode rejection ratio is chosen as the first stage of the signal conditioning circuit. The remaining two operation amplifier adopt OP07 chip. The circuit is shown in Figure 4.

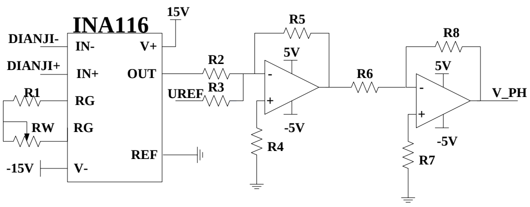

Figure 4. Signal Conditioning Circuit of the pH Electrode

The water level in the pond does not require precise measurements. It is to be determined is whether the water level is within the required top and low levels. The double-level float liquid switch is used. When the water level is below the low limit or above the upper limit, the system alarms. The output signal is fed to CC2530 after processed by the logic circuit.

2.2. Routing Node

The routing nodes play the role of data transfer. They receive the data sent by the sensor nodes and retransmits to the coordinator node. Also they convey the commands from the coordinator node to the sensor nodes. If the received data are abnormal, the routing node communicates with the control node. The corresponding device is started to control automatically. The structure of the routing node is similar to the sensor nodes, but without the sensors and conditioning circuits.

2.3. Control Node

The control nodes adjust the water quality parameters of the breeding pool. The CC2530 chip in the control node receives the control command and parameters from the routing nodes and operates the inlet valve, the outlet valve, pumps and oxygen increasing machine via the photocoupler, relays and actuators. The circuit structure is shown in Figure 5.

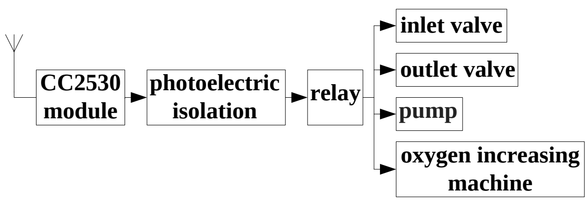

Figure 5. Circuit Block Diagram of the Control Node

2.4. Coordinator Node

The coordinator node organizes the ZigBee network, transmits and receives the data and control commands in the network, and communicates with the local and remote monitoring centers. The circuit diagram of the coordinator node is shown in Figure 6.

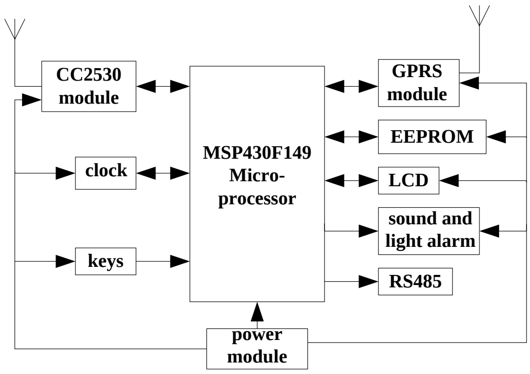

Figure 6. Circuit Block Diagram of the Coordinator Node

The TI's MSP430F149 microprocessor is the core of the circuit. The radio unit CC2530 is adopted to communicate with the routing node. The GPRS module is utilized to communicate with the remote monitoring center. The RS485 bus is connected to the local monitoring center. The coordinator node can automatically store data, real-timely display the query results by the LCD and keys. The users can query the water temperature, pH value, dissolved oxygen concentration and battery charge of the pond by selecting the node's address.

3. System Software Design

Due to the differences of crystal accuracy, external interference and many other factors, the time deviations occur among the nodes. The deviations continuously accumulate, and may lead to the communication failure of the nodes. The time synchronization [10] method is adopted in this paper to make the nodes sleep and wake up synchronously. The power consumption is decreased correspondingly. The coordinator node sends the time synchronization instruction to each node in the network. The sensor and routing nodes transmit the collected water quality parameters to the coordinator node within their respective time slices.

3.1. Program Design of the Sensor Node

The sensor nodes are responsible for sensing the changes of water quality parameters and sending the data to the routing node. The sensor nodes can only communicate with the routing node. There is no communication between two sensor nodes. The program flow of sensor nodes is shown in Figure 7. After initialization, the sensor nodes start to search the network, then send a request for accessing the network. The address of the node is distributed when it is connected to the network. The sensor nodes acquire the water quality parameters at regular intervals. When acquiring the data, the sensor nodes start the timer for uploading data, control the built-in ADC to digitize voltage signal from the signal conditioning circuit, process data and store into EEPROM. If the data exceeds the set threshold, it is marked as urgent. It is packaged into the pre-set data format and immediately uploaded to the routing node. If the data does not exceed the threshold value, it is marked as general data. The data is stored to EEPROM and uploaded every 24 hours. Once no events occur, the sensor goes into sleep mode until the start of a new round of data collection to reduce the power consumption.

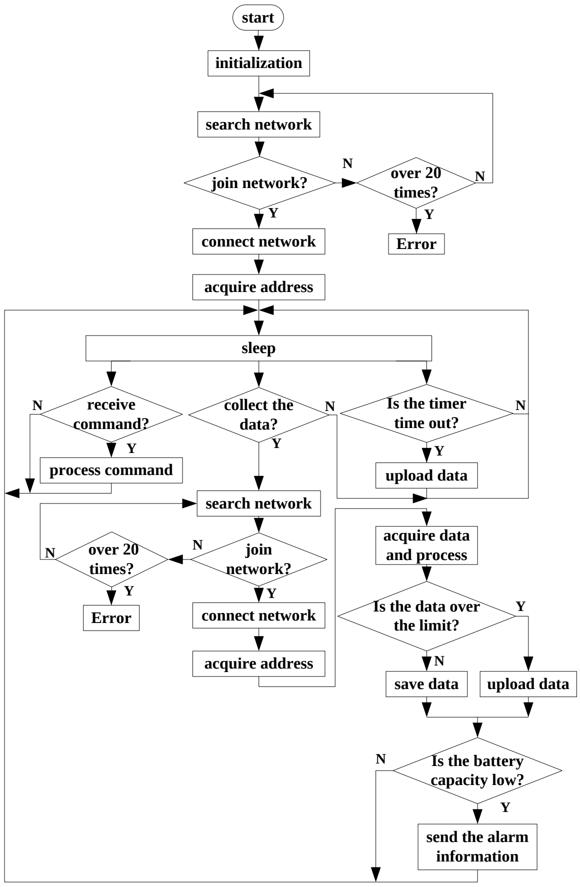

Figure 7. Software Flow Diagram of the Sensor Node

3.2. Program Design of the Routing Node

The routing node is responsible for uploading the data and conveying the instructions. After initialization, the system starts to search and access the network. If the routing node receives the access request from the sensor node, it check the sensor node information and assign an address. If the routing node receives the instruction from the coordinator node, it forwards to the sensor nodes within the region. If the routing node receives the data from the sensor node, it uploads the data to the coordinator node during the prior appointed time slice.

3.3. Program Design of the Coordinator Node

The coordinator node is responsible for founding and maintaining the wireless sensor network, issuing the command, receiving and transmitting the data. The program flow chart is shown in Figure 8. After the coordinator node is initialized, it firstly founds a new network and allows other nodes to join. The data and instructions between the coordinator and the remote monitoring center are transmitted via the GPRS module.

4. Test Results

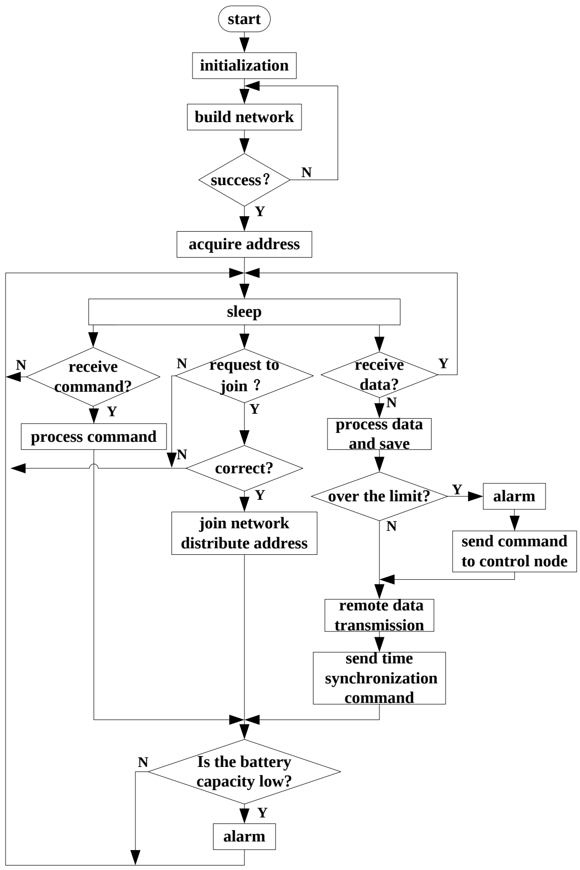

Figure 8. Software Flow Diagram of the Coordinator Node

A point to point test is performed to verify the stability and reliability of the wireless sensor network communications. The results are shown in Table 1. The number of transmitted data packets is 4,000. Adjust the distance between the two nodes to be 20, 40, 60, 80, 100 meter away respectively, count the number of received packets, and compute the packet loss rate of the network. The test results show that the packet loss rate is less than 2%, which meets the design requirements.

Table 1. Results of Point to Point Tests

communication distance(m)	sent packets	received packets	packet loss rate(%)
20	4000	3998	0.05
40	4000	3992	0.2
60	4000	3981	0.48
80	4000	3967	0.83
100	4000	3933	1.68

To verify the correctness of water quality data collection and transmission, the test of the whole system is performed. A sensor node is deployed in each of the four breeding pools, and a coordinator node is deployed in the local monitoring center. Four routing nodes are deployed between the sensor nodes and the coordinator node. The coordinator node is connected to the computer of the monitoring center via the RS485 interface. The sensor nodes collect the data at every 5 min intervals. The monitoring has been continuous for five days. The system runs smoothly. The test data of the 5-day at the same time point are averaged. The result is shown in Table 2. The test results show that the system can accurately capture water quality parameters. The data transmission in the wireless sensor network is stable and reliable, which meets the requirements of aquaculture.

Table 2. Results of the Water Quality Parameter Tests

monitoring point	Temperature (℃)	pH value	dissolved oxygen(mg/L)
1	21.4	7.3	6.6
2	21.2	7.3	6.7
3	21.2	7.5	6.6
4	20.9	7.4	6.5

5. Conclusions

A water quality monitoring system based on wireless sensor networks for aquaculture is presented in this paper to realize the water parameter acquisition and real-time online monitoring. The MSP430 chip is the core of the system that is battery-powered. The wireless technology is applied in the whole monitoring system. The water quality parameter data collected by the sensor nodes are uploaded to the coordinator node via the routing nodes. The wireless sensor network communicates with the remote monitoring center through GPRS module. Based on the measurement results, the control node can automatically adjust the oxygen increasing machine and pump to realize the automatic monitoring, remote wireless transmission and short message alarm. The time synchronization algorithm is utilized to enable all nodes in the network wake up and sleep synchronously. The power consumption is reduced, and the reliability of data transmission is improved. A consecutive 5-day real-time monitoring of the water quality parameters is performed to verify the accuracy of the data collection and reliability of the network communication. The test results show that the system runs smoothly, and the measures are accurate and reliable. When the communication distance is 80 m, the packet loss rate of the network is 0.83%, which meets the needs of real-time monitoring of water quality in aquaculture. The system is characterized by perfect function, medium price, strong extensibility, low power consumption, and has broad application prospects.

Acknowledgments

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