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Research Paper

A wireless sensor network-based monitoring system for freshwater fishpond aquaculture

Bing Shi [a,*], Victor Sreeram [b], Dean Zhao [c], Suolin Duan [a], Jianming Jiang [a]

[a] School of Urban Rail Transit, Changzhou University, Changzhou 213164, PR China
[b] School of Electrical, Electronic and Computer Engineering, University of Western Australia, Perth 6009, Australia
[c] School of Electric Information Engineering, Jiangsu University, Zhenjiang 212013, PR China

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Cabled intelligent systems bring with them the complexities of structures, the complications of data measurements and transmission, and a limited scale of application. A wireless sensor network is used to eliminate these disadvantages, however reliability of data transmission and energy saving in a wireless sensor network are two challenges that still need to be addressed. The design information on three types of nodes in a wireless sensor network is described in detail. Tree topology for WSN is adopted to decrease the packet loss rate and improve reliability of data transmission. Allowing sensor nodes to sleep and reorganising the data frames are the two approaches used to achieve energy-saving. The experimental results demonstrate the usefulness of these approaches in solving the challenges.

1. Introduction

In 2016, the national total output of aquatic products in China was 69 Mt, of which 32 Mt (46%) were freshwater aquatic products. The freshwater aquaculture area was 6.18×10^5 ha, of which 2.76×10^5 ha (44.71%) were freshwater fishponds. There is a huge increase in demand for freshwater aquatic products in China. However, the total aquaculture area is rapidly diminishing because of industry's need for land. For example, the annual national decrease in total aquaculture area was 0.9% in 2015 and 1.4% in 2016 (Wang et al., 2017).

To alleviate the situation, some intelligent systems which can contribute to increased production and reduced costs are being applied in freshwater aquaculture to monitor important water environmental variables in real time, such as dissolved oxygen (DO) concentration in water, water temperature, pH etc. (Simbeye & Yang, 2014; Simbeye, Zhao, & Yang, 2014).

Siemens Corporation developed a system for monitoring 5 to 12 online water parameters in 2011 (Jawad, Nordin, Gharghan, Jawad, & Ismail, 2017). The American YSI Corporation also developed the YSI5200 aquaculture monitoring system for monitoring six kinds of water quality parameters in 2008. Researchers from the Chinese Academy of Fishery Sciences developed a multi-point online water quality testing

* Corresponding author.
E-mail address: shibing@cczu.edu.cn (B. Shi).

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system which can simultaneously monitor six water parameters in 2010. Scientists from Jiangsu University in China, developed a distribution monitoring system to determine a variety of key water parameters in real time, and the system had capacity for wireless data transmission in 2011 (Huan, Liu, & Chong, 2014; Huang et al., 2013). However, most of these existing monitoring systems, utilised in freshwater fishpond aquaculture, exchange information between the remote intelligent unit and monitoring computer through cable transmission. Cable communication systems carry many wires which results in a complex system and complications of data measurements and transmission. Moreover, such systems, once deployed, are inconvenient to expand to cover more targets. Further development of the freshwater fishpond aquaculture industry based on a cable communication system is limited, as cable communication systems are more suitable for a simple and small-scale scenario.

A wireless sensor network (WSN) is a kind of wireless network working on the IEEE 802.15.4 technical standard which consists of sensor nodes, routing nodes and a gateway node. The data generated in the networks are transmitted by means of one-hop or multi-hop to a gateway node. A WSN is often used to monitor situations in a region, such as environmental protection, traffic administration, even military surveillance. Some research projects on WSN have been launched in the US and Europe, and the technology of WSN has been applied in environmental monitoring in agriculture. In 2002, the Intel Corporation took the lead to create the first wireless vineyard in the State of Oregon (Duy, Tu, Son, & Khanh, 2015; Ma, Zhao, Wang, Chen, & Li, 2015). An animal farming centre in Australia deployed wireless sensor nodes on the animals to monitor physiological states, such as pulse, blood pressure, etc. (Adu-Manu, Tapparello, Heinzelman, Katsriku, & Abdulai, 2017; Ndzi et al., 2014). Researchers in Brazil developed a remote-control system based on WSN to monitor 1500 ha of farmland irrigation (Jiang et al., 2014; Rashvand, Abedi, Alcaraz-Calero, Mitchell, & Mukhopadhyay, 2014). Chandanapalli, Reddy, and Lakshmi (2014) designed an aqua monitoring system using WSN and IAR-Kick. Most research in the area of WSN in China focuses on fine detail management of field farming.

In this study, we introduce a WSN system for freshwater fishpond aquaculture to monitor DO concentration and water temperature in a freshwater fishpond. A feasible topology for the WSN system is confirmed and two energy-saving strategies are adopted after taking into account the reliability of data transmission and WSN node survival.

2. System overview and work principle

Figure 1 shows the architecture of the system. It consists of three elements: the WSN unit, the monitoring centre, and the remote clients.

The WSN unit is the fundamental element for the system, and is responsible for measuring some important environmental variables such as DO concentration and temperature in the fishpond water. The WSN unit consists of a number of WSN sensor nodes, some routing nodes and one gateway node. The gateway node automatically creates the wireless network and administrates it according to default or manual configurations. The gateway node is responsible for not only accepting data from sensor nodes, but also transmitting them to the monitoring computer in the monitoring centre for further processing using the GPRS module. Meanwhile, the sensor nodes are connected to different kinds of sensors through sockets, and are responsible for measuring variables in the water of targeted fishponds in real time. The collected data are transmitted to the gateway node by one-hop or multi-hop according to the topology of the WSN. The routing nodes work as route planners to find the best route to the gateway node for the data that originate far from the gateway and only reach the gateway node by multi-hop. Finally, the gateway node, the sensor nodes and the routing nodes all work together to achieve the tasks of measurement and transmission.

The monitoring centre has three essential pieces of equipment which are the monitoring computer, the database server and the web server. The monitoring computer works as a communication server, it accepts data transmitted by the remote gateway node and then uploads these data to the database server in the monitoring centre. All these transmissions are achieved via internet. In addition to the processes mentioned above, the monitoring computer also aggregates data and displays them in graphical user interface. The database server, running on Microsoft SQL Server 2013,

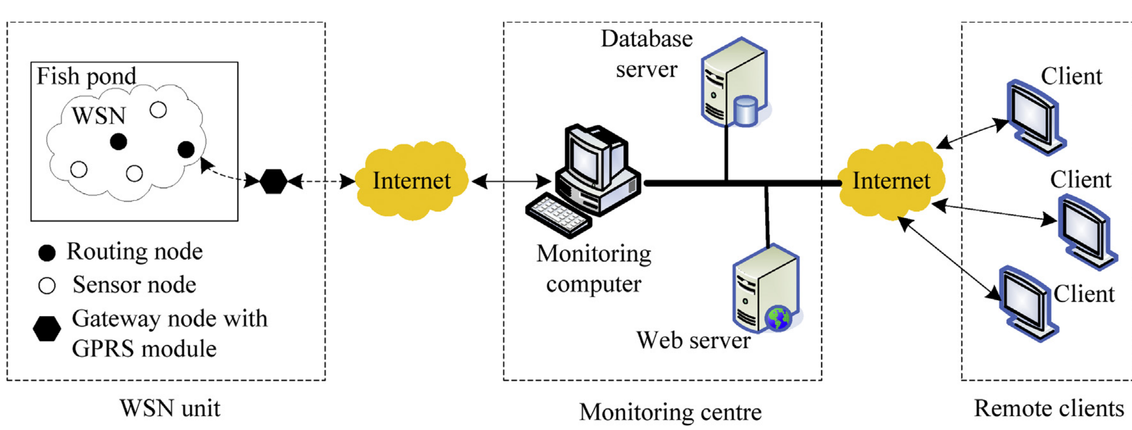

Fig. 1 – Architecture of the system.

can store and manage all kinds of data, and data of DO concentration and water temperature are stored there. The database server is also the data source for the web server. Meanwhile the software for the web server is developed with ASP.NET technology and the programming platform is embedded in MS VS 2010 which is an integrated development environment (IDE). The Web server is responsible for offering information services for remote administrators to observe the environmental variables using browsers, such as Microsoft Internet Explorer (IE) and Google Chrome, without installation of any special software (Jiang et al., 2014; Li, 2014). In most situations the web server needs data support from the database server to respond to requests from remote clients who are authorised to access these information services.

3. Design for wireless sensor network unit

3.1. Topology for the wireless sensor network

An appropriate topology can not only ensure that the sensor nodes cover the targeted area as far as possible, but also ensure smooth communications. There are three common topologies for WSN: star network, tree network, and mesh network (Fig. 2).

A star network consists of two kinds of nodes: sensor nodes and one gateway node. Sensor nodes only transmit data to the gateway node by one-hop without communications between them. This topology has the advantages of simplicity of structure and energy-saving because it does not require route planning computations. However, it also has a significant disadvantage of limited distance between the furthermost sensor node and the gateway node, which is commonly about 25–35 m at an acceptable level of communication quality, dictated by one-hop communication (Andrewartha, Elliott, McCulloch, & Frappell, 2016; Xiaoman & Xia, 2016). Therefore this topology is often applied in small-scale scenarios, such as an office or courtyard, and is not suitable for applications in large-scale scenarios, such as in environmental surveillance or the aquaculture industry.

A tree network consists of three kinds of WSN nodes: a gateway node, routing nodes and sensor nodes. Communications between sensor nodes are still not permitted, and they each only transmit data to their own parent nodes. Routing nodes play very important roles as route planners running the algorithm of sensor protocols for information via negotiations to find the best way to a gateway node. A tree network has drawbacks of complexity of structure and less energy-saving (Basagni, Petrioli, Petroccia, & Spaccini, 2015; Cario, Casavola, Lupia, Petrioli, & Spaccini, 2017). However it overcomes the disadvantages of limited distance of communications as in a star network, making it suitable for application in large-scale scenarios. Usually there would be less than 10 routing nodes between a sensor node and a gateway node after balancing the complexity and cost of system relevant for the aquaculture industry.

A mesh network has the same three kinds of nodes as a tree network. Sensor nodes and routing nodes also work in the same way as their counterparts in a tree network (Chandanapalli, Reddy, & Davuluri, 2015). All routing nodes have the same status, and communications between them are permitted. A mesh network results in increased robustness of communications, but at a cost of higher energy consumption due to more calculations for complex route planning (Cheunta, Chirdchoo, & Saelim, 2014).

In this study, we applied the system to a fishpond (100 m in length, 60 m in width, and 2 m water depth). We tested all three topologies and adopted the optimal one to build the WSN after balancing the complexity, energy-saving and data packet loss, and the more detailed information is presented by experiments in Sections 5 and 6.

3.2. Hardware description for wireless sensor network node

All nodes (sensor nodes, routing nodes, and the gateway node) in the WSN adopt the CC2530 chip (Texas Instruments (TI)) as micro-controllers. The CC2530 combined with the Zigbee protocol stack (Z-Stack) developed by TI is a true System-on-Chip solution for IEEE 802.15.4 and Zigbee applications. The CC2530 chip combines the excellent performance of a leading RF transceiver with an industry-standard enhanced 8051 MCU with 256 KB of flash memory. Meanwhile the CC2530 also has an embedded ADC with eight input channels and various operating models that make the chip highly suitable for ultra-low power consumption (Choudhury & Kalita, 2014; Encinas, Ruiz, Cortez, & Espinoza, 2017).

Z-Stack is an implementation of the ZigBee specification. It is certified as a ZigBee Compliant Platform (ZCP) by the ZigBee Alliance. The downloaded Z-Stack installation package contains all of the documentation and software required to install, configure, and develop applications using Z-Stack. Z-Stack consists of the following components:

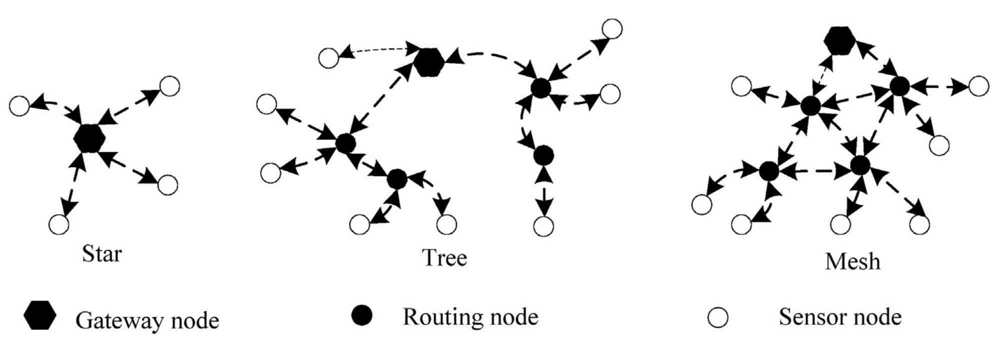

Fig. 2 – Common topology for WSN.

- HAL (hardware abstraction layer)
- OSAL (operating system abstraction layer)
- MAC on IEEE 802.15.4
- User application
- MT (monitor test)

Figure 3 shows the appearance of the motherboard for WSN nodes. The motherboard provides different sockets for connections to peripheral equipment, such as keyboard, LED indicator, and sensors.

3.2.1. *Sensor node of wireless sensor network*

The sensor node (Fig. 4) consists of the sensors, such as the DO sensor and temperature sensor, CC2530 motherboard and power module, in our case four AA batteries.

The sensor node is built based on a CC2530 motherboard, and sealed in a waterproof buoy fixed by the anchor. The digital sensor DS18B20 (Leici Corporation, Shanghai, China) responsible for measuring water temperature is connected to the enhanced 8051 controller through the general purpose I/O socket on the CC2530 motherboard. The analogue sensor DO-954A (Leici Corporation, Shanghai, China) is connected to the A/D converter embedded in the CC2530 chip and is used to measure DO concentration in water. The A/D converter converts the adjusted voltage signals from the DO sensor into digital signals for further processing. Table 1 provides the features of the two sensors.

3.2.2. *Gateway node and routing node*

The gateway node (Fig. 5) is also developed based on the CC2530 motherboard, without connection to any sensor. However, one GPRS module ME3000 (ZTE Corporation, Shenzhen, China) is connected to the motherboard through a RS232/USB cable interface.

The Gateway node in the WSN plays an administrating role which has two basic functions. Firstly, it is responsible for starting the WSN, dealing with requests for joining from any other nodes, and providing synchronous clock service, etc. Secondly, the Gateway node is considered as a data centre for accepting data transmitted by other WSN nodes such as sensor nodes and routing nodes, and also wirelessly sends them to a monitoring computer via GPRS module ME3000. The features of the GPRS module are shown in Table 2.

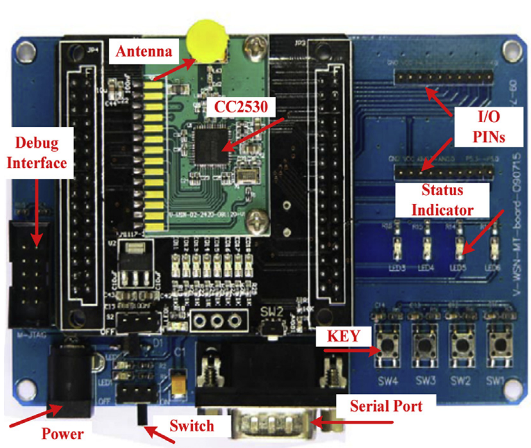

Fig. 3 – Appearance of motherboard for WSN nodes.

In regards to the routing nodes, the CC2530 motherboard provides sufficient hardware, and any peripheral equipment is no longer needed. The routing nodes also perform two basic tasks—the first is to find an optimal route to the gateway using the algorithm of sensor protocols for information via negotiations, and the second is to forward data from the sensor nodes to a next routing node. The gateway node and the routing nodes have almost the same hardware except the GPRS module, and the differences in functions between them are achieved by software programming.

3.3. *Software description for wireless sensor network node*

We use the platform of IAR Embedded Workbench as a tool to develop software for all WSN nodes based on the Z-Stack 2007 version which is a kit of software development (Texas Instruments Inc., TX, USA) (Faustine et al., 2014; Guerrero, Carrollton-Farmers Branch, Edwards, & Frisco, 2013).

The software for the gateway node has two basic functions—the first is to build the wireless network and manage it, and the second is to accept data from routing nodes and upload them to the remote monitoring computer via GPRS module ME3000. The software for the sensor nodes also has two necessary steps—the first is to apply to join the wireless network built by the gateway node, and the second is to measure the water variables and transmit them to routing nodes. Meanwhile, the most important task for the routing node software is to find the best route to the gateway node. Figure 6 shows the software flow for the each node.

Before the gateway node builds the wireless network, the topology of the network should be configured manually, and the more specific topology is shown in Fig. 7.

This tree topology has three levels in depth, the top level ($L = 0$) is the gateway node which is permitted to have a maximum of two children nodes, and a maximum of two routing nodes among their children nodes are allowed. Then every routing node at the middle level ($L = 1$) is permitted to have a maximum of five children nodes, and routing nodes are not allowed among them. There are only sensor nodes at the lowest level ($L = 2$), and sensor nodes cannot have any child nodes.

4. Energy saving strategies

Each WSN node in this system is powered by AA batteries. Energy saving is one of the most important tasks because a WSN node's life cycle heavily depends on it. In addition, WSN nodes are deployed on the surface of the fishpond, making frequent battery changing inconvenient. Therefore, energy-saving strategies are not only beneficial in extending the WSN node's life, but also in reducing the costs of maintenance. Any WSN node has four types of running mode, shown in Table 3 with their features (Nam et al., 2014; Parra, Sendra, Lloret, & Rodrigues, 2017).

The first way to save energy is to configure the software to allow the WSN node to sleep. Active mode is the default mode for a WSN node. This uses so much energy that it would drastically reduce the node's battery life. However, the

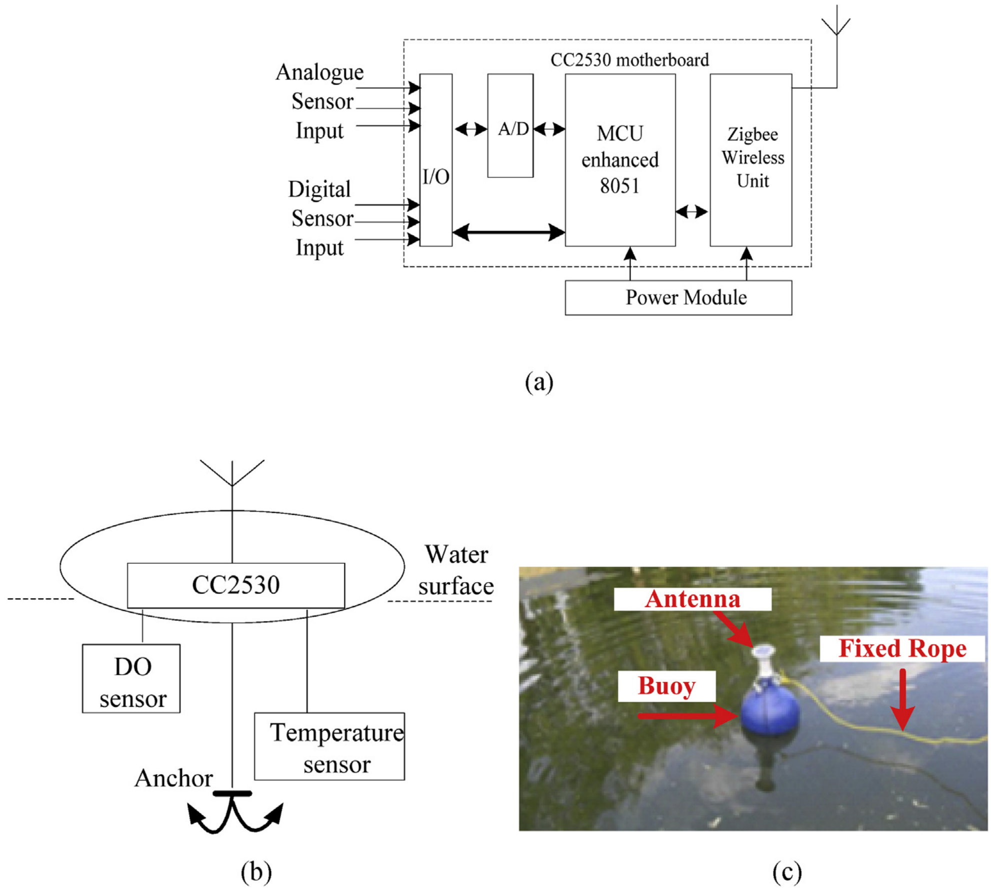

Fig. 4 – Sensor node: (a) schematic diagram; (b) appearance diagram; (c) physical appearance.

Table 1 – Features of the two sensors.

Item	DS18B20	DO-954A
Measurement range	−55 °C to +125 °C	0–20 mg L^{-1} (5–40 °C)
Output	Digital	Analogue voltage (mV)
Scenario	Water temperature	Aquaculture, environmental protection
Temperature compensation	Yes	Yes
Measurement precision	±0.5 °C (−10 °C to +85 °C)	±0.1 mg L^{-1}
Voltage	DC 3–5.5 V	DC 4–6.5 V
Cost	Around 0.8 USD	Around 100 USD

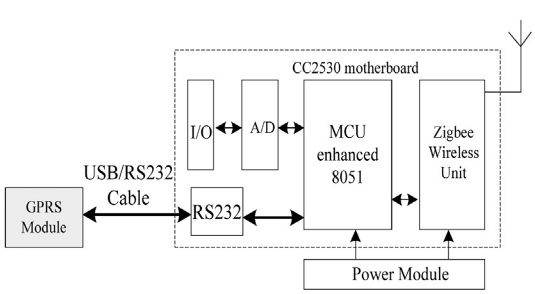

Fig. 5 – Gateway node.

Table 2 – Features of the GPRS module.

Item	Description
Voltage	DC 3.3–4.25 V: typical 3.9 V
Dimensions	30 × 25 × 2.68 mm
Ambient temperature	−40 °C to +80 °C
Frequency Band	850/900/1800/1900 MHz
Data rate	Download: 85.6 Kbps/Upload: 42.8 Kbps
Cost	Around 10 USD

battery-life can be extended by changing the running mode from active to one of the sleeping modes. PM3 mode is not suitable for this system because PM3 mode cannot be wakened by any inner timer except external interrupts. Either PM1 or PM2 mode is an option, but the latter is optimal because of its greater energy saving. We can modify the node's software to configure each node. After configuration, the system is allowed to enter PM2 mode.

The second way to save energy is to adopt a data merging technique to reduce the frequency of data transmission. For a sensor node, when water temperature is within ±0.5 °C of the last measurement, then the new measurement will be discarded. Likewise, the DO concentration measurement will also not be used when it varies within ±0.2 mg L^{-1}. Because of the predominantly stable conditions of fishponds, this

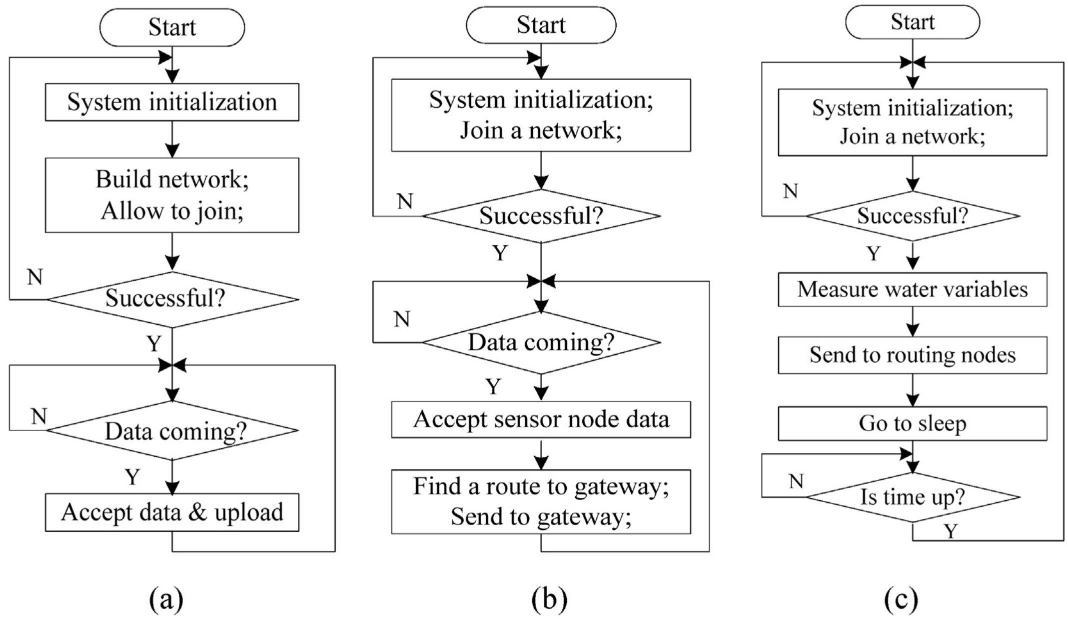

Fig. 6 – Software flow for WSN nodes: (a) gateway node; (b) routing node; (c) sensor node.

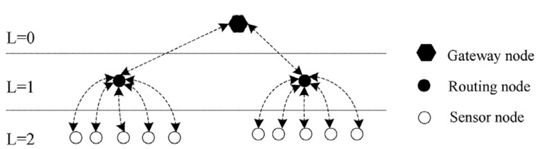

Fig. 7 – Specific topology for the WSN.

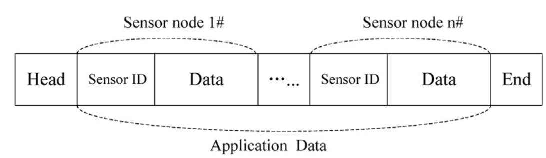

Fig. 8 – Structure of compound data frame.

Table 3 – Features of four types of running mode.

Mode	Description
Active	Full-function mode and all devices are powered.
PM1	The voltage regulator to the digital part is on. Neither the 32 MHz XOSC nor the 16 MHz RCOSC is running. Either the 32 kHz RCOSC or the 32 kHz XOSC is running. The system goes to active mode on reset, an external interrupt, or when the sleep timer expires.
PM2	The voltage regulator to the digital core is turned off. Neither the 32 MHz XOSC nor the 16 MHz RCOSC is running. Either the 32 kHz RCOSC or the 32 kHz XOSC is running. The system goes to active mode on reset, an external interrupt, or when the sleep timer expires.
PM3	The voltage regulator to the digital core is turned off. None of the oscillators is running. The system goes to active mode on reset or an external interrupt.

approach can significantly reduce the frequency of data transmission and contribute to energy saving. For a routing node, there is another way to cut down the frequency of transmission. We can reorganise a compound data frame by combining several original data frames from sensor nodes, and then the compound data frame can be transmitted to the gateway node. The gateway can recognised the data according to the sensor ID. Similarly, the gateway node also can use a compound data frame to decrease the frequency of transmission. The structure of a compound data frame is shown in Fig. 8. The length of a compound data frame is variable, but less than 127 bytes.

5. Materials and methods

5.1. *Packet loss rate experiments*

The first set of the experiments for the comparison of the effects on packet loss rate of three different topologies were performed in a fish breeding centre which is located in Shanghuang Town, Liyang County, Changzhou City, Jiangsu Province, China. The dimensions of the fishpond are 150 m in length, 50 m in width, and 2 m water depth. The experimental WSN (Fig. 9) had one gateway node, two routing nodes and nine sensor nodes. We respectively built the networks of star, tree and mesh through different software configurations based on these WSN nodes. We also developed test programs which could be downloaded to sensor nodes, routing nodes and a gateway node. Each sensor node respectively sent 200 packets, each of them the same 8-bit data, including the

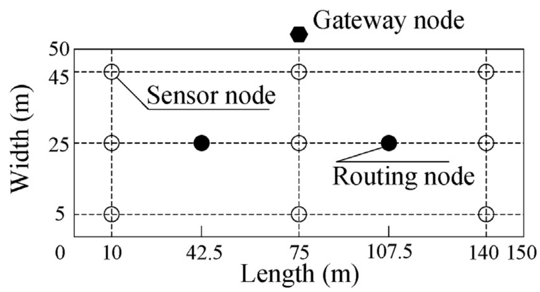

Fig. 9 – Deployment of WSN nodes.

node's ID, to the gateway node at different intervals. The gateway node calculated the number of packets from each node, and displayed them. This is a feasible way to assess the packet loss rate of different topologies at different intervals. The sending experiments were performed once, and repeated in each of the three networks.

5.2. *Dissolved oxygen concentration and water temperature experiments*

The second set of the experiments were performed in the same place as the initial experiments. The aim of these experiments was to verify the effects of the WSN system. Every sensor node was connected to four sensors: two temperature sensors DS18B20 for measuring the water temperature and two DO concentration sensors DO-954A. A pair of one DS18B20 and one DO-954A was deployed at the water depth of 1.9 m from the bottom, meanwhile another pair of one DS18B20 and one DO-954A at 0.1 m (Fig. 10(a)). The WSN topology (Fig. 10(b)) has the sensor nodes transmitting data to their common parent routing node, and then the data were forwarded to the gateway node.

5.3. *Energy-saving experiments*

The third set of the experiments were performed to verify the effects of the energy-saving strategies. We bought new 3000 mAh NANFU AA batteries (Nanfu Corporation, Fujian, China) and chose those batteries that were all equivalent in voltage, measured using FLUKE 12E voltmeter (Fluke Corporation, Washington, USA), to supply energy for nodes. Four batteries were connected in series to provide 6 V for each WSN node. During the experimental period, we measured the remaining voltage every 48 h using FLUKE 12E voltmeter, and then calculated a percentage of remaining energy by the following equation:

$$X = \frac{U_{remaining} - U_{cutoff}}{U_{initial} - U_{cutoff}} \tag{1}$$

where X, $U_{remaining}$, $U_{initial}$ and U_{cutoff} respectively are percentage of remaining energy, measured remaining voltage, initial voltage of batteries, and cut-off voltage of batteries. The values of $U_{initial}$ and U_{cutoff} in the experiments are 6 V and 4.4 V respectively for the adopted batteries.

In a sixty day experiment, we designed three phases with each phase lasting twenty days. In the first phase, each sensor node was designed to run in the Active mode; in the second phase, in the PM2 mode; and in the third phase, in PM2 and data merging mode. We replaced the new batteries for each node at the beginning of each experimental phase.

6. Experimental results

6.1. *Packet loss rate results*

Table 4 shows that the packet loss rates of three topologies for five sending intervals. A star network has the highest packet loss rate because data transmitted by three sensor nodes that are furthermost from the gateway cannot reach the gateway node due to the distance limit of one-hop transmission. A mesh network is more complex than a star and tree networks, and it offers more chances to reach the gateway. In comparison with a star network, the packet loss rate of a mesh network decreases for any sending interval in this experiment. However, more complexity also results in more possibility of conflicts of data, contributing to a slightly higher packet loss rate in a mesh network than a tree network. We can also observe that a higher interval between transmissions led to better performance for any topology because there were fewer package collisions due to simultaneous transmission.

A star network has a simple structure and a high efficiency of transmission, but it is often only used in a small-scale scenario because of the limits of transmission distance. A mesh network has a significantly greater reliability of transmission because multi-hop transmission is adopted, and it is often applied to a large-scale and massive node adopted scenario. For this fishpond scenario, which has a medium scale and a limited number of WSN nodes, a tree network is reliable and affordable.

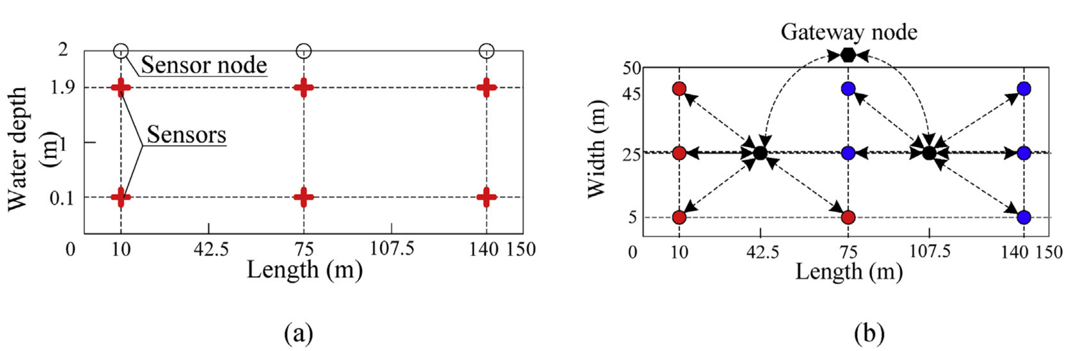

Fig. 10 – Measurement experiments: (a) deployment of sensors; (b) WSN topology.

Table 4 – Packet loss rate tests.

	Sending intervals				
	0.1 s	0.5 s	1 s	1.5 s	2 s
Star	42.5%	36.6%	33.3%	33.3%	33.3%
Tree	11.2%	7.5%	4.3%	3.2%	3.2%
Mesh	12.3%	8.7%	5.2%	4.3%	4.1%

Table 5 – Data from WSN at 11:00.

Position	DO concentration ($mg\ L^{-1}$)	Water temperature (°C)
(10, 5, 0.1)	4.2	9.6
(10, 5, 1.9)	6.5	12.3
(75, 5, 0.1)	4.3	10.2
(75, 5, 1.9)	6.3	12.8
(140, 5, 0.1)	4.6	10.8
(140, 5, 1.9)	6.7	12.2
(10, 25, 0.1)	4.6	9.8
(10, 25, 1.9)	6.5	12.7
(75, 25, 0.1)	4.2	10.8
(75, 25, 1.9)	6.6	12.1
(140, 25, 0.1)	4.0	9.5
(140, 25, 1.9)	6.4	12.1
(10, 45, 0.1)	4.2	9.8
(10, 45, 1.9)	6.6	12.7
(75, 45, 0.1)	4.1	10.9
(75, 45, 1.9)	6.5	12.2
(140, 45, 0.1)	4.2	10.3
(140, 45, 1.9)	6.7	12.2

6.2. *Dissolved oxygen concentration and water temperature results*

The experiments were performed continuously from September 20 to November 18, 2017. To demonstrate the results, data for 11:00 and 23:00 on November 3, 2017 were chosen (Tables 5 and 6 respectively).

Using data in Tables 4 and 5, an algorithm of linear interpolation on the platform of MATLAB (an embedded feature in the monitoring computer) builds the three-dimensional distributions of DO concentration and water temperature at 11:00 on November 3, 2017 in Fig. 11(a) and (b), and at 23:00 on the same day in Fig. 11(c) and (d). Fishpond water has greater DO concentration and higher water temperature at 11:00 than at 23:00.

These three-dimensional distributions can be used to manage the fishpond as a whole and act when the DO concentration or water temperature decreases below a threshold, triggering an alarm or other intervention.

6.3. *Effects on energy-saving*

For the sensor nodes, there were different percentages of average remaining energy for sensor nodes running in three different modes: Active mode left 19% on the first 20th day; PM2 mode 43% on the second 20th day; and PM2 and data merging mode 58% on the third 20th day. Sensor nodes running in Active mode consumed more energy than running in the two other modes because data transmissions and environmental variables measurements contributed the most energy consumption. We could improve the performance of sensor nodes from 19% to 43% average percentage of remaining energy by configuration of PM2 mode. Furthermore, the mode of PM2 and data merging could achieve average remaining energy of up to 58% due to stability and minimal change in the DO concentration and water temperature at most times.

For the routing nodes, the remaining energy levels were, on average, 3% on the first 20th day and 5% on the second 20th day when the sensor nodes were running in Active mode and PM2 mode respectively. However, there was a significant improvement in energy saving when sensor nodes were running in PM2 and data-merging mode and the routing nodes were also running in data-merging mode at the same time. The average percentage became up to 42% on the third 20th day. The gateway node's average percentages of remaining energy were 2% on the first 20th day, 3% on the second 20th day and 29% on the third 20th day for Active mode, PM2 mode, and PM2 and data merging mode respectively. We can draw a conclusion that PM2 mode does not have notable effects on energy saving for both routing nodes and the gateway node according to the average percentage of remaining energy because these nodes will have to handle all incoming messages from sensor nodes or routing nodes. But WSN nodes running in the mode of PM2 and data merging can truly make a significant energy saving and contribute to the WSN node's length of working hours.

Table 6 – Data from WSN at 23:00.

Position	DO concentration ($mg\ L^{-1}$)	Water temperature (°C)
(10, 5, 0.1)	3.1	7.5
(10, 5, 1.9)	5.4	10.1
(75, 5, 0.1)	3.3	7.9
(75, 5, 1.9)	5.5	9.8
(140, 5, 0.1)	3.4	7.7
(140, 5, 1.9)	5.7	10.1
(10, 25, 0.1)	4.0	7.9
(10, 25, 1.9)	5.2	10.2
(75, 25, 0.1)	3.8	7.5
(75, 25, 1.9)	5.6	9.7
(140, 25, 0.1)	3.2	7.5
(140, 25, 1.9)	5.8	9.8
(10, 45, 0.1)	3.1	7.4
(10, 45, 1.9)	5.5	10.1
(75, 45, 0.1)	2.8	7.2
(75, 45, 1.9)	5.3	10.2
(140, 45, 0.1)	3.1	7.5
(140, 45, 1.9)	5.6	9.8

7. Conclusion

In this study, we present a monitoring system based on a WSN to measure environmental variables (DO concentration and water temperature in this application) in freshwater fishpond aquaculture. The hardware of WSN nodes, topology of WSN and software for different types of nodes are also described in detail. The experimental results show that tree topology brings less packet loss rate than star or mesh and reached 3.2% at a measurement interval of 2s in this application. Meanwhile, the experimental results also show that there are

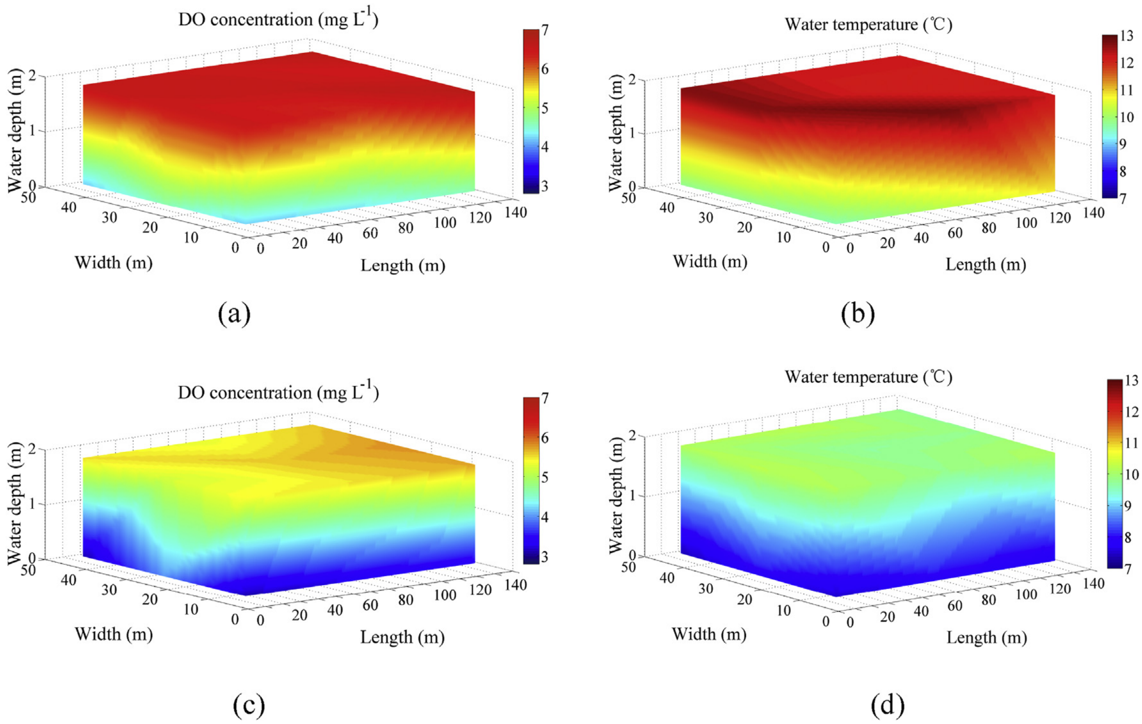

Fig. 11 – Three-dimensional distributions of measurements: (a) DO concentration at 11:00; (b) water temperature at 11:00; (c) DO concentration at 23:00; (d) water temperature at 23:00.

significant positive effects on a WSN node's continuous working hours through adopting energy-saving strategies including PM2 and data merging mode. The average remaining energy of sensor nodes, routing nodes and gateway node respectively reach 58%, 42%, and 29% after running for 20 days.

Further work will focus on multi-functions of the system, improvement of energy saving, and forecasting of DO concentration and water temperature in the three-dimensional space of a fishpond. Further work will also assess solar energy to replace AA batteries, to avoid producing waste batteries. Consideration of short series of multiple measurements at a lower frequency, and the effects on the efficiency and reliability of transmission imposed by increasing sensor nodes are also needed.

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