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Wireless greenhouse environment monitoring system based on lora network

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Research

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ABSTRACT

Monitoring environmental parameters contributes to the promotion of the crop production and quality in the vegetable greenhouse. LoRa technology is one of most promising candidate to build up wireless monitoring network due to its long data transmission distance, strong anti-interference ability, low power consumption. Here, we proposed an environment monitoring system based on LoRa network for vegetable greenhouse. The system consisted of sensor nodes, gateways and a data server, which could acquire real-time information on temperature, humidity, light intensity and carbon dioxide concentration at 1/3 of the cost of a similar system. Under indoor conditions where the distance between two nodes is 80m, the packet loss rate of the system is less than 0.05%. The greenhouse deployment results demonstrated that there was significant spatial variability in greenhouse environment and the difference of average soil temperature , air humidity, solar intensity and CO_2 concentration value in different places was respectively up to 1.6 °C, 3.7%, 4681 lux and 141 ppm. This provides an important reference for the future precise control of greenhouses and the decision-making of relevant management measures. In addition, the harsh condition test and real-world deployment displayed our proposed system has high communication quality and work stability in the complicated greenhouse environment.

Keywords: Wireless sensor network; Greenhouse environment monitoring; Precision agriculture; Spatial variability.

1. INTRODUCTION

According to a report of the Food and Agricultural Organization of the United Nation, the world population will reach about 7.6 billion people by 2020 and 9.6 billion people by 2050(FAO, 2009). To feed those people in the future, food production all over the world must increase by 70 percent before 2050. Meanwhile, the population growth also results in enormous demand for high-quality agricultural products. What is more serious is that the natural resources such as soil to develop agriculture have been gradually decreased in the past due to pollution, climatic change, etc. One of effective ways to solve problems is the precision agriculture (PA) (Zhang *et al.*, 2002). Because it can finely and accurately adjust cultivation measures according to the actual needs of each crop growth in farms, optimize the utilizing of various agricultural inputs to obtain the highest yield and maximum economic benefits, protect the environment and agricultural resources such as water (Viani *et al.*, 2017). Controlled environment agriculture (CEA) is a relatively better place to apply this technology compared to the open-field agriculture to realize modern sustainable agricultural development due to its relatively easy control. There is no denying that greenhouse is comparatively ideal places in which can avoid influences of season changes on vegetables and fruits.

When we deploy precision agriculture technology in controlled environment agriculture, the first step is to collect comprehensive information about crops as its environment variability is more complex and significant. The growth of each crop has specific requirements on environmental conditions. Some key growth factors can cause significant differences in crop production and quality, as well as influence the occurrence, proliferation of a variety of plant diseases and pests (Dae-Heon and Jang-Woo, 2011). To avoid or reduce negative impacts of climate condition factors on plant development as much as possible, it is necessary to acquire climatic and environment information in real time. Wireless sensor network(WSN) can opportunely undertake the above tasks due to its easy relocation and dynamic mobility benefits(Kim *et al.*, 2011).

Nowadays, with the development of sensors technology, wireless communication technology, embedded system technology and distributional information processing technology, the data processing capability and communication quality of wireless sensor system have greatly enhanced in recent times (Akyildiz *et al.*, 2002). Meanwhile, wireless sensor networks intend to become cheaper, smaller and smarter with driving of technological innovation (Chen *et al.*, 2015). That makes it feasible to achieve wide-range environment monitoring in technology and deployment costs. (Cambra *et al.*, 2014). WSNs typically comprises of several nodes equipped with lots of sensors and transmit it wirelessly to base stations or data base servers, which store the received data for later processing and analyzing (!!! INVALID CITATION !!!). In agricultural domain, WSN have played an important role in dynamic environment monitoring, which help farmers reduce potential production risks primarily coming from severe weather, various plant pests or diseases(Dang *et al.*, 2013), human intervention.

In recent years, the researches and applications in environmental monitoring system based WSN for scientific cultivating, fertilizing and harvesting are rapidly growing in developed and developing countries(!!! INVALID CITATION !!!). Mendez et al. reported a smart WSN based on Wi-Fi technology in order to monitor various environment factors (Mendez *et al.*, 2011). Mehlmet et al. put forward a wireless environment system based on Bluetooth, which was deployed in tomato greenhouse to acquire air temperature, relative humidity and soil temperature data (Dayioğlu, 2014). The SMS (Short Message Service) communication has also been applied in building a greenhouse monitoring system and supplied those environmental information for owners in real-time (Liu *et al.*, 2007; Rangan and Vigneswaran, 2010). GPRS technology is often used to build remote environmental monitoring systems due to its long transmission distance (Xia *et al.*, 2011; Li *et al.*, 2014; Liang *et al.*, 2015). Compared to high transmission rate, high power consumption, high cost Wi-Fi, Bluetooth technology, people are more interested in low-cost and low-power wireless technologies like IEEE 802.15.4 protocol in consideration of cost and maintenance upgrade especially in agriculture is a place where large-scale deployment of wireless sensor networks is required. Many real-world deployments have indicated that ZigBee-based greenhouse monitoring systems are feasible to monitor environmental parameters and climate conditions associated with plant growth in real time (Wang and Cao, 2009; Yu *et al.*, 2009; He *et al.*, 2010; Tafa *et al.*, 2018). Tirelli et al. proposed an automatic monitoring system based on ZigBee technology for pest insects traps. It used image sensors to acquire images of the trapping area and transmitted to a remote PC. The system evaluated the insect density and produced a warning when it exceeds the threshold (Tirelli *et al.*, 2011). Ferentinos et al. reported a wireless monitoring system deployed at different positions of a cucumber greenhouse based on IEEE 802.15.4 protocol. They found that there was obvious spatial variability in greenhouse climate conditions especially in temperature, which can be up to 3.3℃ in summer. They also analyzed the collected data and found out possible problematic situations (Ferentinos *et al.*, 2017).

There are three crucial factors about wireless sensor network operation: power consumption, accuracy of measurement, network connectivity. Besides, there are other considerable aspects for WSN like stability, cost, data security. Many companies, institutions and researchers proposed communication agreements, network topology architectures and energy management solutions that maximize network coverage and ensure adequate battery life (Ghiasi *et al.*, 2002; Dargie, 2012). Keshtgary et al. investigated the efficient topologies in Wi-Fi sensor network and found the grid topology was better (Deljoo and keshtgary, 2012). Srbinovska et al. applied the gossip algorithms(Hou *et al.*, 2004) in WSN communication strategies and the experiment results showed that the algorithm could decrease the risks of overall system operation caused by node failure (Srbinovska *et al.*, 2015). Low power wide area network (LPWAN) is one of most popular communication technologies in industrial and research communities due to its three advantages: long communication range, low power consumption and low-cost. Because of a new creative physical layer design, its communication range in urban zone is up to 1–5 km and in rural zones the value can to 10–40 km. (Centenaro *et al.*, 2015). Recently, LoRa is one of promising LPWAN solution in physical layer, which is designed and patented by Semetch Company. Its special spread spectrum technique make itself spreads a narrow-band signal over a wider channel bandwidth. This makes it have low level signal noise, strong anti-interference ability (Reynders *et al.*, 2016). T. Compared with Zigbee and Bluetooth's 20m maximum transmission distance, LoRa has a wireless transmission distance of 1 to 2 kilometers in urban areas and up to 20km in open rural areas. The most the work time of Lora is in sleep mode, with an operating current of only 1 µA and can operate for more than 10 years with 1 AA battery (Bao *et al.*, 2018).In addition, it uses unlicensed ISM radio frequency bands like 915 MHz (North America), 868 MHz (Europe) and 433 MHz(Asia), which is quite suitable for scientific study and agricultural production (Mekki *et al.*, 2018). It has been applied in smart building(Trinh *et al.*, 2017), driving safety(Chou *et al.*, 2017), health and medical work (Hayati and Suryanegara, 2017) and made tremendous contributions to their development. However, it is rarely reported that LoRa technology is applied to greenhouse environmental monitoring.

Considering all of the above, we established a wireless greenhouse monitoring system to acquire key environmental parameters such as temperature, humidity, and carbon dioxide concentration at low cost and low power consumption. This work would help farmers keep track of greenhouse environmental information in real time and provide support for precise control and optimization of crop growth process in the future. Besides, we tested the anti-interference ability and work stability of LoRa network in complex and varied harsh environment of the greenhouse.

2. ARCHITECTURE OF MONITORING SYSTEM

The greenhouse monitoring system consists of sensor nodes, gateways, a data server and user clients. The architecture of the system used the traditional star topology as shown in Figure 1.

The small size sensor nodes were deployed in the several different regions to ensure reliability of data acquisition, which were responsible for collect and monitor environment parameters such as temperature and carbon dioxide concentration. Then, the collected data were simple processing and encoding and sent to nearby gateway by LoRa technology. Next, the gateway transferred them to the data server through 3G/4G/Wi-Fi/Ethernet network. After receiving the environment information, the server decoded the data and stored them in database. Finally, managers use user clients to view environment statistics in anytime and anywhere. In the near future, the staff will dynamically adjust management strategies according to data analysis results produced by big data technology, deep learning technology, cloud computing or something else.

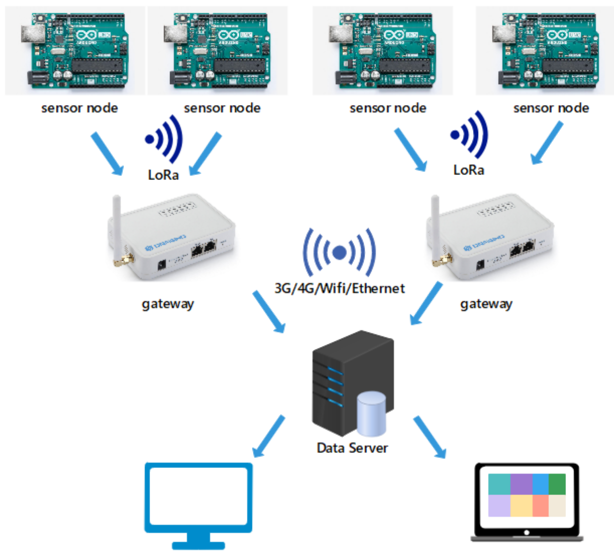

Fig. 1. Wireless monitoring system topology.

2.1. Sensor nodes

The sensor nodes adopt a modular design for easy maintenance and upgrade. They consist of four modules: sensor module, control module, wireless transceiver module, battery module. The sensor module is in charge of collecting environmental information, the wireless module is used for communication with the outside, the control module is responsible for controlling sensor operation and data calculation, storage and transmission, and the power module is employed for providing power to this node.

2.1.1. Sensor module

It is critical to single out proper sensors which could bear harsh greenhouse environment like high temperature and high humidity and keep in high sensitivity, reliability and long working life. Therefore, we picked out low power consummation air temperature/humidity sensor, carbon dioxide concentration sensor and other three types of sensor to acquire agricultural environment information. SHT20 was selected in the experiment to measure air temperature and humidity. Compared to the previous temperature and humidity sensors of Sensirion Company like SHT1x and SHT7x generation, SHT20 sensor adopted a completely new designed chip and its performance had been largely improved in accuracy and stability. Its temperature range is from -40 ℃ to 100℃ and accuracy could up to ±0.3 ℃ at room temperature. The range of humidity is 0% RH to 100% RH with ±3% RH accuracy. It uses a direct-current power supply of 3.3 V/5 V and its work current is only 300μA. Single chip microcomputer and other data collector can gain the calibrated digital signals by I^2C bus interface.

Subsequently, we chose DS18B20 to detect the soil temperature and used a kind of soil moisture content sensor to acquire soil volumetric water content. The DS18B20 digital thermometer provides -55℃ to 125℃ temperature measurements with ±0.5℃ at -10℃ to 85℃ and communicates with a central microprocessor over a 1-wire bus protocol. It is waterproof, moisture-proof and rust-roof because it adopts high quality stainless steel tube package. It uses a direct-current power supply of 3.0 V-5.5 V and its work current is only 200 μA. The detailed information of other sensors is presented in table 1.

Table 1. The performance parameters of other selected sensor.

Sensor	Measuring project	Operating Range	Accuracy (%)	Operating Voltage (V)	Price	Power (mW)
Soil Moisture	Soil Moisture	0% RH-100% RH	±3	7-24	$30	2.52
BH1750	Light Intensity	1 lux-65535 lux	±10	5	$1	0.66
SEN0219	Carbon Dioxide Concentration	0 ppm-5000 ppm	±10	4.5-5	$25	-

2.1.2. Control module

The core part of control block is microprocessor which desires high integration small size, low power, easily programing. The sensor nodes are built on Arduino Uno R3 board with ATmega328P microcontroller. The recommended input voltage of this microcontroller is 1.8-5.5V and work current is 30 mA (16MHZ). The ATMega328 is capable of operating 2 major categories of power modes: active and sleep mode. The lowest one among seven sleep modes is power-down mode and it merely needs 3.6μA current to maintain its work. The board has 6 analog inputs and14 digital input/output pins in which 6 pins can support PWM outputs. There are an I^2C bus, a power interface, a reset button, a USB connection interface which can serve as virtual com port for downloading program and other peripheral complements.

2.1.3. Wireless transceiver module

Choosing proper wireless transceivers can not only ensure that packets are sent and received accurately and without errors but also significantly lengthen the work time of sensor nodes. Most of battery power was consumed on wireless transceiver module in a sensor node. As shown in table 2, we made a list of common wireless network communication technologies and compared their fundamental characteristics. Although Wi-Fi and Bluetooth have higher data rate, their energy consumption is also obviously higher. In addition, the cost of building a wireless sensor network based on Wi-Fi is high and it also needs support from a wired network. The transmission range of Bluetooth and ZigBee is shorter compared to LoRa, although ZigBee can increase its range by adding more repeater. Besides, LoRa has low noise level signal and high anti-interference due to its chirp spread spectrum (CSS) technology. So, we selected the Dragino LoRa shield presented in Figure 4 as wireless transceiver module, which was a cheap and long range transceiver adopted modular construction. The wireless communication module is based on SX1278 chip which is a relatively common and mature LoRa chip. The module has a slice of advantages: high interference immunity, long range signal communication, modest price and low power consumption. Its working current is 10.3mA, and sleeping current is only 20nA. It also has high sensitivity and can receive -148dBm low radio signal. The Radio-head communication library was used to drive this module by modifying and adding our function.

Table 2. Comparison of different wireless communication technologies.

Wireless Technology	Transmission Range	Data Rate	Energy Consumption	Cost
Wi-Fi	20-100 m	1Mb/s-6.75Gb/s	High	High
Bluetooth	8-10 m	1Mb/s-48Mb/s	Medium	Low
LoRa	<15 km	0.3 Kb/s-50Kb/s	Low	Low
ZigBee	10-20 m	20 Kb/s-250 Kbps	Low	Low

2.1.4. Comparison with other embedded platforms

It is also an essential consideration to opt for the suitable hardware platform for any WSN deployment especially in agriculture. Embedded platform is currently a popular choice owing to its low-power, long-term stability and strong capacity of resisting disturbance. We can compare various hardware platforms according to key performance parameter such as data processing, storage, power dissipation, sensor support capacity, communication capabilities, scalability, programming and cost.

The summary sheet of common and popular platforms used in recent deployments (Tzounis *et al.*, 2017) is presented in Table 3. Most of them possess an 8/16 bit microcontroller and a wireless transceiver such as Bluetooth or Wi-Fi. Although the data rate of Wi-Fi and Bluetooth is high, the battery consumption of them is higher than the IEEE 802.15.4 protocol and LPWAN in an ideal situation. Raspberry Pi 3 Model B and Intel Edison have more powerful microcontroller, larger memory and external storage, which have relatively fast reaction speed, strong data processing capability and are suitable for processing data in complex scenes. But their power supply could not depend merely on battery and they need more external power source for energy supplement if working in long time. TelosB supports IEEE 802.15.4 protocol while EZ430-RF2500 adopts a special low-power wireless protocol which is designed by Texas Instruments.

In general, 2 AA batteries can be enough for power TelosB and total active power is only 3mW. One matter that merit attention is that the voltage should be over 2.7 when we program it. The working voltage of EZ430-RF2500 boards is 3.6 V and need 2 AAA batteries to power radio module. Arduino boards have a number of power options to choose from as long as it meets their requirements of the supply voltage. The Arduino Yun recommended to power via the micro-USB connection with 5 V DC and also compatible with power over Ethernet standard. The standard supply voltage supply voltage Intel Edison is 3.5 V - 4.5 V and Intel provides a 12 V charging power supply that can switch to working power. But its standby power is up to 13 mW while they are respectively 21.5mW and 35mW at open state of Bluetooth and Wi-Fi. Similarly, supply voltage of Raspberry Pi 3 Model B is 5 V by micro USB and total active power is about 5 W or more.

The programming language of listed embedded platforms is mainly based on C language. Arduino platform provides simple, clear programming environment, which is a relatively easy-to-use for beginners, yet flexible enough for advanced users as well. The price of LoRa shield is 20.2 dollars, so the cost of Arduino UNO wireless platform is less than 44 dollars. The scheme of Arduino UNO and LoRa shield is relatively cheap solution listed in following table and applies to the following scenarios where the electricity in the greenhouse is inconvenient and lots of sensor nodes are far away from gateway.

Table 3. Summary table of WSN embedded platforms.

Platform name	Microcontroller	Transceiver	Memory	Flash, EEPROM	Programming	Price (U$)
Arduino Uno/ Mega	ATmega328P/ ATmega168	External modules	2 KB SRAM/8 KB SRAM	32 KB, 1 KB/256 KB,4 KB	C, Processing, Linux	$23.4/ $41
EZ430-RF2500T	MSP430F2274	CC2500	1KB RAM	32KB Flash	C,C++	$58
TelosB	MSP430	IEEE 802.15.4 compliant radio	8 KB RAM	48 KB	NesC, C	$104
Arduino Yun	ATmega32U4/ Atheros AR9331	Ethernet, Wi-Fi	2.5 KB, 64 MB DDR2	1 KB/16 MB	C, Processing, Linux	$57.3
Raspberry Pi 3 Model B	ARM Cortex-A53	Ethernet, Wi-Fi, Bluetooth	1GB	SD card	Linux	$35
Intel Edison	Intel Atom	Wi-Fi, Bluetooth	1 GB RAM	4 GB, SD card	C, Processing/ Linux	$294.74

2.1.5. Battery module

On the one hand, the voltage soil moisture sensor need to the 7-24 voltage while the recommended input voltage of control module is 7 V - 12 V and output voltage is 3.3 V/5 V that can power other sensor. So, we choose one 12 V battery to power the sensor node considering difficulty of wiring in a greenhouse. On the other hand, in order to decrease consumption of energy and enhance the use of renewable technologies on farms, we pick out battery powered by solar panels. The charge way by solar panel can deal well with the problem of no electric power supply in simple greenhouse. The module is composed of solar cell panel, charge and discharge controller, voltage reducing device and storage battery.

2.2. Gateway node

In this greenhouse monitoring system, Dragino LG01-P LoRa real-time gateway was chosen to receive the data from sensors nodes. With a 400 MHz processor and a SX1278 radio LoRa Chip, this gateway is competent to communicate with 20 up to 200 sensor nodes if the corresponding order of node is arranged wisely. The Dragino LG01-P gateway also features an 80 MB memory space which is propitious to running openwrt system and data-logging application software. The openwrt system could support the Transmission Control Protocol and Internet Protocol (TCP/IP) and User Datagram Protocol (UDP). Moreover, LG01-P provides flexible methods for users to bridge LoRa wireless network to an IP network by Wi-Fi, Ethernet, and support 3G or 4G network.

2.3. Software architecture

The Arduino Uno and Dragino LG01-P gateway are programmed on Arduino IDE, which is user firmware programming application with friendly interface. The program in Arduino Uno for sensor nodes consists of three parts: one is information reading and processing of sensors, another one is wireless communication, the last one is microcontroller working mode switch. For sensor data, the microcontroller first determines if the data is an outlier, then calculates the average for every five values, finally it packs all the data in the specified data format. The program sets two power modes for the microcontroller. In the working mode, the microcontroller continuously collects information and sends data. In the power saving mode, the microcontroller closes the peripheral devices, leaving only the watchdog timer to trigger the working mode. The program in gateway is used for receiving collected data from LoRa nodes and transfer forward to the database server.

We wrote data sending and receiving programs which were written in C# and perfectly support Winsock which establishes the standard for programming Windows software on TCP/IP network (Li *et al.*, 2006). Data sending and receiving programs also were called server and client programs that were used to connect the remote computer and gateways. Firstly, the server program begins to enable listening mode and make provision to receive information. Then client in the gateways sends the connection request. Finally, the server confirmed socket connection request and the gateways establish the communication connection with the cloud server.

An addressing scheme based on the relative location of the node (RLN) was used for sensor nodes location identification. The sever program is able to judge the data source and store it into different sheets in MySQL database by RLN. We rent a cloud database server to store data collected from greenhouse which is cheaper and easier maintained than conventional one. In this way, we do not need to build a host computer to receive the uploaded information of the gateway in real time. At the same time, we can also use cloud computing and artificial intelligence technology to process and analyze the information of the database server.

In addition, considering using MySQL software check data difficultly, we designed one computer user client to monitor real-time state of environment in greenhouse, which is shown in Figure 2. This client is written in C# and could run all computers with a window system. C# is a high-level object-oriented programming language based on .NET framework launched by Microsoft. This client can remotely access the cloud database server and get the data information that the user wants. Data from nodes was statistically analyzed and the time changing trends of different environment parameter was stated in the different plots. Farmers can easily monitor the environment information of every node and observe their changes in the periods by line charts or others.

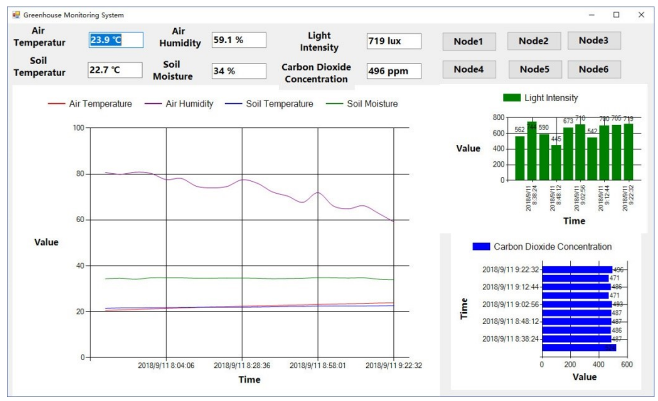

Fig. 2. Greenhouse monitoring client.

3. Experiment design

It is well known that the high temperature and high humidity environment of the greenhouse will cause damage or even damage to the electronic circuit. In this regard, we designed a communication quality test for testing the LoRa communication module in high temperature, high humidity and normal temperature and humidity conditions. The NO.1 communication module is placed in an incubator with a set temperature of 50 degrees Celsius to simulate a high temperature situation. The NO.2 module is placed in the freezer to simulate a high humidity situation. As a control, we placed The NO.3 module in the lab. The distance between the three modules and the gateway node is about 5 meters, and an about 12 KB data package is sent to the gateway every 5 minutes at 433.5 MHz. The reason for choosing to send a packet with a volume of 12 KB is that it is close to the size of the data sent by the experimental sensor node. The experiment was conducted for 24 h, and a total of 288 messages were sent.

Besides, the second experiment was set up to find out the relationship between LoRa communication quality and node distance in indoor environment and confirm the feasibility of the application of lora technology in greenhouse monitoring. It was carried out in a laboratory area of 90m long and 10m wide at Shandong University of Technology in China. The environment in this area is relatively empty, there are no large buildings, and occasionally people walk around. We arrange the LoRa node to send data at one end and the gateway to receive data at the other end. The transmitting node sends a 12 KB data package to the gateway every 5 seconds at a frequency of 433.5 MHz, for a total of 1000. We set a test point every 10 meters to measure the LoRa signal strength at the height of 50cm. In order to test the communication performance between nodes at a relatively close distance, a test point is added at a distance of 5 meters between the node and the gateway.

The last experiment was deployed in a real-world eggplant greenhouse. Eggplant is a common kind of vegetable in the north China and greatly sensitive to environment changes. So, it is necessary to keep the appropriate environmental conditions for Eggplants' growth. It is a thermophilic crop and the temperature during its growth is generally several degrees higher than that of peppers and tomatoes. The optimal temperature value of the Eggplant crops should be maintained between 25 ℃ and 30 ℃ at day, at night should be 18 ℃ - 20 ℃. When the temperature is below 5 ℃, it will suffer cold damage, and even freeze to death. That temperature below 15 ℃ or above 30℃ in eggplant pollination period would result in bad fertilization and falling flowers. Its soil should be relatively fertile, with large water content on account of its feature of not drought tolerant.

Another parameter has a profound and lasting influences on the eggplant is illumination intensity. It affects the photosynthesis of the eggplant and the accumulation of organic matter, thus the production and quality of the eggplant. Like temperature and humidity, the carbon dioxide concentration is another vital environment parameter in the greenhouse (Bai *et al.*, 2018), so it is indispensable to monitor the carbon dioxide concentration in the greenhouse.

We put the sensor nodes in one of the conventional, double-span, arched eggplant greenhouses of the Zibo, Shandong, China (39°48′N, 118°02′E) and tested the monitoring system. This greenhouse is north-south, with an area of about 1000 square meters, covered with polyethylene plastic film. The Greenhouse entrance was located at the south side and air vents are in east side of greenhouse roof. To verify the significant spatial variability in greenhouse environment in the experiment, the sensor nodes were located in different positions shown in Figure 3 and transmitted the environment data every 5 minute for 9 days from August 17 in 2018. In order to prevent the high temperature and high humidity environment in the greenhouse from damaging the sensor and affecting the measurement, we placed the SHT20 and SEN0219 sensors in a louver 30 cm from the ground. The soil moisture and temperature sensor are inserted directly into the ground approximately 10 cm, and the BH1750 is mounted on top of the louver to receive sufficient light. In order to prevent large disturbances to the LoRa signal during eggplant growth, we installed the wireless communication antenna at a height of 1.5 m. In the first three days, the weather of Zibo was cloudy or rainy while the weather was sunny in the following days. The door and air vents were open all the time to avoid the high temperature doing harm to crops. Besides, the top of the greenhouse is also covered with a layer of shading net.

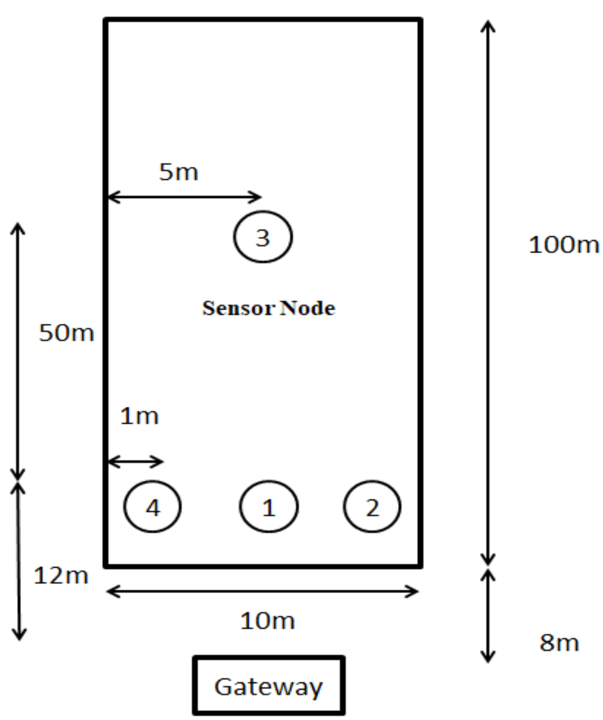

Fig. 3. The layout of sensor nodes.

4. RESULTS AND DISCUSSION

The results of communication quality test in different environment are shown in Table 4. The data shows that the high temperature or high humidity environment does have an impact on signal communication, but the maximum lost packages rate is 4.9%, which satisfies its requirements in data transmission.

Table 4. Signal test results in different environments

Module	Temperature (°C)	Humidity (%)	Received Signal Strength Indication	Lost Packages Rate (%)
1	51.5	19.6	-47	4.9
2	29.0	62.7	-38	0
3	-30.5	78.7	-47	1.2

The test results of the second experiment are shown in the table 5. In general, the transmitted signal strength gradually weakens with increasing distance, which is similar to previous research results (Rudeš *et al.*, 2018). From the table we can see that the signal attenuation speed is faster at 0-5 meters. It is possible that the transmitter and receiver interfere with each other during short distance transmission. At 30 m, the signal intensity is lower than the adjacent distance, and roughly similar to 60 m. It is possible that this result is related to its location near the exit of the laboratory and the signal is easily under the influence by interference from the outside world. The lost packages rate of all test points is under 0.05%, which proves that LoRa technology has strong anti-interference ability in real indoor environment and long transmission distance.

The obtained measurement results for the environmental parameter in the eggplant greenhouse, for nine days are shown in Figure 4 - Figure 9. In the whole, most parameters' changes at the four observation sites were consistent and showed periodic changes. The air temperature value measured in the greenhouse was between 20 ℃ and 40 ℃ and differences of nodes in air temperature were not obvious. The lowest temperature was about 23 ℃ occurred before sunrise while highest temperature was about 37 ℃ recorded at afternoon. From Fig. 4, we noticed that the air temperature is higher than the maximum temperature eggplant can tolerate at afternoon in the sunny days. The combination of the enormous heat from the intense solar radiation and its own greenhouse effect had led to this problem. As a result, the growth of crop was bound to be affected due to the reduction or cessation of photosynthesis. Although we had taken some cooling measures to prevent this problem in advance, this was not enough.

Table 5. Signal test results in different communication distances.

Distance (m)	Received Signal Strength Indication (dBm)	Lost Packages Rate (%)
0	-21	0
5	-35.6	0.02
10	-39.6	0.02
20	-48.1	0
30	-56.8	0
40	-51.2	0.03
50	-53.2	0
60	-57.1	0.01
70	-66.8	0.01
80	-61.4	0.04
90	-71.8	0

The soil temperature changed similarly with air temperature and differences among nodes were relatively obvious. The air humidity was changed negatively correlated with air temperature in some extent. The value of soil moisture was relatively stable in long time and the differences of nodes were evident. The value of soil moisture at node2, 3, 4 fluctuates dramatically as farmers irrigated their greenhouse on Aug. 24. The reason for the jump of node 1 vale in soil moisture was that the farmer moved the position of the sensor. When the weather was sunny and the light was sufficient, the solar intensity among four nodes was obviously different. In the beginning, the carbon dioxide concentration with four nodes was changed little while it is much bigger in node3 than in other node in the following days.

We respectively calculated the mean value and standard deviation of temperature and humidity, light intensity and carbon dioxide concentration of the four monitoring nodes as shown in table 6,7. The maximum difference of soil temperature is 1.6℃ which happened in the night when the maximum difference of air temperature is less 0.5℃. Because the location of each node is different, the growth state of the crop is different, the air temperature and humidity vary in different places. The difference in temperature and humidity at each node reveals that the spatial distribution of the greenhouse climate is not uniform, and the relevant research got similar results (Kono, 2010; López *et al.*, 2012). We also found the maximum differences between light intensity and carbon dioxide concentration respectively up to 4681 lux and 141 ppm. Since the roof of the greenhouse is arched and the growth height of the eggplant is high, the nodes 1, 3 are located in the middle of the greenhouse, and are less affected by the growth of the plants and can receive sufficient light. Nodes 2, 4 are located on both sides of the greenhouse, which are easily blocked by plant leaves, and the acceptance of care is insufficient, so the light intensity of nodes 1, 3 is much larger than that of nodes 2, 4. Differences in greenhouse soil temperature could be mostly put down to solar intensity with their distributing similarly in nodes. At the same time, the mean value of soil and air humid in different nodes was different and the maximum difference of humidity was 3.7%, which it happened in night time. Differences in carbon dioxide concentrations values can be attributed to ventilation system with the carbon dioxide concentrations values progressively increasing from the east side to west side. In addition, the accuracy of the infrared carbon dioxide sensor is not high, the location is located in the lower part of the greenhouse, use, the air circulation is weaker than the upper part of the greenhouse with vents. So, the measured data is larger, and the difference between the nodes is also significant. This provides an important reference for the future development of greenhouse climate control strategies to help provide a more uniform and appropriate environment for crop growth.

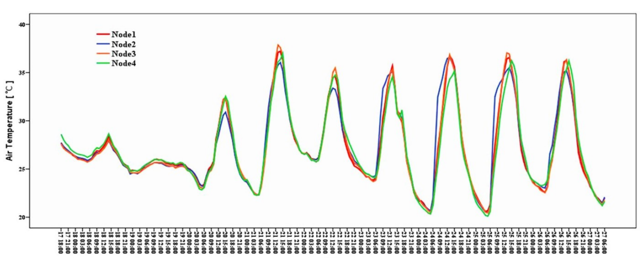

Fig. 4. Measurement of air temperature with four sensor nodes.

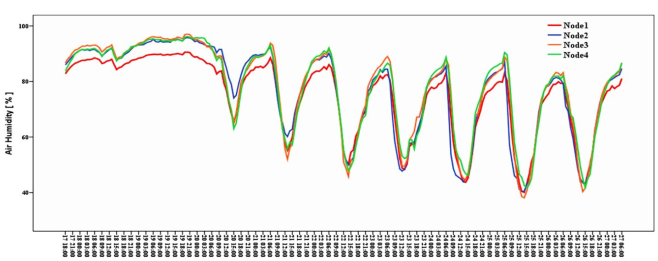

Fig. 5. Measurement of air humidity with four sensor nodes.

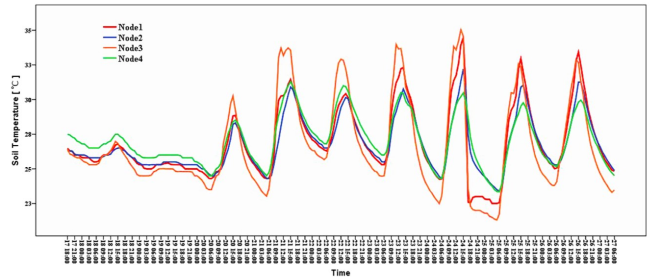

Fig. 6. Measurement of soil temperature with four sensor nodes.

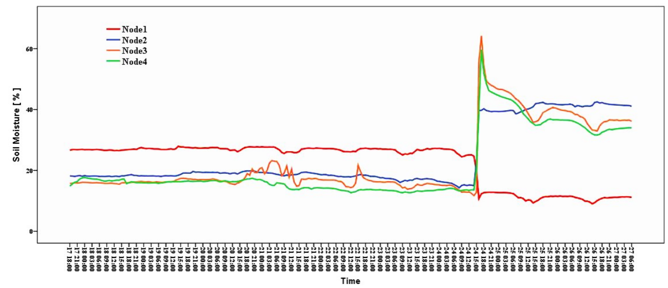

Fig. 7. Measurement of soil moisture with four sensor nodes.

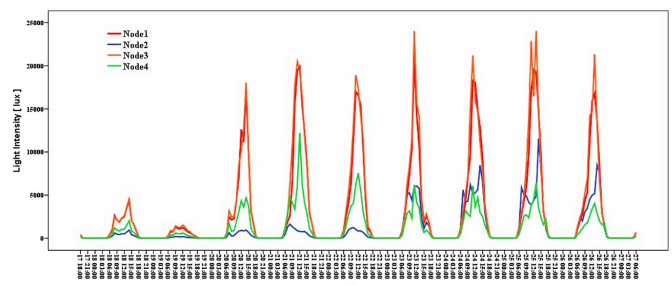

Fig. 8. Measurement of light intensity with four sensor nodes.

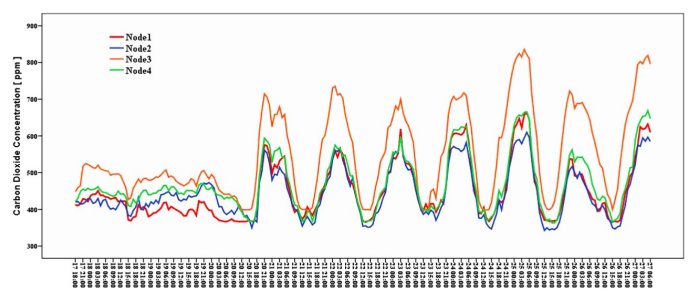

Fig. 9. Measurement of carbon dioxide concentration with four sensor nodes.

Table 6. Average temperature and humid values and standard deviations (SD) of each sensor node for daytime and night time periods.

Sensor Node	Air Temperature (°C)				Air Humidity (%)				Soil Temperature (°C)				Soil Moisture (%)			
	Day		Night		Day		Night		Day		Night		Day		Night	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	29.8	4.12	24.7	2.06.	69.0	16.30	79.7	8.16	28.0	2.84	25.9	1.67	22.7	6.82	22.5	7.11
2	30.0	4.00	24.8	2.11	69.9	18.78	83.1	9.32	27.4	2.19	26.2	1.32	23.3	9.84	24.8	10.28
3	29.6	4.35	24.6	2.14	71.7	18.90	83.4	9.01	28.5	3.43	24.8	1.67	21.8	10.79	24.6	11.82
4	29.6	4.02	24.9	2.36	71.2	17.90	83.0	10.07	27.8	1.97	26.4	1.35	20.3	10.01	22.2	11.04
Max diff	0.4		0.3		2.7		3.7		1.1		1.6		3		2.6	

Table 7. Average solar intensity and carbon dioxide concentration values and standard deviations (SD) of each site for daytime and night time periods.

Sensor Node	Light Intensity (lux)				Carbon Dioxide Concentration (ppm)			
	Day		Night		Day		Night	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	6306	6461.38	28	107..96	409	48.73	484	81.65
2	2176	2560.43	13	59.26	406	48.45	478	67.40
3	6857	7024.82	28	109.09	477	81.47	620	111.24
4	2320	2307.69	12	44.32	426	52.27	509	76.13
Max diff	4681		16		71		142	

Besides, we counted the mean and standard deviations of four nodes' signal strength indication values as shown in Table 8. As a result, the LoRa signal strength gradually decreases as the distance increases. The signal strength of node 3 is significantly lower than that of the other three nodes. It can be seen from the standard deviation that the greenhouse environment and crop growth interfere with the signal intensity very much, but in an acceptable range. In this regard, we can think that the system has strong stability and environmental adaptability.

Table 8. Average received signal strength indication (RSSI) values and standard deviations (SD) of each sensor node.

Sensor Node	Mean (dBm)	SD (%)
1	-68.25	6.83
2	-68.47	6.41
3	-82.17	3.86
4	-68.09	5.14

Finally, the cost of a sensor node and the whole system was counted as shown in table 9 and table 10. One of important issue of estimate the growth in the market especially in development country is cost. The total cost of this system is $751.4, which is an affordable price for farmers. The per cost of every sensor node is about $188 and only 1/3 of existing monitoring platform available in the market such as Beijing Nongchuang MC series. Most of them adopted wired communication and need to arrange power and communication lines in the greenhouse, which is not conducive to later upgrades and maintenance. In terms of transmission distance and packet loss rate, this system is far better than similar greenhouse monitoring system using ZigBee technology (Zhang *et al.*, 2013). More importantly, it has better environmental adaptability and anti-interference ability, and can adapt to the high-temperature and high-humidity environment of the greenhouse.

Table 9. The cost analysis of sensor node.

Component name	Price (US)
Sensors	$84.5
Arduino Uno R3 Board	$23.4
Dragino LoRa Shield	$20.2
Battery device	$30
Total Cost	$158.1

Table 10. The cost analysis of our system.

Component name	Unit Price (US)	Unit s	Price (US)
Sensor nodes	$158.1	4	$632.4
gateway	$118	1	$118
Cloud sever	$1	1	$1
Total Cost	$751.4	1	$751.4

5. CONCLUSION

In this paper, a low-cost vegetable greenhouse monitoring system based on LoRa network was proposed, which was capable of working in this environment of no power supplying and wired network. This signal experiment showed the proposed system can work stably in the high temperature or high humidity environment and its maximum lost packages rate is only 4.9%. In a real indoor environment, this system is capable of guaranteeing a packet loss rate of less than 0.05 in long-distance communication of 80 m. The cost of the system is only 1/3 that of similar commercial products and is more suitable for use by farmers in developing countries that are more sensitive to cost.

The results of eggplant greenhouse experiment highlight that our system was capable of achieving the design targets and verified the spatial variation of the greenhouse environment status. After processing the obtained information, we found significant spatial variability in temperature, humidity, light intensity and carbon dioxide concentration. The maximum difference in temperature and humidity is separately up to 1.6 ℃ and 3.7%, with the greatest variability occurring during night period. Similarly, the maximum difference with average solar intensity and carbon dioxide concentration is respectively up to 4681 lux and 141 ppm. The entire greenhouse climate is not completely uniform everywhere, so the development of management measures needs to consider the differences and take appropriate measures to provide a good climatic condition for vegetable growth. All these observations can be processed and analyzed to help them to come up with precise environmental control algorithms or irrigation strategies for the better crop yield and higher qualities. In the future, there will be more scientific, precise and smart cultivating technology, algorithms and systems based on WSN.

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