Design and test of wireless monitoring system based on expandable awning composite greenhouse

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Abstract

Wireless technologies like wireless fidelity (WIFI) and ZigBee have drawbacks such as short communication distances or high-power consumption, and the half-duplex nature of long range (LoRa) communication, traditional solutions generally use time division multiple access (TDMA) or polling communication methods-cannot provide differentiated services. Therefore, based on an extensible awning structure with fans and wet communication protocol combining TDMA and random delayed competitive access random delay competitive access (ALOHA) is proposed, which allows for real-time communication with contention nodes that have high real-time requirements, ensuring no data collisions during communication in static timeslot (TS) nodes, reducing node power consumption, and therefore achieved differentiated services. Practical verification demonstrates that the greenhouse achieves a 100% success rate in long-distance communication with low transmission power consumption. Although the competing node communication has data collision, the success of communication can be guaranteed by retransmission mechanism.

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Introduction

The necessity of people to control and enhance the environment for agricultural production promoted the development of greenhouse. Greenhouse provides optimal growing conditions for crops, independent of seasons and regions, which is conducive to increasing crop yields and is currently the mainstream agricultural planting and production methods. With advancements in technology and changes in agricultural production methods, greenhouse technology has developed significantly, promoting efficient use of agricultural and water resources, and playing an essential role in the swift development of the national economy (Wang, 2024; Guo *et al.,* 2024). With the growing demand for greenhouse construction scale and control technology, innovation and advancement in greenhouse technology have become one of the important directions of modern agricultural development.

The operational basis of a greenhouse involves enclosing a space with thermal insulation materials, thereby isolating the inside environment from the exterior one. The optimal growing conditions for crops can be achieved by controlling environmental parameters such as air temperature and relative humidity of air. The structure and control methods of greenhouses directly determine construction costs, operating costs, service life, and effectiveness (Wang *et al.,* 2024; Guo *et al.,* 2019). Consequently, the construction of an effective physical foundation for greenhouses is essential. By establishing an ideal growing environment that significantly enhances crop growth, quality, and overall agricultural production efficiency.

This paper focus on developing a communication protocol that combines TDMA and ALOHA to address the half-duplex nature of LoRa communication and provide differentiated services. The proposed system uses low-power chips and modules to design the hardware, including STM32 microcontrollers, air temperature and relative humidity of air of air sensors, light sensors, and soil moisture sensors. The data collected by these sensors is transmitted to a central base station using long range (LoRa) technology, then uploaded to a remote message queuing telemetry transport (MQTT) server *via* Wi-Fi. The paper also discusses the principles and implementation of the communication protocol, network access, time allocation process, and hardware design. Experimental results validate the feasibility and reliability of the monitoring system.

Related work

With the advancement of technology, foreign greenhouse technology has evolved from the traditional extended growing seasons to now integrating advanced technologies such as automated control systems, climate regulation and efficient irrigation systems, also proposed urban farming technology such as hydroponics, aeroponics, aquaponics and so on (Singh *et al.,* 2024). It is essential to monitor environmental parameters in greenhouses, including soil moisture, ambient air temperature and relative humidity of air, and illumination, to regulate crop growth. Consequently, numerous researchers have implemented information technology to monitor these parameters. Among them, the integration of advanced sensor technology, artificial intelligence (AI) and machine learning technology is currently the mainstream direction of foreign research. For example, the integration of internet of things (IoT) technologies, particularly sensor-based systems, were used for strawberry cultivation in greenhouses (Samuel *et al.,* 2024). In order to realize more efficient cultivation, a smart monitoring system for controlled greenhouse plantation was proposed for the large-scale cultivation of figs (Ibrahim *et al.,* 2023), which equipped with LoRa and global system for mobile communications (GSM) to overcome the distance and data transmission limitations. An intelligent greenhouse control system based on IoT and machine learning algorithm (Teja *et al.,* 2020) and a microcontroller that integrate the IoT and AI were proposed to improve agricultural efficiency and sustainability (Riskiawan *et al.,* 2024). Notably, LoRa as one of the advanced wireless communication technologies, is widely used to connect and use the IoT to ensure monitoring, management and control of the greenhouse environment (Salih *et al.,* 2020).

Chinese researchers have also proposed many methods to monitor and control environmental parameters in greenhouse. An integrated IoT technology and machine learning algorithms into greenhouse control technology to monitor and regulate environmental data (Wang *et al.,* 2024). Zhang *et al.* (2023) studied a remote greenhouse visual monitoring system based on an IoT that uses LoRa wireless communication technology to detect environmental parameters such as temperature, humidity, and light intensity inside the greenhouse. This system can promptly monitor the growth of crops and achieve functions like automatic ventilation, supplemental lighting, *etc*. Liu *et al*. (2021) combined embedded technology, IoT, cloud computing, *etc*. to propose a solution for real-time query data and remote adjustment of parameters of smart greenhouse based on ZigBee wireless communication technology and cloud platforms. Li *et al.* (2021) designed a smart greenhouse monitoring system based on Alibaba Cloud. The system transmits environmental data collected by sensors to the Alibaba Cloud platform *via* a GPRS network and industrial router to realize remote monitoring of greenhouses.

However, wireless technologies like Wi-Fi and ZigBee used in these approaches have drawbacks such as short communication distances or high-power consumption. LoRa communication technology addresses the seemingly contradictory problem of ultra-long distance and low power transmission (Li *et al.,* 2022; Rong *et al.,* 2023). Nevertheless, due to the half-duplex nature of LoRa communication, traditional solutions generally use TDMA or polling communication methods (Ou *et al.,* 2022; Sumalan *et al.,* 2020). Terminal collection nodes actively report data within specific timeslots assigned by the central base station, entering sleep mode during other timeslots to minimize power consumption, and effectively addressing data collision issues. However, this method cannot provide differentiated services, failing to meet equipment's needs for random control or communication of unexpected situations. In order to realize automatically adjust environmental parameters to meet the particular requirements for crops growing, based on an expandable awning structure of greenhouse , a communication protocol combining TDMA and random delayed competitive access (ALOHA) is proposed, which applied to form a star-type network consisted of a central base station and several terminal nodes, low-power chips and modules are selected to design the hardware. It can effectively realize the communication between different types of nodes with differentiated services, and ensure that the static nodes communication without data collisions and the also the competing nodes can quickly communicate with the central base station, while reducing node power consumption.

Design of greenhouse monitoring system

The greenhouse's ultimate objective is to employ organic materials in its construction, installing awning on the roof to regulate indoor light and use warm air fans, wet curtains and fans to adjust internal air temperature and relative humidity of air. To effectively monitor main parameters such as air temperature and relative humidity of air, soil moisture, and quantity of illumination in greenhouse, this work designs an environmental monitoring system based on long-range radio for greenhouse, therefore, monitoring and uploading relevant data to a remote server for managers to view.

Overall scheme of the monitoring system

The monitoring system in this project proposes a LoRa communication protocol based on the combination of TDMA and ALOHA, while choosing low-power chips and modules to design the hardware. The STM32 microcontroller, air temperature and relative humidity of air sensors, light sensors, *etc*. are used to collect environmental parameters and transmit them to the central base station using LoRa technology with strong anti-interference capabilities and a combination of TDMA and competing access The central base station uploads the data to a remote MQTT server (Kathrine, 2022; Lee *et al.,* 2019) *via* WIFI, where it is stored in a database for user queries. The system architecture is shown in Figure 1.

Protocol principle and implementation of communication

The LoRa network based on the TDMA and ALOHA is a start network, which consists of one central base station and several terminal nodes. Terminal nodes are divided into two categories: one is the static node based on TDMA, which mainly uses the characteristics of slow change environmental parameters in the greenhouse to divide the channel time slot into two zones. Each node upload data in the specific time slot I zone of the division. There is

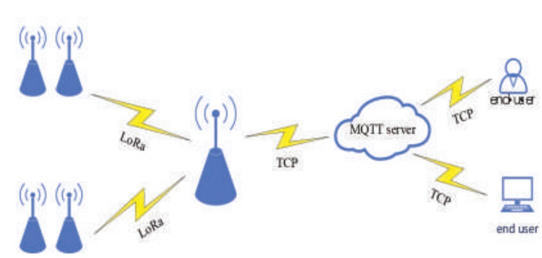


Figure 1. Monitoring system architecture diagram.

no data collision between such nodes and the central node communication, so the nodes will be retransmitted due to delay and have the lowest power consumption; the other type are contention nodes based on ALOHA, this category of nodes are mainly used to randomly control the device and report some unexpected status. In case of relatively high real-time requirements, data can be uploaded in zone II of any time slot. In the best case, data can be delivered or reported immediately without waiting.

Principle of timeslot division

The timeslot (TS) allocation schematic for LoRa communication with TDMA combined with ALOHA is shown in Figure 2. A polling cycle is divided into several timeslots, with each TS further divided into two zones: zone I for static timeslots and zone II for contention timeslots. The static timeslot in zone I is used for data reporting by data collection nodes (static nodes) and frame transmission of the data sent by the central base station. The contention timeslot in zone II is used for emergency data transmission with high real-time requirements, where all contention nodes can participate in the competition.

Clock synchronization

As the protocol necessitates the division of the channel into timeslots, it is imperative that the central base station and all nodes perform clock synchronization (Tsakmakis *et al.,* 2022). The clock synchronization in this protocol is achieved by the central base station sending a clock synchronization packet at a specific time, with all nodes opening a receiving window at a specific time to receive the clock synchronization frame. After receiving the clock synchronization frame, the current time is calculated according to Eq. (1) and the local clock is corrected and will be synchronized with the central base station clock.

In this method, the terminal node only adds one receiving window per time synchronization cycle to receive the clock synchronization frame, avoiding redundant data transmission, additional transmission power consumption and reducing costs compared to commonly used high-precision clocks or satellite timing.

$$T_c = T + T_{preamble} + T_{payload}T + d \quad \text{(Eq. 1)}$$

where, T_c (current time): current time when the relevant calculation or manipulation is performed.

T (central base station transmission time): time when central base station sends information to other devices or terminals.

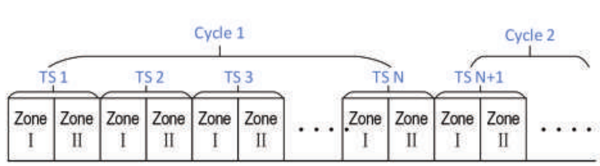


Figure 2. Timeslot allocation schema.

$T_{preamble}$ (guide code transmission time): a guide code is a specific code used in signal transmission. The transmission time refers to the time interval from the start of sending guide code at the sending end to the complete receiving of the guide code at the receiving end.

$T_{payload}$ (data packet transmission time): a data packet is a unit of information that contains valid data. The data packet transmission time is the time it takes for a data packet to be successfully sent from its sending end to its receiving end.

d (fixed time): a fixed value determined by software time delay testing. It represents the time delay due to various factors (*e.g.*, software processing speed, system resources allocation, *etc*.) in a given software environment and system.

Network access and timeslot allocation process

The timeslot allocation in this protocol includes both static and competition timeslots. Before a node accesses the network, it must send a network access request data packet to the central base station, including information such as network ID, node address, and node network type. After receiving the network access request data packet, the central base station determines the node's access number based on the node network type and the number of nodes already in the network. If the node is a static timeslot type, the access number increases sequentially from 1 to a maximum of 254. If the node is a competition type, the access number is 255, and the information of the node is saved locally while forming a network access confirmation data packet to be sent to the node. After receiving the network access confirmation frame, static network nodes calculate their own timeslot time, while competition network nodes calculate the transmission time for each timeslot II zone. When a node successfully accesses the network, the central base station will send a time synchronization frame to synchronize the newly added node's clock. The length of each timeslot, the timeslot cycle, and the time length of zones I and II can be determined by the central base station during initialization and sent with the network access confirmation data packet. The specific timeslot allocation calculation methods are as follows:

For static timeslot network nodes, the first upload timeslot start time after clock synchronization is:

$$T = t + (P - t\%P) + (\Delta t_1 + \Delta t_2) \times index \qquad index \in [1 \cdots 254] \quad \text{(Eq. 2)}$$

The start time of each remaining timeslot:

$$T = floor(\frac{t}{P}) \times P + P \quad \text{(Eq. 3)}$$

For competition-type network nodes, the next transmission time is:

$$T = floor(\frac{t}{\Delta t_1 + \Delta t_2}) \times (\Delta t_1 + \Delta t_2) + 2\Delta t_1 + \Delta t_2 + r \quad \text{(Eq. 4)}$$

where, T is the start time of the next timeslot or the next transmission time, Index is the device access sequence number obtained from the network access confirmation data packet sent by the central base station, Floor is the floor function.

Theoretical analysis

In the TDMA part, the total time is divided into frames of a fixed-length, each containing “” time slots. “” time slots are allocated as dedicated TDMA slots for static nodes. time slots are allocated as ALOHA competitive slots for competitive nodes. Time slots are allocated on demand to K devices with periodic flow. If the flow demand of device k is R_k time slots, then:

$$S_{TDMA} = \sum_{K=1}^{K} R_K, \sum_{K=1}^{K} R_K \leq M_1 \quad \text{(Eq. 5)}$$

In the competitive node part, suppose there are N devices in the system, and λ is the average transmission attempt rate of each device (the number of attempts to transmit per frame). In one competing slot, only one device sends data successfully. If each device transmits data independently, the collision probability is:

$$P_c = 1 - \left(1 - \frac{\lambda}{M_2}\right)^{N-1} \quad \text{(Eq. 6)}$$

The success probability is:

$$P_s = \frac{\lambda}{M_2}\left(1 - \frac{\lambda}{M_2}\right)^{N-1} \quad \text{(Eq. 7)}$$

The throughput of the competing part is the proportion of time slot for successful data transmission and is defined as:

$$S_{ALOHA} = M_2 \cdot P_S| \quad \text{(Eq. 8)}$$

The total throughput is the sum of the TDMA and ALOHA throughputs:

$$S_{ALOHA} = S_{TDMA} + S_{ALOHA} \quad \text{(Eq. 9)}$$

By adjusting M_1 and M_2, S_{total} can be maximized under the given flow demand and competitive flow, that is:

$$\max_{M_1, M_2} S_{total} = \sum_{k=1}^{K} R_k + M_2 \cdot \frac{\lambda}{M_2} \cdot \left(1 - \frac{\lambda}{M_2}\right)^{N-1} \quad \text{(Eq. 10)}$$

It can be seen from this that the increasing M_2 enhances the throughput of competitive nodes but reduces the throughput of static nodes. Therefore, a balance must be found according to the device requirements. In general, the hybrid protocol based on TDMA and ALOHA can meet the transmission requirements of both periodic and bursty flow by dynamically allocating time slots, thereby optimizing the throughput and efficiency of the system. Theoretical analysis shows that, with reasonable parameter selection, the hybrid protocol is significantly superior to the single protocol.

Processing flow of central base station

The central base station is mainly responsible for the admission management and data forwarding of each node. After receiving the network access request data packet of node, it initially determines whether the access information is stored locally. If this is the case, the node is re-accessing the network and transmitting the locally stored network information to the node. Alternatively, depending on the network type of the node, a network access confirmation data packet is generated and transmitted, and the network access information is saved locally. Unexpectedly, the central base station restarts, all node network access information will be lost, however the nodes are unable to sense it. Since static nodes will enter slumber mode and are unable to receive the broadcast re-networking commands from the central base station, when the central base station receives a data reporting packet, it initially checks whether the network access information of the node is stored locally. If there is, the data is processed directly, and send back a data confirmation packet. Otherwise, the node accessed the network before the central base station restarted, requiring re-networking. The data is processed and returned to a re-networking confirmation packet to re-access the network. The processing flow of the central base station is shown in Figure 3.

Node network access and data processing flow

Since environmental parameters change slowly in greenhouses, most sensor data do not need to be uploaded in real-time. Therefore, sleep should be prioritized by nodes to optimize battery life. The nodes above use static timeslots, woken up by alarms and upload data only in their communication timeslot, and no data collisions occurs during normal operations, which minimizes data retransmission and reduces power consumption. A small number of nodes that require higher real-time need to interact with the central base station, and communicate using a competitive access method, where data can be sent competitively with a random delay in II zone. each timeslot’s The node network access and mainly processing flow of data is shown in Figure 4.

Hardware design

Hardware design of data collector (static node)

The low-power data collectors (static nodes) that operate on long-range radio (LoRa) are extensively distributed throughout the greenhouse, where the environment is intricate, and wiring is challenging. Consequently, they are typically battery-operated. STM32L051 microcontroller of STMicroelectronics was chosen as the main control chip which was connected with SHT30 (SHT30 sensors, a high-precision air temperature and relative humidity of air sensor from Sensirion, Switzerland) sensor GY-30GN (GY-30GN Light Intensity Sensor from Shenzhen Yueguan Technology Co, Ltd., China); GY-30GN measures light intensity in lux(lx), with 380-780 nm wavelength (visible light). Light intensity sensor integrated BH1750FVI chip through IIC and connected with the Grove soil moisture sensor through the AD conversion interface to collect environmental parameters. The STM32L051 microcontroller communicates with the LoRa module Ra-01 based on the SX1278 chip through the SPI interface, using five IO ports to obtain and control the status of Ra-01 module. The data collected by the sensors are transmitted to the central base station, and the main circuit schematic shown in Figure 5.

In the entire hardware circuit, the SHT30 and GY-30 sensors connect to the main control chip *via* IIC, consuming extremely low power when idle, in the nanoamp range, so no special processing is required for their interfaces. The Grove soil moisture sensor, however, consumes milliamps of current according to tests, so to reduce system power consumption, its power supply is cut off via the main control chip pin when not collecting data to reduce the energy consumption. While the SX1278 module has a hibernation function, consuming about 200nA during the hibernation period, so no special handling is required for its power supply. The module is controlled by the program, sleeping while not sending or receiving data. The STM32L051 chip operates within the voltage range of 1.65V to 3.6V, the SHT30 sensor operates within the voltage range of 2.4V to 5.5V, the soil sensor operates within the voltage range of 2.0V to 5.0V, and the GY-30 light sensor operates within the voltage range of 3V to 5V. The LoRa module, which is dependent on the SX1278 chip, operates within the voltage range of 1.8V to 3.7V, with a typical operating voltage of 3.3V. To reduce the impact of power conversion chip efficiency on overall battery life when using battery power, with a maximum a lithium iron phosphate battery voltage of 3.6V and a rated voltage of 3.2V is selected to directly power the system.

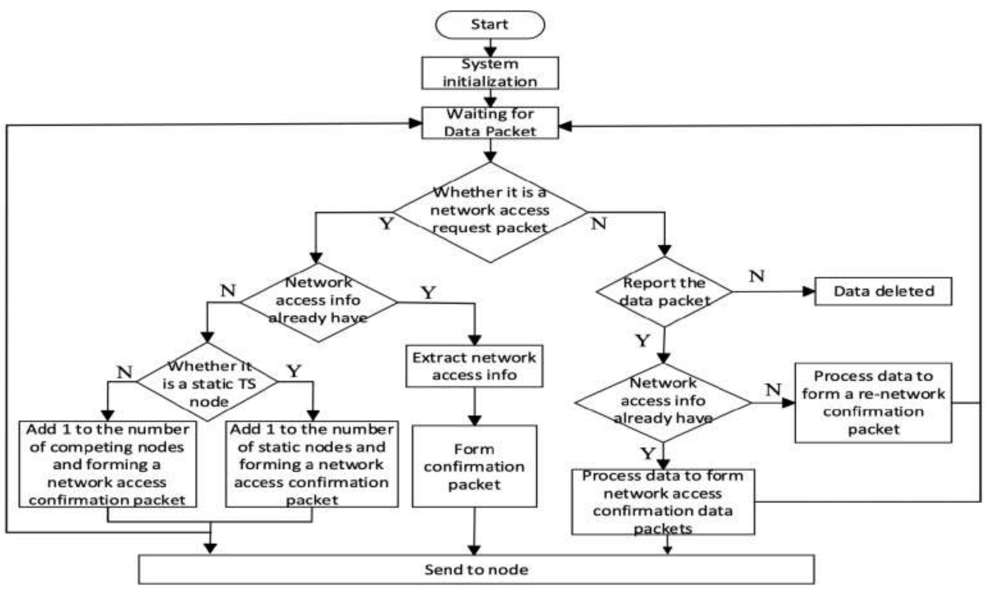


Figure 3. The processing flow of central base station.

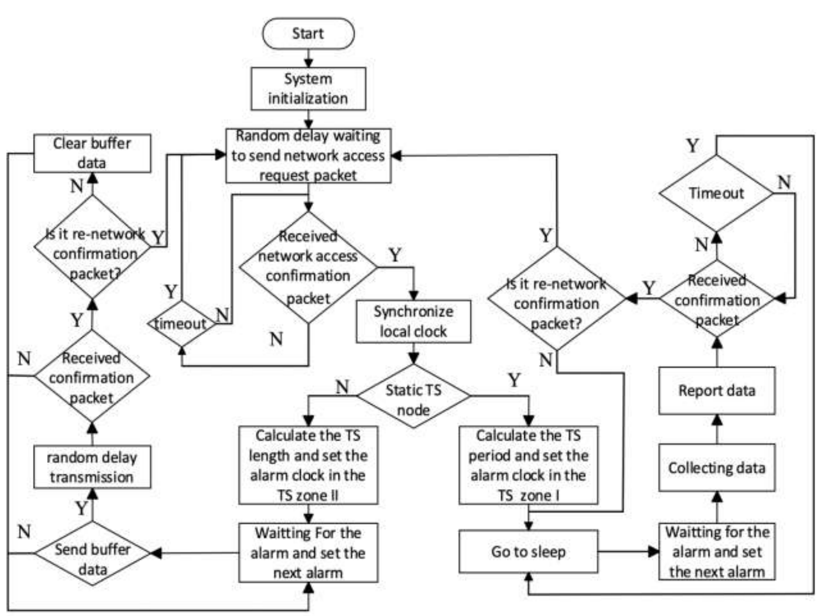


Figure 4. The processing flow of node.

Hardware design of central base station

The central base station, which serves as the nerve center of network, is accountable for the administration of nodes, the transmission of data uploaded by nodes to the server, and the receipt of commands from the server. It also needs to output relevant data via a serial port for debugging, use USB to provide 5V power supply to the system, and convert it into 3.3V to supply power to the other modules. The minimum microcontroller system and LoRa module circuits are the same as in the collection node circuit. The Wi-Fi module selection is based on Espressif's low-power ESP8266EX chip NODEMCU module, which communicates with the main control chip through serial port 2. The CH340C device from Nanjing Qinheng is employed in the serial port module for debugging output, which converts TTL to USB for subsequent connection to a computer. The circuit includes two main power-consuming modules: the LoRa module with a maximum current of about 90mA and the WIFI module with a maximum current of about 500 mA when powered on, with an average operating current of about 100 mA. Therefore, the current of the power supply should be ensured at least 600 mA. The 5V input power is stepped down to 3.3V for system power using an LDO linear regulator device AMS1117-3.3, which has a maximum output of 1A.

Experimental research

The main objective of this experiment is to test the feasibility and reliability of the communication of the monitoring system by monitoring the changes of air temperature and relative humidity of air inside the greenhouse. Since the test site is in southwest China, it belongs to the mid-subtropical humid monsoon climate. The test time was April, and the ambient air temperature was high when the weather was clear, so the greenhouse cooling test was chosen. The test is mainly divided into two parts:

i) When the air temperature of the greenhouse rises due to sunlight exposure, open wet curtains and awnings to monitor the air temperature and relative humidity of air changes in the greenhouse.
ii) Build a monitoring system software and hardware platform to collect data for communication protocol testing and hardware power consumption testing.

Setup of the experimental environment

The greenhouse is divided into three regions front to rear and five regions left to right, for a total of 15 awnings. The designed components in the structure are rod-shaped parts (made of metal water pipes and profiles) with low strength and rigidity, capable of withstanding limited torque. The structure must be designed with the torque that each component can withstand in consideration, as the awning area is significant, and the movement resistance is substantial. Additionally, since the main movements in the awning system are axial movements of the traction shaft and lateral movements of the traction rod, the movement speed of the traction shaft must be kept as slow as possible to avoid tearing the sunshade cloth during movement and to minimize torsional elastic deformation caused by manufacturing and installation errors. to prevent the sunshade cloth from being torn during the movement, and the torsional elastic deformation of the shaft is increased due to the gear shaft being long in the process of movement, the uneven driving resistance caused by the manufacturing and installation accuracy errors of each traction shaft, the movement speed of the traction shaft should be as slow as possible. The designed speed is 1 m/min, and the motor of 0.55KW is chosen to meet the requirements. The actual greenhouse is shown in Figure 6. The low-power data collectors (static nodes) based on LoRa are distributed over a wide range of the greenhouse. The collection modules are battery-powered to facilitate deployment, and the system power consumption must be minimized. The data collection module collects data every 10 min and uploads them wirelessly to the gateway, and sleeps in the rest of the time to reduce system power consumption and facilitate battery power. STM32L051 microcontroller of STMicroelectronics was chosen as the main control chip which was connected with SHT30 sensor GY-30GN light intensity sensor integrated BH1750FVI chip through IIC and connected with the Grove soil moisture sensor through the AD conversion interface to collect environmental parameters. The actual deployment of the collection modulus is shown in Figure 7. The static nodes connect to all sensors, with the fork-shaped probe of the soil sensor wrapped in a wet cloth to simulate insertion into the soil. All nodes are set to a channel frequency of 433 MHz, with a spreading factor of 7, a bandwidth of 250 KHz, a coding rate of 4/6, a timeslot period of 10 min, a timeslot duration of 5 s, zone I duration of 1 s, and zone II duration of 4 s. The soil moisture, ambient air temperature and relative humidity of air, light intensity, and other sensor data

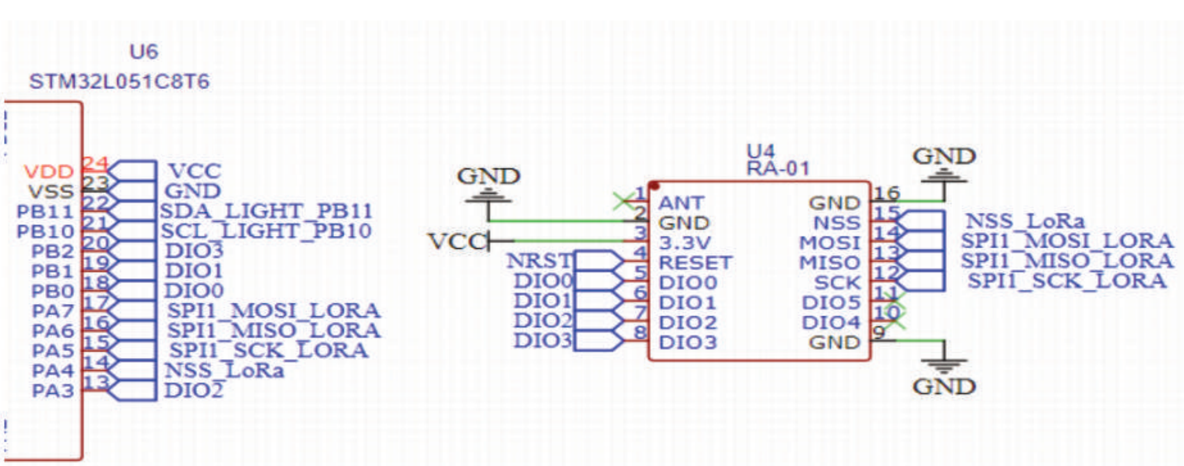


Figure 5. Ra-01 module and STM32 microcontroller interface circuit schematic.

are combined to create a data packet that is wirelessly uploaded *via* LoRa in each report.

Cooling test results and analysis

The test was performed at noon on a sunny day, when the air temperature in the greenhouse rises sharply, the awning was fully opened (expanded), the wet curtain and fan was turned on and set to the maximum speed to simulate the reduction of the indoor greenhouse air temperature. The specific test data are shown in Table 1 and Figure 8. At 12:00 noon, the outdoor air temperature was 18°C, the air temperature indoors near the flowerpots was 23°C, and the air temperature near the support frame about 3 meters above the ground was 32°C, with a relative humidity of air of 44%. At this time, the wet curtain, fan (set to maximum speed), and awning were activated. By examining the air temperature and relative humidity of air curves, after 90 min, the air temperature near the flowerpots dropped to 15°C, 8°C lower than the initial air temperature and 4°C cooler than the outdoor air temperature. The air temperature near the support frame dropped sharply to 19°C, with relative humidity of air increasing to 90%, and light intensity decreasing significantly. This indicates that the proposed solution effectively regulates the air temperature, relative humidity of air, and light in greenhouse. During the test, the greenhouse structure awning system operated smoothly, achieving the expected results.

Test of monitoring system communication

The central base station was designed according to the central base station processing flow shown in Figure 3, and the nodes were designed according to the nodes processing flow shown in Figure 4. The data collection nodes (static nodes) enter sleep mode when no data collection and transmission are required, waking up only during their timeslot to collect data and form a data packet for transmission *via* LoRa, then returning to sleep mode. The contention nodes use the same hardware as the static nodes but are programmed differently to simulate control functions of nodes, randomly delaying and contending to send and receive data in II zone of each timeslot, reducing communication delays and using this as hardware for testing.

Design of protocol test

For the common communication protocols such as Zigbee, Wi-Fi, NB-IoT, and LoRa, communication tests were conducted using the Network Simulator 3 (NS3) simulation platform. NS3 is a powerful network simulation tool suitable for research and development of various network protocols and communication technologies. In the simulation experiment, a total of 5 network nodes were created, where node 1 is the central node, nodes 2, 3, and 4 are static sub-nodes, node 5 is a dynamic sub-node. The probability of node 5 generating data packets obeyed the Poisson distribution. Under the same communication period (30 s), the performance in terms of latency, throughput, and power consumption is compared and shown in the Table 2.

Figure 6. Ra-01 module and STM32 microcontroller interface circuit schematic.

Table 1. Temperature and humidity test comparison.

Collection point	Initial Temperature (°C)	Initial humidity (%RH)	Temperature after 90 min (°C)	Humidity after 90 min (%RH)
Outdoor	18	/	19	/
Near flowerpots	23	/	15	/
Near support frame	32	44	19	90

Through the simulation experiments, it can be seen that LoRa is suitable for applications with low-power and low data rate. Wi-Fi has the lowest latency and is suitable for large data communications. Considering the application scenarios of greenhouse sheds, LoRa communication technology is more appropriate to be chosen.

Ablation testing

For ALOHA, TDMA, and TDMA+ALOHA access protocols, recording process and time of each sub-node transmitting data packets, and process and time of main nodes receiving data packets, setting different data packet lengths, the simulation results are shown in Figure 9. As shown in Figure 9, as the length of the data packet increases, the network throughput of the ALOHA protocol, TDMA protocol, and TDMA + ALOHA protocol keeps on rising. A relatively severe data packet collision issue exists in the ALOHA protocol, leading to the minimum network throughput and significant packet loss. In the TDMA and TDMA + ALOHA protocols, monitoring nodes only send data packets in fixed time slots and there is a retransmission mechanism. Therefore, packet loss is less and the network throughput is higher than that of the ALOHA protocol. Meanwhile, the TDMA + ALOHA protocol avoids the waste of idle time slots and shortens the time length of each time slot, and has a shorter network delay than the TDMA protocol. More data packets can be received within the same period of time. Therefore, the network throughput of the TDMA + ALOHA protocol is higher than that of the TDMA protocol.

As depicted in Table 3, through ablation comparison analysis, the hybrid protocol based on TDMA and ALOHA can take into account the communication requirements of different nodes under reasonable parameter settings, and optimize the throughput of the system and the reliability of data transmission.

Protocol test results

After testing, the information output from the serial port of the central base station is shown in Figure 10. The STM32L051C8T6 microcontroller packaged in an LQFP48 package with structural dimensions of 7.00 × 7.00 × 1.60 mm. The SX1278-based LoRa module Ra-01/02 is a small-volume, dual-row, postage-stamp-hole SMD package with dimensions of 17×16×3 mm.

As shown in Figure 11, a total of 6,521 timeslot cycles were conducted, with the communication statistics of the central base station and nodes summarized in Table 4. The static timeslot node (Node 1200) had no data collisions in its data transmission, successfully transmitting 1,081 times with a 100% success rate. Contention

(a) Soil moisture sensor

(b) Illumination sensor

Figure 7. Collection modules deployment diagram.

Table 2. Experimental comparison of four communication methods.

Feature	LoRa	NB-loT	Zigbee	Wi-Fi
Average latency	1.3 s	3.7 s	40.3 ms	25.1 ms
Average throughput	39 kbps	55 kbps	73 kbps	102 Mbps
Energy consumption (Average current)	Standby: 12.4 uA Active: 62.8 mA	Standby: 31.5 uA Active: 72.2 mA	Standby: 25.5 uA Active: 69.5 mA	Standby: 97.5 uA Active: 160.5 mA

Standby includes both sleep mode and standby mode, while active includes receiving and transmitting modes.

Table 3. Experimental comparison of three protocols.

Protocol type	Network error rate	Average throughput (bit/s)	Average latency (s)
ALOHA	0.238	106.4	0.328
TDMA	0.039	147.8	0.276
TDMA+ALOHA	0.021	201.7	0.203

Table 4. Communication results.

Node	Number of data transmissions	1 communication success	2 retransmission success	3 retransmission success	3 retransmissions still fail	Success rate
Central base station (contention transmission)	1793	1719	37	0	0	100%
Static node (1200)	1081	1081	0	0	0	100%
Contention node 1 (1201)	1948	1801	66	5	0	100%
Contention node 2 (1208)	1936	1791	71	1	1	99.95%

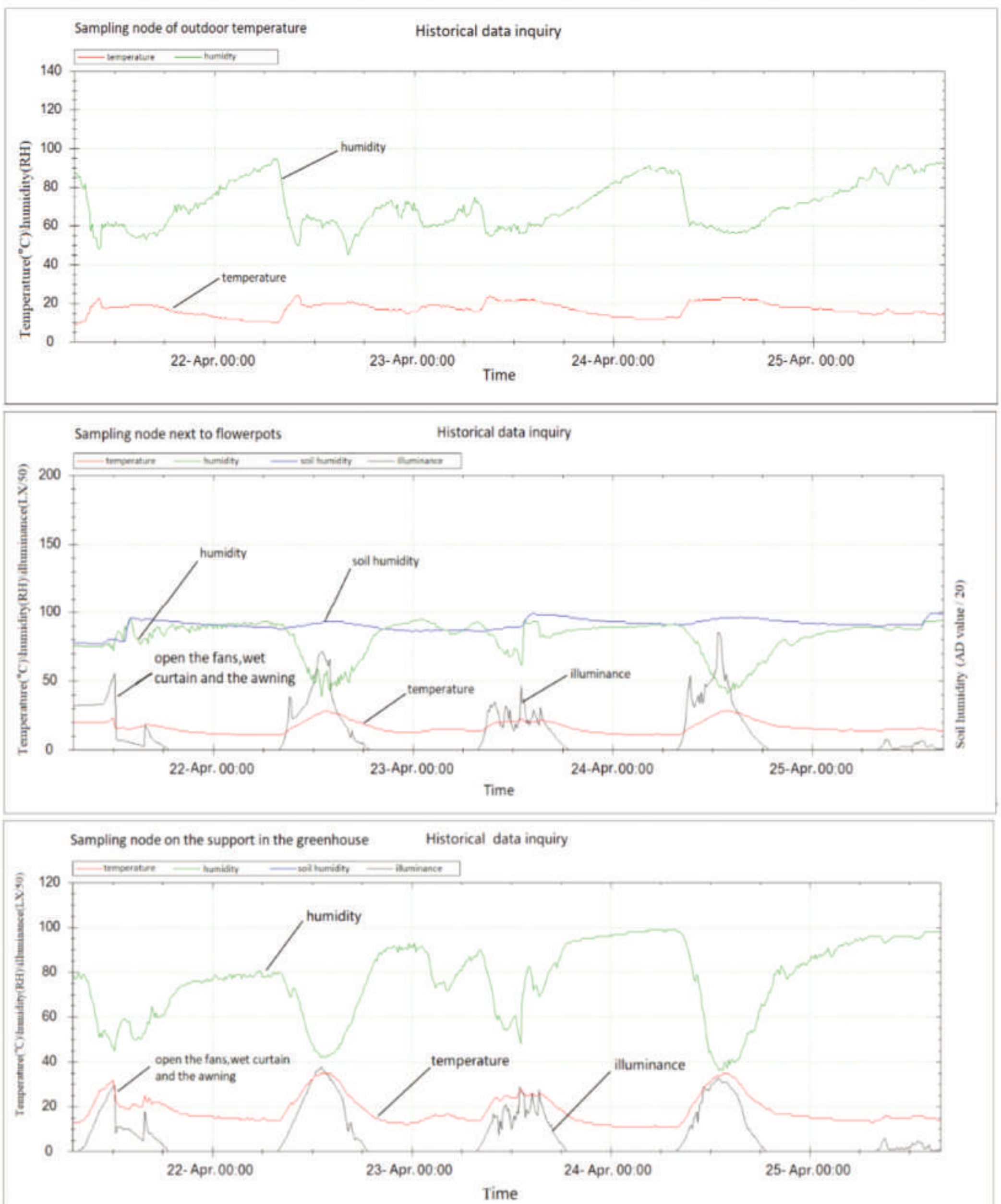
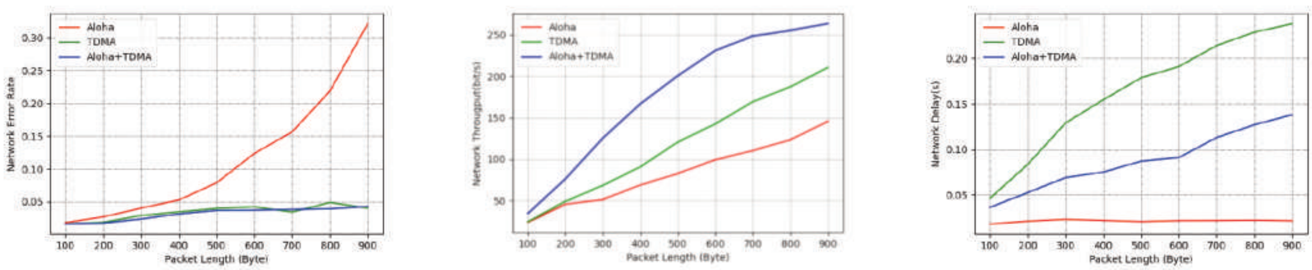


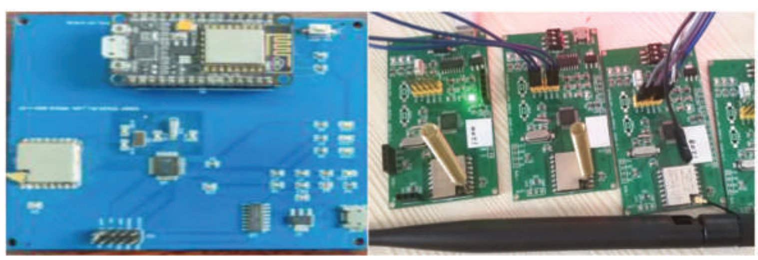
Figure 8. Historical data curve of indoor and two outdoor collection points.

nodes experienced data collisions, leading to retransmissions. Node 2 (Node 1208) communicated 1,936 times, with one experience of failure after two retransmissions, resulting in a 99.95% success rate. By adjusting the number of retransmissions, data communication can be ensured 100% successful. Further analysis of the communication log reveals that retransmissions were mainly caused by data collisions, with a few failures due to unknown interference. Multiple tests with different parameters, such as reducing bandwidth and increasing the spreading factor, were conducted. Using the same timeslot parameters as the previous test increased the probability of data collisions, while the opposite reduced the probability of data collisions, significantly improving the communication success rate. Increasing the zone II timeslot duration also effectively reduced the probability of data collisions. Consequently, the



(a) Network error rate (b) throughput (c) latency

Figure 9. Comparison of ablation experiments under different data packet lengths.



(a) Central base station (b) Node hardware

Figure 10. Physical drawing of test.

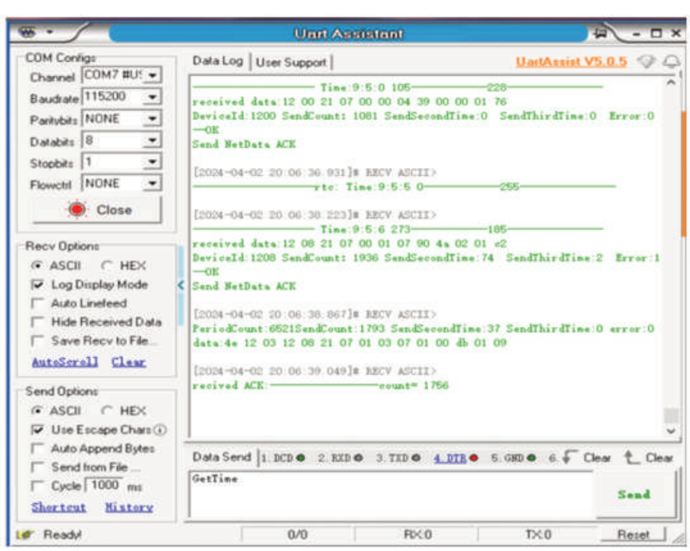


Figure 11. Communication log of central base station.

LoRa parameters, timeslot duration, and other specifications need to be adjusted in accordance with the specific application scenario.

Test of hardware power consumption

Test equipment

UNI-T UTP3313TFL-II (adjustable power supply). Desktop Multimeter: KEITHLEY DMM6500 6.5-Digit Multimeter.

Test parameters

Static nodes access to all sensors, with the fork-shaped probe of the soil sensor wrapped in a wet cloth to simulate insertion into the soil. All nodes are set to a channel frequency of 433 MHz, a spreading factor of 7, a bandwidth of 250 KHz, a coding rate of 4/6, a timeslot period of 10 min, a timeslot duration of 5 seconds, with zone I lasting 1 s and zone II lasting 4 s. The soil moisture, ambient air temperature and relative humidity of air, light intensity, and other sensor data are combined to create a data packet that is wirelessly uploaded *via* LoRa in each report.

Test process and results

Setting adjustable power supply to 3.3 V and use it as the node power supply. The positive terminal connected to the power positive terminal of the node, the power negative terminal of the node connected to the positive terminal of the desktop multimeter, and the negative terminal of the desktop multimeter connected to the negative terminal of the adjustable power supply. The test results are shown in Figure 12, which indicates that during the data transmission, the current is 102.5 mA at maximum and 2.68 uA at minimum, and a sleep current is generally maintained at 3.2 uA, with an average current of about 16.5 uA. If a 1000 mAH battery is used, the battery can theoretically last about 6 years.

Data forwarding test of central base station

The MQTT server-side host, developed in C# is capable to manage the central base station, retrieve node-reported data forwarded by the central base station, and send commands to contention nodes. During actual operation, the nodes and central base station ran stably, with occasional data upload failures due to unstable wireless Wi-Fi. However, the system automatically reconnected and logged into the server when Wi-Fi stability was restored. The collected historical data curves are shown in Figure 13.

Conclusions

From the above analysis, the expandable awning structure and composite greenhouse structure designed with wet curtains and fans can effectively reduce the air temperature and relative humidity of air in the greenhouse, with tests showing a air temperature reduction of 4°C compared to outdoor conditions, with relative humidity of air rapidly increasing to 90%.

Based on the shading greenhouse described above, the TDMA and ALOHA combined communication protocol is used to manage communication by node type, ensuring no data collisions for static node transmission while minimizing power consumption, improving data transmission real-time performance for contention nodes, and reducing data transmission delay. By selecting appropriate communication parameters and controlling the number of retransmissions attempts for transmission failures, communication reliability is ensured, achieving differentiated services. The data collector designed with the STM32 microcontroller based on this protocol was tested and found to have low power consumption, making it suitable for battery-powered collection nodes in greenhouses.

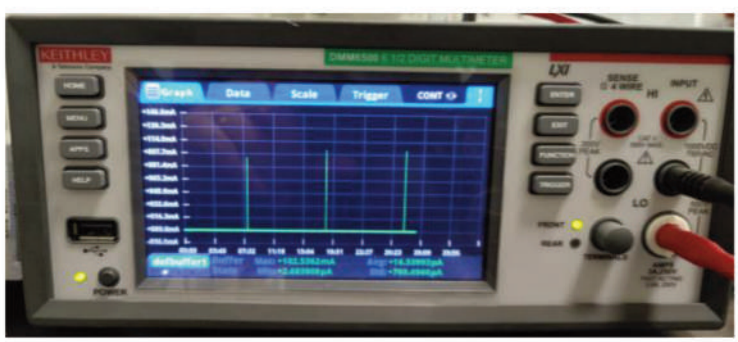


Figure 12. Power consumption test result.

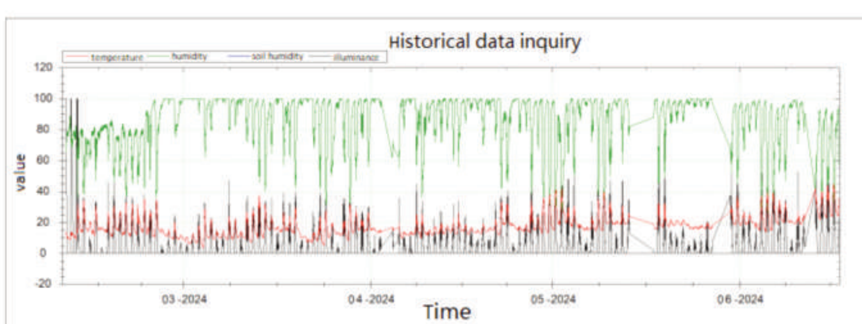


Figure 13. Central base station reported historical data query.

The optimization schemes facilitate the embedding of greenhouse automatic control systems to improve the application of greenhouse automatic control technology.

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