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Article

Design of Wireless Sensor Network for Agricultural Greenhouse Based on Improved Zigbee Protocol

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Abstract: Greenhouse cultivation technology has greatly contributed to the development of agriculture in Malaysia. Understanding how to monitor the greenhouse environment with high efficiency and low power consumption is particularly important. In this research, a wireless sensor network for agricultural greenhouses based on the improved Zigbee protocol is designed. Its hardware consists of various sensors and Zigbee nodes commonly used in agricultural greenhouses. On the basis of this hardware, this research designed the network topology of WMN (Wireless mesh network) by comparing the advantages and disadvantages of various topologies, and combined with this structure, proposed an improved ZigBee routing protocol EMP-ZBR to solve the question regarding energy loss and the network congestion of wireless networks. After testing EMP-ZBR and traditional Zigbee routing protocols, the improved EMP-ZBR protocol is superior to traditional Zigbee routing in terms of the end-to-end average delay, packet delivery rate, routing control overhead and routing discovery frequency, which were optimized about 1.1%, 15.2%, 15.2%, 8.1 ms in different mobile pause times, and 9.8%, 19.3%, 15.7% and 121 ms in different packet sending rates. The agreement proves that EMP-ZBR can more effectively alleviate the impact of congestion and improve the overall performance of the data monitoring system for agricultural greenhouses.

Keywords: agricultural sensor network; EMP-ZBR; network topology; routing transmission algorithm

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1. Introduction

In the early stages, agricultural data monitoring relied mainly on manual statistical methods and instrument-based monitoring [1]. However, in recent years, various information technologies have begun to be applied to the data monitoring of agricultural greenhouses [2]. Since agricultural greenhouses usually occupy a large area and require many monitoring nodes, and agricultural greenhouses are generally distributed in the suburbs [3], this requires high networking performance and the power consumption of data collection equipment. ZigBee technology is a wireless two-way communication technology based on the IEE802.15.4 protocol standard. It has the characteristics of a low frequency band, low power consumption and low cost [4], which can meet the needs of agricultural greenhouse monitoring; some scholars have carried out research on Zigbee or other types of technology in agricultural greenhouse monitoring and achieved some results.

Kang BJ and other scholars [5] developed an automated system for greenhouses, which stores information on greenhouse temperature, moisture, leaf temperature and leaf moisture in a database. The system is designed using Zigbee to enable the collection and automated control of plant information within the system. T.Veeramani kandasamy and other scholars [6] used GSM and Zigbee to build an automatic system for monitoring agricultural water resources and crop growth, so as to achieve the purpose of increasing food production. Zhang Hui and other scholars [7] proposed a wireless communication data acquisition system based on Zigbee and 4G, which meets the short-distance communication and long-distance data transmission. Yang Wei and other scholars [8] proposed a wireless-based real-time monitoring environment solution in accordance with the environmental monitoring requirements. It is designed to monitor environmental parameters using Zigbee. Xiao Xiao and other scholars [9] improved the Zigbee routing algorithm according to the actual application environment, and optimized the data transmission process and node energy usage according to the characteristics of different systems. Li Yan and other scholars [10] improved the ZBR routing algorithm and clustered the entire network. When the algorithm selects the cluster head, it has various factors around the cluster head, the life cycle of cluster head and the remaining energy of nodes. Niu Yugang and other scholars [11] addressed the congestion problem in the Zigbee network by considering node congestion avoidance and energy consumption balance, but the algorithm did not consider the node load and energy issues. Shan Chenggang and other scholars [12] designed a multi-path selection algorithm SMSA. This algorithm calculates the frequency of data packet collisions in the transmission process, and selects the least collisions as the reference target, which can effectively reduce the transmission delay, but it also does not consider the remaining energy of the nodes in the transmission path.

In the above studies, although researchers in various countries have conducted extensive research and made some improvements to Zigbee routing algorithms, most studies are aimed at general Zigbee algorithm improvements or the application of Zigbee in some specific environments, and few studies have combined the above two aspects. At the same time, most studies on Zigbee are mainly for outdoor crops and there are few studies on greenhouse vegetables. Although there are new technologies similar to Zigbee, for example, in May 2015, Huawei and Qualcomm jointly researched a solution called NB-CIoT (NarrowBand Cellular IoT) [13,14], but since the new technology has only been developed for a few years, it is far less mature than Zigbee.

Therefore, this research uses Zigbee as the research object; a greenhouse monitoring system based on the improved Zigbee algorithm is designed, which forms the wireless sensor network through various sensor nodes, and improves the network topology and routing algorithm of Zigbee to achieve high-efficiency and the low-consumption monitoring of environmental parameters. Compared with the previous research, this research innovatively combines the wireless topology structure with the improved Zigbee routing algorithm; it not only optimizes Zigbee itself, but also optimizes the wireless network composed of Zigbee, and is mainly oriented to the vegetable and fruit scenes in greenhouses, making the research more realistic.

2. Design and Implementation of the Wireless Sensor Network

2.1. Topology Design of the Wireless Sensor Network

In this research, the data required for crop monitoring were collected using various sensors commonly used in greenhouses and Zigbee in battery self-powered mode to form a wireless sensor network [15]. Due to the large number of Zigbee nodes required in actual production, a good network topology is particularly important for the fast communication between the network nodes. There are three types of Zigbee networks, namely, star topology, tree topology and WMN topology [16]. By comparing the advantages and disadvantages of various topologies, this research designed a WMN network topology; it uses direct data communication between routers, which can prevent the potential failure of the entire network system in the star model in case a problem with the coordinator is caused by a single link (Figure 1 shows the Zigbee wireless network topology).

The coordinator, router, and terminal are interconnected in layers, which expand the monitoring area and the establishment and later maintenance of the network. The devices communicate with one another in the Zigbee wireless network, and their own addresses are unique. According to the IEEE802.15.4 standard [17], the address of the devices consists of a 64-bit physical address and a 16-bit network address. However, it is worth noting that the physical address of all Zigbee devices is standardized at 64 bits, with nothing required to be carried out to the physical address or the Zigbee network structure; thus, the allocation of the network addresses is indeed crucial in the Zigbee network. The distribution of Zigbee network addresses is determined by the relationship between parent nodes and child nodes within the network. The parent node in the lower layer can establish connections with child nodes. On the other hand, child nodes can only connect to the parent nodes in the upper layer. L_m, C_m and R_m are three essential values in the Zigbee network, which, respectively, represent the Zigbee network level, the number of child nodes that can be connected to the parent nodes and the number of routers in the network [18,19]. The address interval can be calculated. The address interval can be calculated according to Equation (1):

$$Cskip(d) = \begin{cases} 1 + C_m \times (L_m - d - 1) & R_m = 1 \\ \left(1 + C_m - R_m - C_m \times R_m^{L_m - d - 1}\right) / (1 - R_m) \end{cases} \quad (1)$$

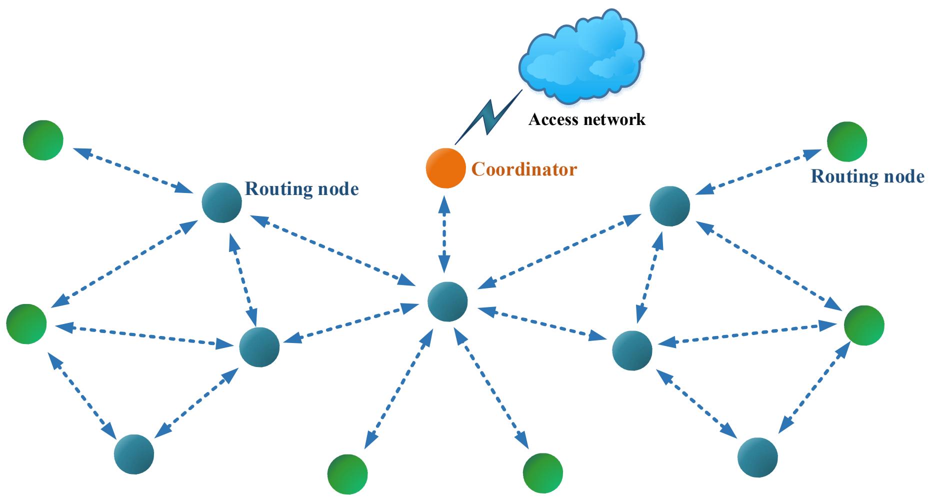

Figure 1. Zigbee wireless network topology.

In a Zigbee wireless network, the network topology works and the network address of each device can be calculated, as shown in Figure 2.

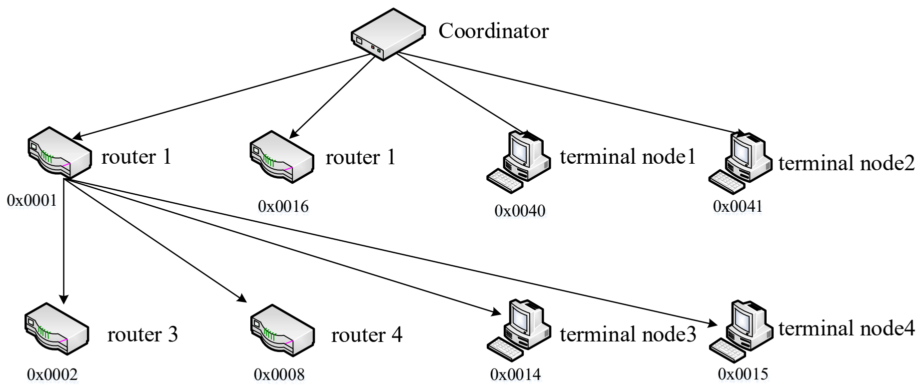

Figure 2. Network address distribution of each device in the WMN network.

Determining the network address of each device is of great importance for wireless sensor networks. If a single device is abnormal or faulty, the network address can quickly determine the faulty node, which can greatly facilitate the operation of wireless sensor networks.

2.2. Routing Protocol Design

The transmission delay and the successful reception rate of data packets in the ZigBee network will be affected by the routing protocol to a large extent. In order to make the network more stable, this study proposes an improved ZigBee-based routing protocol EMP-ZBR after combining the designed WMN network topology, thereby reducing energy loss and relieving network congestion.

First, the cross-layer mechanism is introduced on the basis of the original Zigbee routing protocol, in which the routing layer can obtain the queue buffer packets in the MAC (Media Access Control Address) layer and use the length of the cache queue in the node to determine the load of the node, defined as the queue cache group occupancy, according to the protocol built on an agricultural information monitoring system; the energy consumption of the node is determined against the total energy in the node and the energy consumed [16], and is defined as the energy consumption occupancy ratio. The algorithm description: Q_{cr} and E_{cr} is defined to represent the cache packet occupation ratio and energy consumption ratio of the node, respectively. Q_{cr} and E_{cr} values are defined as Equations (2) and (3):

$$Q_{cr} = Q_{le}/Q_{max} \tag{2}$$

$$Q_{cr} = \left(E_{int} - E_{left}\right)/E_{int} \tag{3}$$

Among them, Q_{le} represents the length of the cache queue at the moment of the node, and Q_{max} refers to the maximum cache queue length that the node can accommodate. E_{int} represents the total energy of the node at the beginning, E_{left} represents the remaining energy of the node after working for a period of time and E_{int} E_{left} represents the total amount of energy consumed by the node during work.

The routing update criterion for the Zigbee routing protocol was then improved accordingly. In the original Zigbee protocol, the shortest hop count is applied as the routing update criterion; while MP-ZBR (Multi-Link Zone Border Router) is the routing protocol, the new routing update criterion cost is applied. The value of cost will be calculated following certain rules through the energy consumption ratio of intermediate nodes, cache packet occupation ratio and link quality. When the RREQ (Route Request Packet) packet arrives at the intermediate node [20], the E_{cr} (the energy consumption ratio in the node), Q_{cr} (cache packet occupancy ratio) and the link quality LQI value are first calculated. Q_{cr} and E_{cr} are calculated in Equations (4) and (5). The LQI value can be obtained by calculating the received signal strength RSSI value, which is an integer from 0 to 255. The larger the LQI value, the better the link quality. The Q_{cr}, E_{cr} and LQI values are added to Q_{crsum} (the sum of the node load ratio), Q_{ersum} (the sum of the energy consumption ratio) and L_sum (link quality sum). To unify the rules, the L_sum value is defined as the reciprocal of the sum of the actual link quality, and the cost value is calculated with the following rules:

$$Q_{crsum} = \sum Q_{cr} \tag{4}$$

$$E_{crsum} = \sum E_{cr} \tag{5}$$

$$\text{L\_sum} = 1/\sum LQI \tag{6}$$

$$\cos t = \alpha \frac{Q_{crsum}}{hop\_count} + \beta \frac{E_{crsum}}{hop\_count} + \lambda \frac{\text{L\_sum}}{hop\_count} \tag{7}$$

where α, β and λ are the weight value and satisfy α + β + λ =1. The greater the weight value, the greater the influence of the node energy condition or the node's buffer queue length and link quality condition on the routing update criterion. Since this research studies the impact of congestion on the network, after multiple experimental verifications, α the value of α is 0.4 and the values of β and λ are 0.3. Q_{crsum} is the sum of the proportions of all node cached packets experienced by the RREQ packet from the source node to the receiving or forwarding node, and E_{crsum} is the sum of the energy consumption proportions of all nodes experienced by the RREQ packet from the source node to the receiving or forwarding node. Also, L_sum is the sum of the link quality of all nodes experienced by the RREQ packet from the source node to the receiving or forwarding node, and Hop_count is the total number of hops experienced by the RREQ packet from the source node to the receiving or forwarding node [21]. $\cos t$ is the energy consumption, queue buffer score, and link quality of the RREQ packet from the source node to the receiving or forwarding node. The smaller the average energy consumption ratio and the average cache packet occupation ratio in the path are, the higher the link quality is, and the lower the $\cos t$ value is, indicating a better comprehensive performance of the path. At this time, the established path will be relatively stable, and can effectively alleviate network congestion.

Finally, this research improves the path establishment method of the Zigbee routing protocol, and finds an effective path for the source node to reach the destination node by RREQ packets during the routing discovery process [22]. Upon receipt of a RREQ packet, the destination node initiates the cache timer and sends the RREP (Residential Real Estate Project) packet back to the source node in the order of their arrival [23]. After the first RREP packet hits the source node, the source node will cache all the RREP packets that arrived during this period before the timer expires, and sorts these packets according to certain priority rules. The path with the highest priority is defined as the primary path, and the path with the second priority is defined as the backup path. When the main path is successfully established, the data are preferentially transmitted to the destination node through this path. When the primary path cannot continue to transfer data due to congestion, the previously established backup path is selected to successfully transmit the data to the destination node. The improved algorithm first compares the comprehensive performance index cost value of each feasible path in the path establishment process, and selects the path with the lowest cost value as the main path during data transmission [24]. As maintaining multiple backup paths would consume more network resources, this article will select only one backup path from other paths. Figure 3 shows the specific flow of the algorithm.

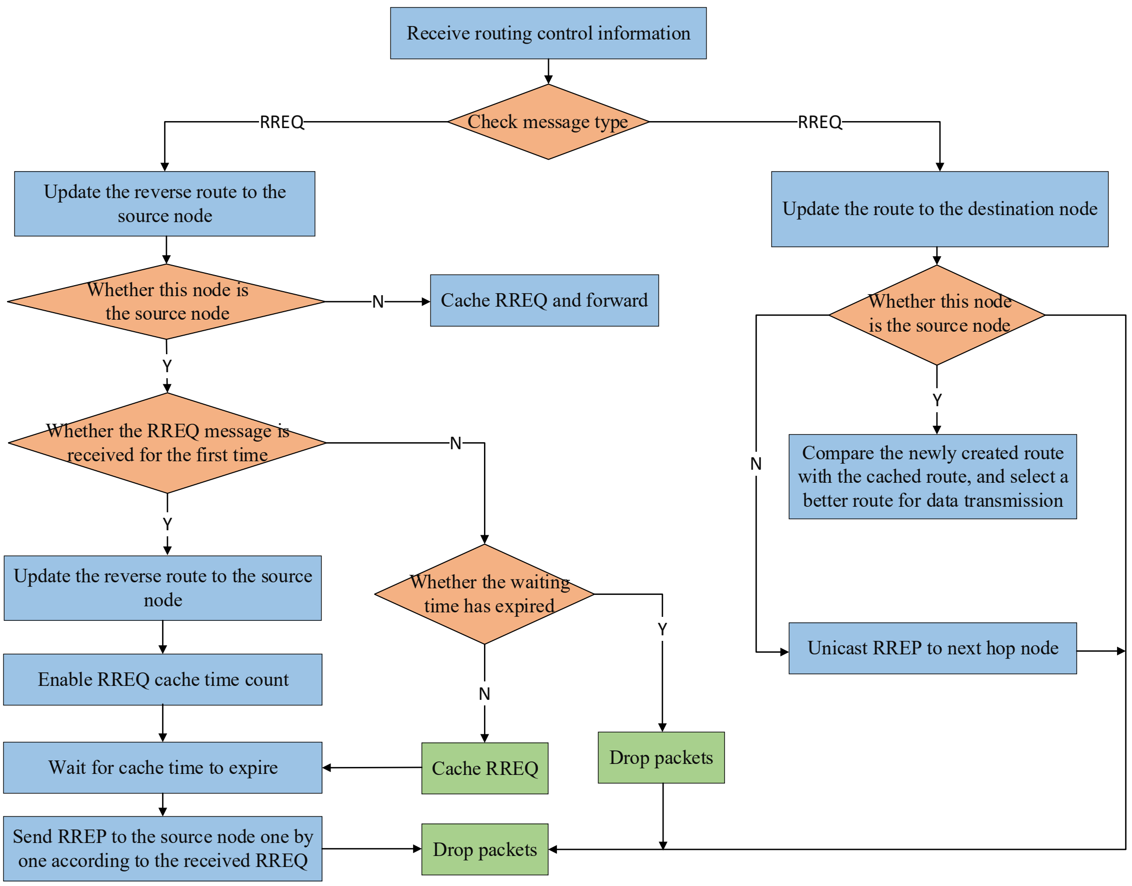

Figure 3. The specific flow of the algorithm.

3. Experimental Design and Results

3.1. Experimental Design

NS2 (Network Simulator Version 2) is a professional simulation software specially used for network simulation [25]. It has very rich module components, its configuration is flexible and its scalability is relatively strong. It is favored by many scholars who study network technology. To this end, this research will randomly arrange a large number of sensor nodes in a certain area on the NS2 platform, imitating the actual system application situation, and set the node energy and packet sending rate in the network. Finally, in the same scenario, the proposed EMP-ZBR routing protocol and the traditional ZigBee routing protocol are simulated separately, and the performance of the two protocols is evaluated in four aspects: packet delivery rate, route discovery frequency, route control overhead, and end-to-end average delay.

3.2. Experimental Indicators

The indicators to measure the performance of the Zigbee routing protocol are the end-to-average delay and packet delivery rate. This research will use the following four indicators for the comparative analysis of the original ZigBee routing protocol and EMP-ZBR routing protocol:

(1) Packet delivery rate: This indicates the ratio of the number of data packets successfully reaching the destination node to the number of data packets sent by the source node. The larger the packet delivery rate, the better the reliability of the transmitted data [26]. Equation (8) is as follows:

$$Packet\ delivery\ rate = \frac{\begin{array}{c}The\ number\ of\ data\ packets\ successfully\\ reaching\ the\ destination\ node\end{array}}{The\ number\ of\ data\ packets\ sent\ by\ the\ source\ node} \tag{8}$$

(2) Route discovery frequency: This indicates the number of route requests initiated by the source node within a unit time. The higher the frequency, the greater the loss of network resources and energy [27]. Equation (9) is as follows:

$$Route\ discovery\ frequency = \frac{\begin{array}{c}The\ total\ number\ of\ routing\ requests\\ initiated\ by\ the\ source\ node\end{array}}{Simulation\ time} \tag{9}$$

(3) Routing control overhead: This indicates the ratio of routing control packets to received data packets. The more routing control packets, the more energy consumed by the network [28]. Equation (10) is as follows:

$$Routing\ control\ overhead = \frac{Total\ routing\ control\ messages}{Total\ number\ of\ packets\ received} \tag{10}$$

(4) End-to-end average delay: This represents the average time from the source node sending out the data packet to the destination node receiving the data packet in the whole process [28]. Equation (11) is as follows:

$$End-to-end\ average\ delay = \frac{Packet\ Received\ Time - Packet\ Sent\ Time}{Total\ number\ of\ packets\ received} \tag{11}$$

3.3. Experimental Environment Settings

In this study, in order to better simulate the real scene, a simulation area with a length of 10 and width of 30 ft $\times$ 90 ft is selected. A total of 60 nodes are randomly arranged in it, and 40 nodes are set to be in a static state. These node simulation systems have coordinator nodes and sensor nodes such as air temperature and moisture, soil temperature and moisture. The remaining 20 nodes are set as random mobile nodes. The random movement of nodes will make the network topology change more frequently so that the performance of the two protocols under different topological conditions can be studied and the final simulation results obtained are more authentic. Table 1 shows the simulation parameters.

Table 1. The simulation parameters.

Parameters	Value
Channel type	Channel/Wireless Channel
Network Interface	Phy/WirelessPhy/802_15_4
MAC type	Mac/802_15_4
Wireless communication model	Antenna/OmniAntenna
Transfer model	TwoRayGround
Topological size	30 ft × 90 ft
Number of nodes	60
Packet size	512 bytes
Simulation time	400 s
Energy model	EnergyModel
Node initial energy	80 J
Transmit power	0.85 W
Received power	0.49 W
Sleep power	0.15 W

3.4. Experimental Results

3.4.1. Result Analysis under Different Pause Times of Mobile Nodes

In this research, the CBR sending rate is always three packets/s, and the pause time of the mobile node is changed to 0 s, 50 s, 100 s, 150 s, 200 s, 250 s, 300 s, 350 s, 400 s. The node pause time will affect the network topology changes. The mobility of nodes in the network will weaken with the increase in the pause time, and the topology changes will gradually become stable [29].

(1) Packet delivery rate

Figure 4 shows the performance difference of the two routing protocols in the packet delivery rate under different mobile node pause times. Under the same circumstances, the packet delivery rate of the EMP-ZBR routing protocol is always greater than that of the ZigBee routing protocol, which increases the packet delivery rate by 1.1% on average, and improves the network congestion to a certain extent [30].

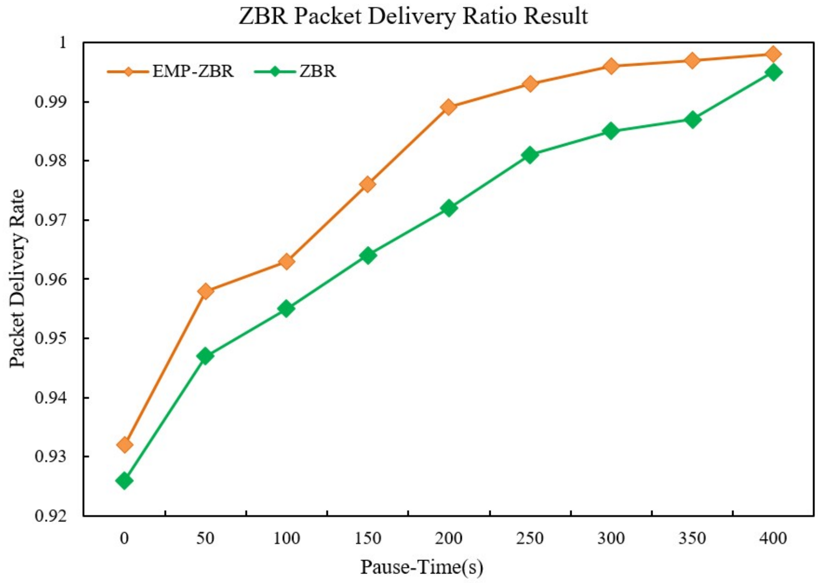

Figure 4. Result of the packet delivery rate at different pause times.

(2) Route discovery frequency

Figure 5 shows the difference in route discovery frequency of the two routing protocols under different mobile node pause times. Under the same pause time, the routing discovery frequency of the EMP-ZBR routing protocol is significantly lower than that of the ZigBee routing protocol, which slows down the routing discovery frequency by 15.2% on average, indicating that EMP-ZBR reduces the number of times the source node routing requests are initiated and that the network is more stable.

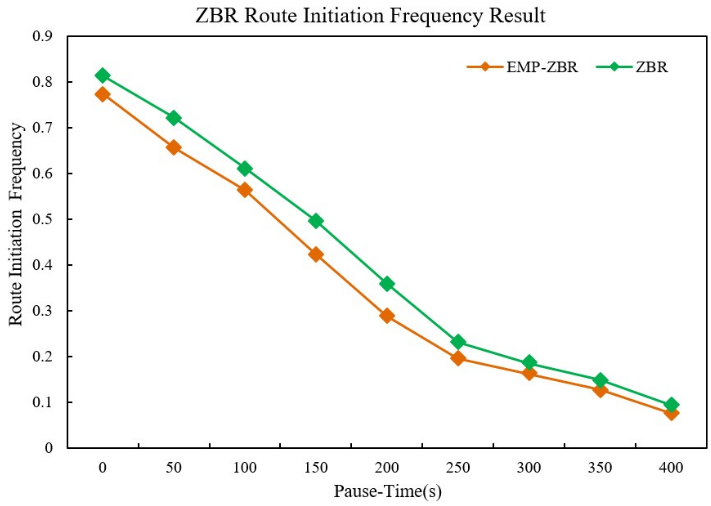

Figure 5. Route discovery frequency result with different pause times.

(3) Routing control overhead

Figure 6 shows the relationship between the routing control overhead and mobile node pause time. Under the same pause time, the EMP-ZBR routing protocol selects nodes with sufficient energy and a large remaining queue buffer length to establish paths, and fewer messages are used for routing initiation and routing maintenance. Compared with the traditional ZigBee protocol, the average reduction of 21% of the routing control overhead more effectively alleviates the impact of path congestion and link breaks on the network.

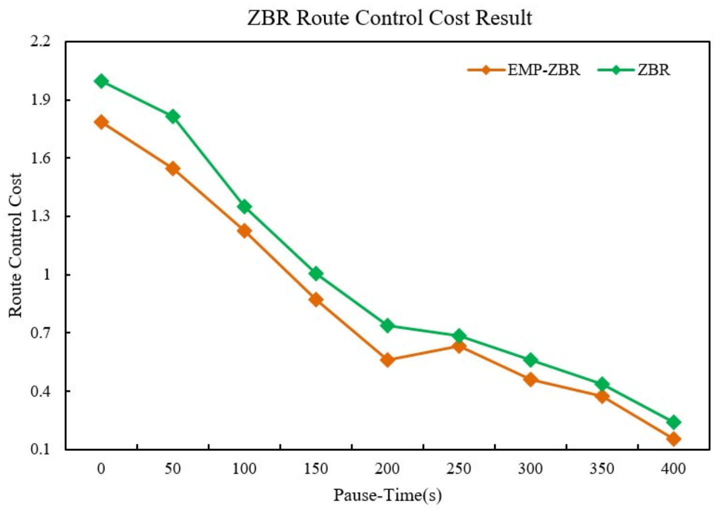

Figure 6. Routing control overhead results for different pause times.

(14) End-to-end average delay

Figure 7 shows the relationship between the end-to-end average delay and mobile node pause time. Under the same pause time, the average delay of the EMP-ZBR routing protocol is significantly lower than that of the ZigBee routing protocol, and it will not pass through congested nodes during data transmission, which reduces the average delay in the network [31]. Compared with the traditional ZigBee protocol, the EMP-ZBR routing protocol reduces the end-to-end average delay by 8.1 ms on average, which plays a great role in alleviating congestion.

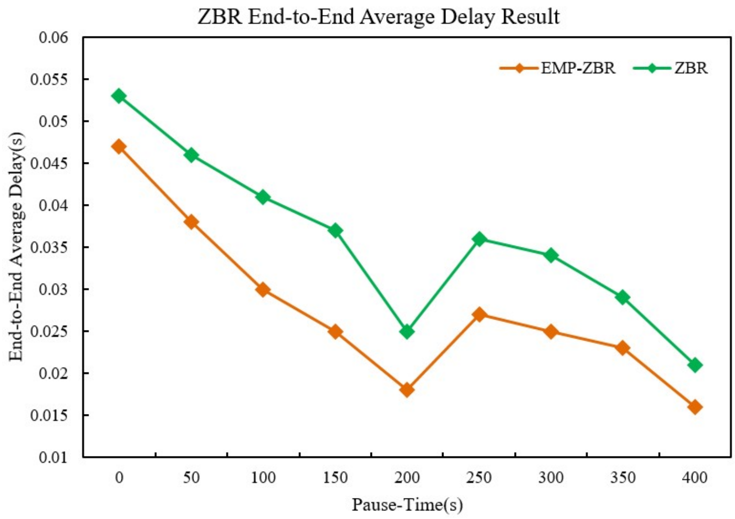

Figure 7. End-to-end average delay results for different pause times.

3.4.2. Analysis of Results at Different Packet Sending Rates

In this research, controlling the pause time of the mobile node remains unchanged (0 s), changing the CBR sending rate to 3, 6, 9, 12, 15, 18, 21, and 24, respectively. It reflects the load level of nodes in the network. The faster the packet sending rate, the stronger the node load, and the more prone to congestion.

(1) Packet delivery rate

Figure 8 shows the variation in the packet delivery rate of the two routing protocols under the background of different CBR packet sending rates [32]. As the packet sending rate increases, the packet delivery rates of the two routing protocols show a downward trend; however, the EMP-ZBR routing protocol always increases the packet delivery rate by an average of 9.8% compared to the traditional ZigBee protocol because it forwards the information criterion to avoid packet loss caused by some nodes due to heavy load, and improves network congestion.

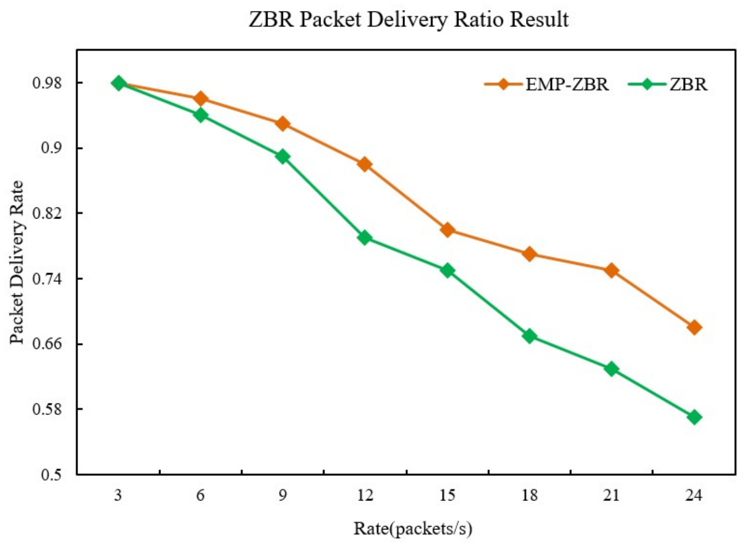

Figure 8. Packet delivery rate results at different packet sending rates.

(2) Route discovery frequency

Figure 9 shows the performance difference between the two routing protocols in route discovery frequency under different CBR sending rates. As the packet sending rate of nodes increases, the route discovery frequency of the two routing protocols gradually increases. However, the route discovery frequency of the EMP-ZBR routing protocol is always lower than that of the ZigBee routing protocol, which slows down the route discovery frequency by 19.3% on average [33]; this is because the IMP and ZBR routing protocol caches the backup path while establishing the main path. It can then use the backup path for data transmission, reducing the number of routing initiations, thereby reducing the energy consumption and network load.

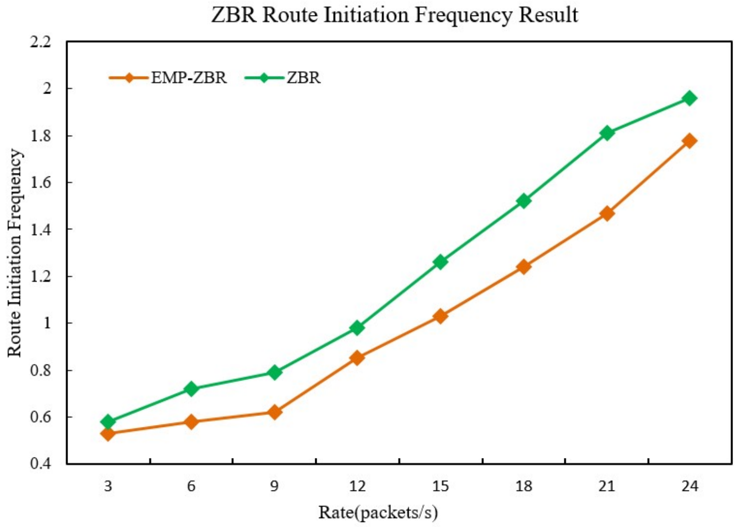

Figure 9. Route discovery frequency results at different packet sending rates.

(3) Routing control overhead

Figure 10 shows the difference in the routing control overhead performance of the two routing protocols at different CBR sending rates. The EMP-ZBR routing protocol improves the forwarding mechanism of the intermediate nodes. When forwarding data packets, it fully considers the energy of the intermediate nodes and the remaining status of the cache queue [34]. The frequency of route discovery and route maintenance saves the route control overhead; compared with the traditional ZigBee protocol, the route control cost is reduced by 15.7% on average.

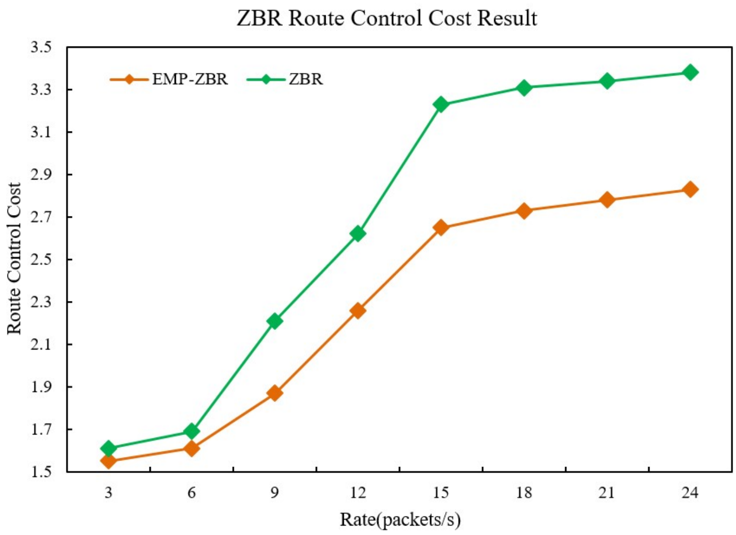

Figure 10. Routing control overhead results at different packet sending rates.

(4) End-to-end average delay

Figure 11 shows the differences in the end-to-end average delays of the two routing protocols at different CBR sending rates. As the CBR packet sending rate increases, the average network delay of the two routing protocols increases, but the delay of the EMP-ZBR routing protocol is always lower than that of the ZigBee routing protocol, reducing the average end-to-end average delay by 121 ms [35]. This is because it selects the effective path with the smallest average energy-occupied ratio, the average queue cache packet, and the largest link quality, thereby reducing the possibility of congestion.

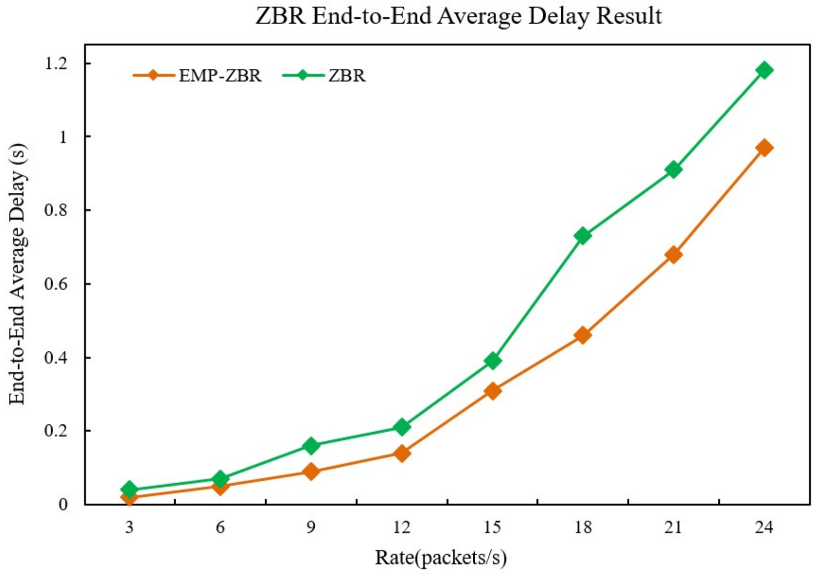

Figure 11. End-to-end average delay results of different packet sending rates.

4. Conclusions

In this research, a wireless sensor network for agricultural greenhouses based on the improved Zigbee protocol is designed. This research uses a variety of commonly used sensors and Zigbee to form an agricultural greenhouse data acquisition network, and improves the topology networking mode and routing algorithm of Zigbee nodes. After NS2 simulation experiments, the improved Zigbee sensor network shows lower network delay. The average end-to-end delay, high packet delivery rate, small routing control overhead and low routing discovery frequency prove that this research can effectively improve the network speed and reduce congestion, improving the overall performance of the agricultural information monitoring system. In the future, we envisage combining the wireless sensor network with 5G technology, connecting the 5G router through the Zigbee coordinator, and transmitting the collected sensor data to the remote terminal faster. In addition, we envisage combining the Zigbee network with the agricultural greenhouse control equipment so that the agricultural greenhouse control equipment can perform regular operations according to the environmental parameters of the Zigbee sensor network, so as to realize automatic production and remote terminal control.

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