A Communication Protocol for Cluster-Chain Wireless Sensor Network Based on Wake-On-Radio

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ABSTRACT To reduce unnecessary node wake-ups, further lower node energy consumption, and extend the network's life-cycle, sensor nodes are designed using a low-power micro-controller with electromagnetic wave wake-up capabilities. A cluster-chain wireless sensor network communication protocol is proposed, which activates nodes via electromagnetic waves. The sink node periodically broadcasts intra-cluster synchronization beacon frames to wake up all sensor nodes within the cluster and schedules cluster member nodes to transmit collected data to the cluster head node in time-sharing mode. By broadcasting multiple inter-cluster synchronization beacon frames, adjacent cluster head nodes are sequentially awakened and scheduled, enabling hop-by-hop data transmission until reaching the sink node. Experimental results demonstrate that the communication protocol performance is stable, and the network's life-cycle is further extended, better meeting engineering application requirements.

INDEX TERMS Cluster-chain WSN, Wake-On-Radio, time synchronization

I. INTRODUCTION

SMART agriculture can improve the efficiency and quality of agricultural production and promote agriculture sustainable. China's National Smart Agriculture Action Plan (2024-2028) vigorously advocates the development of facility agriculture. Wireless sensor network can be flexibly deployed to the monitoring area, can collect environmental data of crops and livestock in real time, can improve the management level of agricultural production, and then improve the yield and quality of agricultural products.

For greenhouse and greenhouse facilities horticulture, some scholars apply wireless sensor network in smart agriculture [1], [2], environmental monitoring [3]–[5], underwater Monitoring [6], [7], smart grid monitoring [8], [9], bridge monitoring [10]–[12], et al. Optimizing the energy efficiency of nodes and developing suitable communication protocols are the primary focuses current research. Usually, the method of timing wake up is adopted to make the MCU wake up periodically, from the sleep state to the working state, and the RF chip is awakened to enter the receiving state. Even if there is no data transmission, the MCU and the RF chip must wake up periodically to monitor the wireless signal, which undoubtedly increases the node energy overhead.

In order to further reduce invalid energy consumption and extend the node life cycle, we adopt the method of electromagnetic wave awakening (Wake-On-Radio, WOR). RF devices periodically enter WOR from sleep state and scan the air signal. When detecting the preset electromagnetic signal, it will be awakened and enter the working state to receive or send data, awaken the MCU and stay in sleep state without data transmission, thus reducing the invalid wake up of MCU and RF chip, and further saving the energy consumption of nodes.

II. DEPLOYMENT MODEL OF CLUSTER-CHAIN WIRELESS SENSOR NETWORK

To apply wireless sensor network to facility agriculture in different scenarios, we must design an appropriate network topology, deploy nodes effectively, and study efficient and reliable communication protocol.

A. CLUSTER-TYPE NETWORK TOPOLOGY

Wireless sensor network topology structure mainly has star-structure, linear structure, mesh structure and mixed structure of several structures, for application-oriented facilities agriculture wireless sensor network, generally adopt the method of deterministic deployment node, usually adopt mixed structure, some domestic researchers also adopt star structure and linear structure deployment network, considering the green house, greenhouses, cages and shed breeding environment is given priority to with rectangle, we use the cluster chain type topology structure, as shown in figure 1:

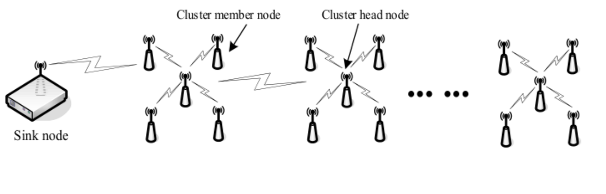

Fig. 1. Cluster-chain network topology

The sink node use electric-power supply with no energy, the sensor nodes use battery power supply with limited energy and operate in low power mode. The network consists of several clusters, each cluster along the type distribution, constitute the cluster chain structure. A network cluster is composed of a cluster head node and multiple cluster member nodes. The cluster member nodes exclusively exchange information with the cluster head node and maintain no direct communication among themselves. Data transfer occurs through multi-hop pathways from cluster head nodes to their respective cluster head nodes. The sink node possesses sufficient radio frequency transmission capability to reach all cluster head nodes and cluster member nodes within the network. In contrast, cluster member nodes have restricted transmission ranges, enabling communication solely with their designated cluster head node or adjacent nodes in the routing path.

Each sensor node is assigned one-byte id, consisting of the cluster number and cluster member number. Each cluster has a cluster number, each cluster member has the same cluster number and different within-cluster member number in a cluster.

B. WOR MACHINE-PROCESSED

When the wireless sensor network sensor node works, in order to save energy consumption, most of the time is in the sleep state of low power consumption. The MCU is periodically awakened, enters from the sleep state to the normal working state, and awakens the RF chip to enter the receiving state. In this mode, the operation and sleep of the RF chip are passively switched under the control of the MCU. Even if there is no data transmission or transmission, the MCU and the RF chip must wake up periodically, monitor the wireless signal, and determine whether to enter the working state, which undoubtedly increases the energy overhead of the node.

To further extend the node life cycle, We use an electromagnetic wave Wake-On-Radio(WOR) function of the low-power wireless micro-controller CC1101 to design the nodes, In the WOR mode, CC1101 sleep in the absence of a signal to save energy, wake-up and sleep periodically, wake-up once every cycle to scan the aerial signals, only when an electromagnetic wave signal meeting the preset conditions is detected, it will be awakened and enter the receive state, simultaneously awakening the MCU using interrupt, continue sleeping when there is no data transfer, thus reducing the ineffective wake-up of the MCU and RF chips, further saving the energy consumption of the nodes.

In this mode, the node has three states: sleep state, WOR state and working state. In terms of the entire operational cycle, it is in WOR state except for delayed sleep and working state. When the node is in the WOR state, the sink node can awaken the sensor node by sending the beacon frame. The WOR state enables the RF chip to automatically wake up from the sleep state regularly, then enter the RF receiving state and maintain for a period of time. If the beacon frame is received within a subsequent period, the MCU is woken up and processed accordingly. If the beacon frame is not received, it returns to the sleep state again and then repeats the above process. This procedure is shown in Figure2.

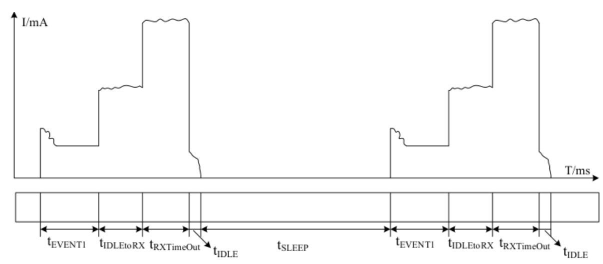

Fig. 2. A schematic diagram of the WOR process

It can be seen from the figure that in a WOR cycle, the time t_{SLEEP} is in the sleep state, while the time $t_{RXTimeOut}$ of the chip is in a relatively small proportion, which consumes the maximum current in the receiving state. By controlling the reasonable ratio of $t_{RXTimeOut}$ and t_{SLEEP} in WOR mode, the low power consumption in the WOR state is realized and the signal is reasonably received.

C. FRAME FORMAT DEFINITION

The protocol defines two frame formats: data frame and beacon frame. In order to save the energy of the network, the confirmation frame is not used. Beacon frames are sent by the sink node for inter-cluster and intra-cluster synchronization respectively, data frames are used for transmitting data between nodes, issued by cluster member node and cluster head node.

1) BEACON FRAMES

Beacons are broadcast by the sink node for intra-cluster and inter-cluster synchronization, identified by frame type. When the sink node is synchronized with the sensor node, several beacon frames will be sent, and the frame number indicates that the cluster node receives the first frame beacon frame for matching.

The frame bit number is used for inter-cluster synchronization, indicating that the beacon frame is the first round of beacon frame sent by the sink node to identify the cluster head node number of two synchronization. The beacon frame-frame format is as follows:

Lead code	Synchronous vocabulary	Frame length	Frame type	Frame number	Frame number
(4 Byte)	(2 Byte)	(1 Byte)	(2 bit)	(6 bit)	(1 Byte)

2) DATA FRAME

Data frames are used to transfer data between nodes, and its length is not fixed. In the load, each 4 bytes includes 1 byte of node id and 3 bytes of data. The node id consists of cluster number and cluster member number, accounting for 5 bits and 3 bits respectively. The data bits are used to store the three data quantities of light intensity, temperature and humidity. The format of the data frame is as follows:

Lead code	Synchronous vocabulary	Frame length	Load
(4 Byte)	(2 Byte)	(1 Byte)	(4*n Byte)

III. NODE TIME SYNCHRONIZATION

Time synchronization is the premise of reliable communication of wireless sensor network nodes. Only when the nodes in the network can be accurately synchronized to the same time benchmark, can the data transmission of the whole network be realized.

For facility agriculture wireless sensor network, the sink node can be powered by power lines, with no limit on energy, and cluster nodes are powered by battery with limited energy. When all sensor nodes enter the sleep state after the deployment of the cluster chain structure, periodically sends the beacon frame, which is awakened by electromagnetic activation (WOR), the cluster member nodes are awakened and sends the data to the cluster head node in the cluster, the complete large period is composed of T_{in}, inter-cluster synchronization cycle $T_{between}$ and sleep cycle T_{sleep}.

A. CLUSTER SYNCHRONIZATION

During the cluster synchronization process, the sink node transmits multiple beacon frames across the entire network, ensuring wireless coverage reaches all cluster heads and their associated member nodes. Both cluster leaders and their subordinate nodes remain in WOR mode, activating their receivers only upon detecting electromagnetic wave signals. Upon successful reception of a complete beacon frame, all nodes record the timestamp marking the frame's conclusion before returning to sleep mode, maintaining this state throughout the remaining broadcast period.

During the data collection phase following the broadcasting period, once all sensor nodes have established their connections, the cluster operates in the following manner: The lead node within the cluster allocates specific transmission intervals to every associated member node. Each subordinate node then enters a low-power dormant state, awakening precisely at its designated transmission window based on its unique identifier and the predetermined duration of its allocated slot. Upon activation, the node transitions to an active transmission mode, where it acquires fresh data and relays it to the cluster's primary node. Should no new information be available, the node remains inactive. Notably, during any given time interval, just one member node remains operational while all others conserve energy by maintaining their sleep state.

Suppose the network has N clusters, each with a cluster head node and n cluster member node, cluster member number of cluster 0, cluster member number is $1 \sim n$, the sink node broadcast m frame beacon frame, a frame beacon length is t_{beacon}, considering the time of wake up and the time of collecting sensor data, in order to ensure the stability of transmission data, the length of each time slot t_{slot} is slightly greater than t_{beacon}.

When the Cluster head node receives a beacon frame with frame number m_j, it sleeps for a period of time t_{rest}:

$$t_{\text{rest}} = (m - m_j)t_{\text{beacon}} \tag{1}$$

Then we enter the receiving mode, keeps the time of n*t slot, receives the data sent by the cluster member nodes, and then enter the WOR mode, waits for the wake up of the sink node, and enters the inter-cluster synchronization cycle.

When a member node with cluster member number $n_i(1 \leq n_i \leq n)$receives a beacon frame with frame number m_j, rest for a time $t_{res\ t}$ is:

$$t_{\text{rest}} = (m - m_j)t_{\text{beacon}} + (n_i - 1)t_{\text{slot}} \tag{2}$$

Then wake up, collect data, if there is new data, send the data in the corresponding time slot, sleep t_{rest} time:

$$t_{\text{rest}} = (n - n_j)t_{\text{slot}} + t_{\text{between}} + t_{\text{sleep}} \tag{3}$$

Then to the next large cycle, if no new data, sleept_{rest} time:

$$t_{\text{rest}} = (n - n_j + 1)t_{\text{slot}} + t_{\text{between}} + t_{\text{leep}} \tag{4}$$

Until the next large cycle. The process of synchronization within clusters is shown in Figure 3.

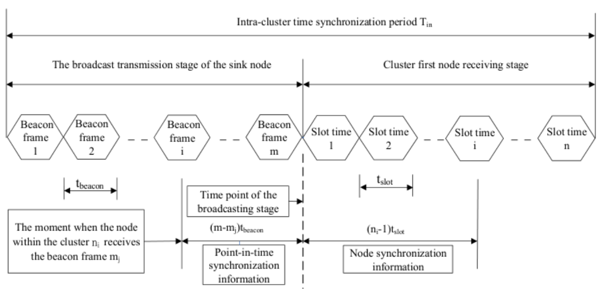

Fig. 3. A schematic representation of the temporal synchronization within the clusters

B. SYNCHRONIZATION BETWEEN CLUSTERS

After intra-cluster synchronization, all nodes in the cluster enter the sleep state, the cluster head node enters the WOR state and wait for the sink node to wake up and enter the inter-cluster synchronization.

For the network with N clusters, The sink node first broadcasts several beacon frames with frame type number 00 and frame bit number N in the first round, all cluster heads are awakened after receiving the synchronous vocabulary, Then receive a full beacon frame, Wake up after a dormancy delay at the head of cluster N and for cluster N-1, The head node of cluster N-1 enters the receiving state, The head node of the N number cluster enters the sending state, with any new data, Sending data to the head node of cluster N-1, sleep until the next large cycle; Node N-1 continues to enter the WOR state, Other nodes go directly into hibernation, Wait for the next round of beacon frames to wake up. Round 2,3... round N until all data is sent to the sink node.

Since the head node of the previous jump cluster needs to inherit the data of the head node, the amount of data transmitted per jump increases with the rounds, and the transmission time increases accordingly. If the transmission time of the head node of cluster N to the head node of cluster N-1 is t_{cluster}, the transmission time of the head node of cluster N-1 is $2t_{\text{cluster}}$, and the transmission time of the head node of the cluster is increased by $1t_{\text{cluster}}$ successively.

Assuming that m beacon frames are broadcast in each round, the time of broadcasting a beacon frame is t_{beacon}. In a certain round of inter-cluster synchronization, if the head node of the Ni cluster receives a beacon frame with frame bit number $N_k(1 \leq N_k \leq N)$ and frame serial number m_j.

When N_i=N-N_k+1, it is the sending node of this current schedule, requiring a delay t_{rest}:

$$t_{\text{rest}} = (m - m_j) * t_{\text{beacon}} \tag{5}$$

Then it enters sending mode, and after the data is sent, it sleeps until the next large cycle. The sleep time is:

$$t_{\text{rest}} = m * t_{\text{beacon}} * N_i + t_{\text{cluster}} * \sum_{N_i}^{N} i + t_{\text{sleep}} \tag{6}$$

When N_i=N-N_k, it is the receiving node of this current schedule, requiring a delay t_{rest}:

$$t_{\text{rest}} = (m - m_j) * t_{\text{beacon}} \tag{7}$$

Then enter the receiving mode, and the receiving time $t_{\text{last}}$is:

$$t_{\text{last}} = (N - N_k + 1) * t_{\text{cluster}} \tag{8}$$

After data reception, they directly enter the WOR mode and are ready to start receiving the next round of beacon frames.

When N_i is the other value, the node directly enters the beacon frame after receiving the WOR mode and waits for the wake up of the next round of beacon frame. The delay time t_{rest} is:

$$t_{\text{rest}} = m * t_{\text{beacon}} + (N - N_k + 1) * t_{\text{cluster}} \tag{9}$$

A schematic representation of the inter-cluster synchronization is shown in Figure 4.

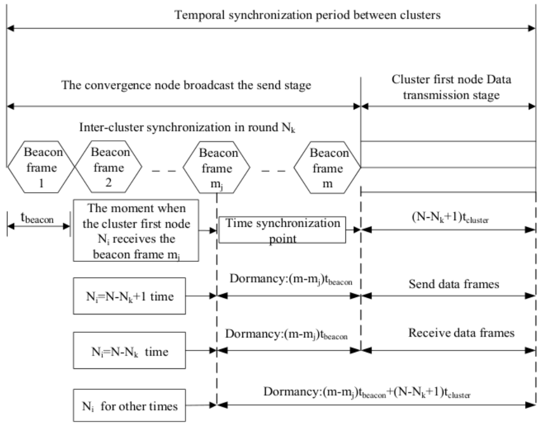

Fig. 4. Schematic of temporal synchronization between clusters

IV. THE MAC PROTOCOL BASED ON TDMA

The MAC protocol utilizing TDMA technology has gained widespread adoption due to its ability to address data collision issues arising from node contention. This approach significantly decreases network energy consumption while fulfilling low-power design specifications. In wireless sensor networks featuring cluster-chain architectures, a hybrid MAC protocol integrates cluster management with TDMA mechanisms. Under this framework, cluster head nodes allocate specific time slots to member nodes. Through coordinated scheduling by cluster heads, member nodes transmit their collected data during designated time intervals before routing the information to the cluster head.

A. SINK NODE

The central aggregation unit incorporates a signal booster mechanism, characterized by enhanced broadcasting capabilities and extended range, enabling comprehensive network coverage. This component plays a pivotal role in gathering information from distributed sensing units. Through regular network-wide transmission of synchronization signals, it employs electromagnetic wave stimulation to initiate sensor activation. The system orchestrates temporal allocation for subordinate nodes to transmit their readings to designated cluster leaders, which subsequently forward consolidated information to adjacent cluster leaders in a multi-hop fashion, ultimately delivering all data to the central aggregation point. The working process of the sink node is as follows:

1. Initialize the node;
2. Start intra-cluster synchronization, send a round of intra-cluster synchronization beacon frame, and wait for nt_{slot} time;
3. Cluster number assigns the initial value and enters the synchronization stage;

4. Send a round of cluster synchronization beacon frame, wait for t_{rest} time;
5. The cluster number decreases 1, if not 0, step 4 and if 0, step 6;
6. The sink node enters the receiving mode for a duration Nt_{cluster};
7. Enter the idle state, start the sleep cycle timing, and then go to step 2.

B. SENSOR NODE

The sensor node is responsible for collecting and sending data, most of the time in the sleep state of low power consumption, periodically entering the WOR state, and listening for wireless signals. During the cluster synchronization cycle, When the sensor node receives the synchronous word, enter the receiving state to receive the beacon frame broadcast by the collection node, The cluster head node completes intra-cluster synchronization with the cluster member node of the local cluster, Then the cluster member nodes collect the data and send it to the cluster head node, All go into dormancy; In the synchronization period between the clusters, When the cluster head node is awakened after receiving the synchronous word, Enter the receiving state to receive the beacon frame broadcast by the collection node, Two adjacent cluster heads complete inter-cluster synchronization, The head node of the second jump cluster sends all the data of the cluster, After several synchronization between clusters, Transfer of data, hop by hop, until transmission to the sink node, And then sleep. The sensor node is operated as follows:

1. Initialize node;
2. Enter the WOR state and prepare to start intra-cluster synchronization;
3. After receiving the beacon frame, go to step 4; if the beacon frame is not received within a certain period of time, go to step 17;
4. If the current node is not the cluster head node, go to step 6;
5. If the current node is the cluster head node, after the t_{rest} time enter the receiving mode and maintain the nt_{slot} time, receive data from all cluster member nodes in the cluster, and then go to step 10;
6. The current node is a cluster member node, sleep t_{rest1} time;
7. Collect data, proceed to Step 8 if new data, otherwise proceed to Step 9;
8. The node sends the collected data to the cluster head node at the t_{slot} time, and then proceeds to step 10;
9. If there is no new data within the set time, take the last data as new data and proceed to step 8;
10. Enter the WOR state and start preparing for cluster synchronization;
11. The judgment is based on the frame number N_k, the frame number m_j and the cluster number N_i, if $N_k = N$, the node is 1 cluster head node, and goes to step 20;
12. If $N_i = N - N_k + 1$, the node is the synchronized transmission node, and goes to step 15;
13. If $N_i = N - N_k$, the node is the synchronized receiving node, goes to step 17;
14. When N_i is other values, goes to step 19;
15. This node is the synchronous sending node, sleep t_{rest} time;
16. Enter the sending mode, send the data, and proceed to step 21;
17. This node is the synchronized receiving node, sleep t_{rest} time;
18. The node enters the receiving mode for t_{last} time. After receiving the data, it enters step 10 to prepare for the next round of cluster synchronization;
19. The node is not the current round scheduling node, directly into the sleep mode, sleep t_{rest2} time, goes to step 10;
20. This node is the head node of cluster 1, sleeps t_{rest} time and sends data to the sink node;
21. The node enters sleep mode and goes to step 2 after the sleep cycle, otherwise wait.

C. TEST

First, the communication distance of the nodes is tested. Because the ordinary plate makes the nodes, the communication quality is affected. After many experiments, when the communication distance between the sensor nodes does not exceed 45m, the communication quality is good, and when the distance exceeds 45m, the packet loss rate increases significantly. Since the sink node has an amplification module, the communication distance can reach 350m under the premise of ensuring the communication quality.

1) SINGLE POINT OF COMMUNICATION

Taking one sink node and one sensor node, the sink node sends 3000 packets to the sensor node with a test distance of 350m, and tests the packet loss rate of transmission. The test results are shown in Table 1:

TABLE I. Test results of communication with sensor node at 350m

Experiment	Send packets	Receive packets	Packet loss (%)
Group 1	3000	2986	0.47
Group 2	3000	2992	0.27
Group 3	3000	2989	0.37

It can be seen from the test data that the packet loss rate of single point communication can be controlled below 0.5%, meet the requirements of system communication.

2) MULTI-POINT COMMUNICATION

Taking one sink node, one cluster head node and four cluster member nodes are used to form one cluster. The cluster member node sends the data frame to the cluster head node successively after receiving the beacon frame sent by the sink node. Three experiments, each group sends 3000 data packets to test the packet loss rate of transmission. The test results are shown in Table 2.

TABLE II. Multi-point communication test results

	Receive packets				Packet loss probability			
	Member 1	**Member 2**	**Member 3**	**Member 4**	**Member 1**	**Member 2**	**Member 3**	**Member 4**
Group 1	2976	2988	2986	2979	0.8%	0.4%	0.47%	0.7%
Group 2	2969	2986	2982	2983	0.7%	0.47%	0.6%	0.57%
Group 3	2975	2978	2980	2985	0.83%	0.73%	0.67%	0.83%

It can be seen that due to the mutual influence between nodes, the packet loss rate of multi-point communication is higher than that of single-point communication, but it can still remain below 1%, which can meet the needs of practical applications.

According to the structural characteristics of cluster chain wireless sensor networks, the cluster head node must relay the data of subsequent clusters. The closer the cluster head node is to the sink node, the more data it relays, and the more energy it consumes, which will lead to earlier "death" and restrict the entire network's life-cycle.

V. CONCLUSION

Life cycle is an important performance index of wireless sensor network. The performance of communication protocol directly affects the energy consumption of sensor node and determines the life of network. According to the practical application scenarios of facility agriculture, the rational deployment of wireless sensor network and the study of high-performance communication protocols can effectively extend the network life cycle.

This paper adopts the method of electromagnetic wave activation, where the RF device periodically transitions from a dormant state to the WOR state to scan signals in the air. When an electromagnetic wave signal meeting predefined conditions is detected, it is awakened and enters a working state to receive or transmit data, while also waking up the MCU. In the absence of data transmission, it remains in a dormant state, thereby reducing unnecessary wake-ups of the MCU and RF chip, further conserving the node's energy consumption. Experimental results demonstrate that this protocol exhibits stable performance, effectively lowering node energy consumption and extending the network's life-cycle.

In order to further improve the performance of the network, unequal spacing and heterogeneous node methods can be used to conduct in-depth research on the deployment of cluster chain wireless sensor networks, so as to balance the energy consumption of cluster head nodes and greatly extend the network life-cycle.

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