A Wireless Sensor Network in Precision Agriculture

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Abstract
Wireless sensor network has been applied in precision agriculture. This paper takes CC1000 RF as wireless transceiver, and MCU MSP430F149 with high performance and Low-Power as the control center of sensor nodes, which can accurately monitor temperature, humidity and light intensity. Meanwhile, choose LM3S6918 which is a high-performance 32-bit ARM and to design sink node. Since the energy of sink node is unlimited, puts forward a new MAC protocol after experimental researches, and gives the specific methods of implementation and deployment. The new system can effectively reduce the maintenance cost. Meanwhile, experiments also prove that the WSN has advantages of Lower-Power and stability. It can be competent for monitoring the general agricultural environment.

Keywords: communication protocol, low power, node design, wireless sensor networks

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1. Introduction
Precision agriculture relies on information technology, whose precondition is providing real-time and accurate information. It depends on various kinds of advanced sensors, such as environmental temperature and humidity, wind speed, light intensity, and other types of sensors. Currently, it is a hot topic how to collect accurate information, the main raw data for agricultural experts, monitored by these sensors timely. In recent years, many researches have been carried out on remote monitoring in agriculture, forestry and animal husbandry via wireless communication, such as wireless public network [1].

Currently, most of the monitoring systems for Precision Agriculture adopt GPRS network, of which cost of design and maintenance is higher, to transmit data. Compared with others, wireless sensor network (WSN) is characerized with precision, low cost and real-time quality, Low-Power, large capacity and wide coverage region [2], [3]. It is suitable for setting up system monitoring environment. And it is of vital and practical value to develop WSNs applied in precision agriculture and to study decreasing power consumption, prolonging the life cycle and reliability.

2. The Proposed Method
Currently, in most of the monitoring systems for Precision Agriculture, GPRS network is used to transmit data. The typical system structure is as Figure 1. In this system, a monitoring point must use a GPRS module. Thus, its cost of design and maintenance is very high in large system. To reduce the cost, WSNs are used to design the monitoring system for Precision Agriculture.
agriculture, in which GPRS module is only used to design the sink node that transmits data to information center.

3. Research Method
3.1. Overview of System Design
   In most monitoring systems of precision agriculture, monitoring areas are close to one another. So sensor nodes, including light intensity, temperature and humidity, can be set in the same radiation area of one sink node [4], [5]. Meanwhile, power of sink node is unlimited. Therefore, this WSN adopts the star topology. Figure 2 is the structure of WSN applied in monitoring precision agriculture (MPA-WSN).
   (i) Information center: Management node, which is responsible for receiving data from sink nodes via GPRS network, and offering Web service. When a sensor node works abnormally, or “dead”, it will take some measures in time.
   (ii) Sink node: Send beacon frames periodically, receive data frames from sensor nodes and forward them to the information center through GPRS network. Receive query commands from the information center, and send them to sensor nodes to fulfill.
   (iii) Sensor node: Acquire monitored data, send data to sink nodes and send alarm information when a node’s power is below a certain electricity threshold in time. It is powered by battery. And when it is not in working order, it will stay in sleep mode.

3.2. Design of Communication Protocol
   MPA-WSN has some characteristics of single coverage, unlimited energy of sink node and less real-time demand than others. To reduce power consumption of nodes and prolong the
life cycle of the network, one STAR-MAC protocol is advanced by improving the traditional MAC protocol based on star MAC protocol of TDMA.

### 3.2.1. Coarse-grained Time Synchronization

Some networks need not to support real-time services, so exact time synchronization costing is not necessary. Coarse-grained time synchronization is sufficient in practice. The sink node broadcasts a certain number of beacon frames to the entire network, which is used as the basis for all nodes in the network to synchronize. When the sink node is transmitting message, senor nodes waiting for sending the data may accept a piece of beacon frame randomly to establish time synchronization. Since each senor node has already been allotted message-sent slot at the beginning of building the network, it needs just one basis to locate the slot allotted to it when it is preparing to send data. Coarse-grained time synchronization is shown in Figure 3.

![Figure 3. Coarse-grained time synchronization](image)

Assuming that the sink node broadcasts \( n \) beacon frames to entire network at the moment of sending message, there will be \( j \) time slices for all nodes in the network to allot. If a node uses beacon frame \( i \) to build its own time synchronization, it will be allotted the \( k \) slot. The sink node spends time \( T \)(ms) finishing a whole message-sending or message-receiving cycle. It uses the following formula to calculate the delay time needed after a node has finished receiving the beacon frame:

\[
\tau = \frac{n - i + k}{2n} T \text{ (ms)}
\]  

(1)

According to traditional TDMA-based communication protocol, the sink node sends a byte of control information to receiving node when senor nodes are trying to use cycle-fixed slot to book a slot. Thus, accurate synchronization is needed; otherwise receiving node may fail to receive control information due to the error of synchronization, which reduces the reliability of communication. Since improved-protocol sink node sends a certain number of beacon frames rather than one, senor nodes need only one beacon frame to achieve synchronization, greatly improving the reliability of data communication and enhancing anti-jamming capability.

### 3.2.2. Format of Frames

Sink node starts a message-sending or receiving cycle when sending a series of broadcasting frame, and the broadcasting frame is used by sensor nodes as basis to synchronize. START-MAC protocol defines three formats of frame: beacon frames, acknowledgment frame and data frame. They all have fixed length, and add preamble and synchronization word into the frame to form physical-layer data packets.

#### 3.2.2.1. Beacon frame

When the sink node is transmitting message, senor nodes who are waiting for sending the data may accept a piece of beacon frame randomly to establish time synchronization. Format of beacon frame is shown as follows:
The length of beacon frame is one byte, and a frame will be recognized as a beacon frame by the system if the frame-format bit is set as 01b. Beacon frames number is used to identify different beacon frame sent at different time. The desirable range of number is 0 ~ n, which can support synchronization and data transmitting of dozens of sensors. After receiving a piece of beacon frame randomly, sensor node extracts the beacon-frame number. This number and prescriptive slot determining the delay time are used to avoid data collision.

### 3.2.2.2. Data frame

Data frame is used to transmit data. Sink node receives data frame from different nodes at different slots when it is in the state of receiving data. A complete one contains format of frame, format of data, address of nodes and data. The structure of data frame is shown as follows:

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Synchronizing Glossary</th>
<th>Frame Type</th>
<th>Data Types</th>
<th>Node Address</th>
<th>Data</th>
</tr>
</thead>
</table>

In STAR-WSN, data can be represented by two bytes. Therefore, the length of the frame is fixed as 3 bytes. A frame will be recognized as a data frame by the system if the frame-format bit is set as 10b. Data type is used to indicate the type of data loaded. The definition is shown in Table 1:

<table>
<thead>
<tr>
<th>Data Types</th>
<th>Description</th>
<th>Nodes Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>00b</td>
<td>Normal sensor data frame</td>
<td>Nodes address</td>
</tr>
<tr>
<td>01b</td>
<td>Low-power warning data frame</td>
<td>Nodes address</td>
</tr>
<tr>
<td>10b</td>
<td>Apply data frame</td>
<td>Sensor types</td>
</tr>
<tr>
<td>11b</td>
<td>Hold</td>
<td>Default</td>
</tr>
</tbody>
</table>

### 3.2.2.3. Acknowledgment frame

If a sensor node sends an alarm data frame or applies to join the network frame, the sink node needs to make a response when the next cycle starts. Acknowledgment frame format is shown below:

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Synchronizing Glossary</th>
<th>Frame Type</th>
<th>Answering Parameter</th>
<th>Parameter Value</th>
</tr>
</thead>
</table>

A complete acknowledgment frame contains a frame type, response parameters and parameter values and it has a length of 1 byte. A frame will be recognized as a data frame by the system if the frame-format bit is set as 11(bit). Table 2 shows the specific definition:

<table>
<thead>
<tr>
<th>Answering Parameter</th>
<th>Description</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>Node time-out</td>
<td>Address of time-out node</td>
</tr>
<tr>
<td>01</td>
<td>Acknowledgment for Low-power warning</td>
<td>Address of low-power node</td>
</tr>
<tr>
<td>10</td>
<td>Acknowledgment for Entering network</td>
<td>Allotting new-node address</td>
</tr>
<tr>
<td>11</td>
<td>Hold</td>
<td>Default</td>
</tr>
</tbody>
</table>

### 3.2.3. Realization of Algorithm

After sink node works normally, it comes into the status of message-sending. Namely, according to the number and status of sensor nodes, it broadcasts a certain number of beacon frame to synchronize sensor nodes in the network and distributes time slice. Then sink node turns into the status of receiving message, receives information which is used to monitor data or ask for entering and exiting from the network sent by sensor nodes. Repeatedly, it stays in the cycle of sending and receiving message again and again. The protocol is shown in Figure 4. If sensor nodes need to send monitoring data or information asking for entering and exiting from
the network, they enter message-receiving status after sleeping cycle and receive beacon frame sent by the sink node.

![Diagram of communication-structure protocol](image)

Figure 4. Complete communication-structure protocol

Then it turns into message-sending status and according to the beacon frame received and its own property of delay time, sends data frame at that time slice. After finishing sending message, it enters sleeping mode.

Pseudo code used by sink nodes to realize protocol is shown as follows:

```plaintext
1 Sending state
2   If receive request at last period then
3       Assign address for new node
4       Give a reply
5   End If
6   If one faulting happen in the net then
7       Transport data to information center
8       Give a reply
9   End If
10  While number of broadcasting frames < n+1 do
11     Broadcast to the net
12  End While
13 Enter receiving state
14  While number of time cracks < n+1 do
15     Receive data
16  End While
17  If need transport data by GPRS then
18     Transport data
19  End If
20 Return
```

Pseudo code used by sensor nodes to realize protocol is shown as follows:

```plaintext
1 Enter receiving state
2 Receive a broadcasting frame
3 Wait a period of time and then wait a period of random time
4 Enter sending state and transport request to sink
5 Enter Low-power consumption state
6 Enter receiving state
7 If receive a reply then
8       Record address and time crack
9       If have new data to transport then
10          Enter receiving state
11          Receive a broadcasting frame
12          Wait a period of time
13          Enter sending state and transport data to sink
14       End If
15  End If
16 End If
17 Else If
18   Enter Low-power consumption state
19 End If
20 Return
```
3.3. Implementation of Sensor Nodes

Low-Power is the most important performance of sensor nodes. Because of its characteristics of ultra-low power consumption, high speed of data processing and stability, MSP430F149, a single-chip, is widely applied in sensor nodes’ design [6, 7]. Therefore, MSP430F149 and CC1000 radio frequency chip (RF chip) are usually chosen to design nodes of temperature and humidity sensor and nodes of light intensity sensor.

3.3.1. Hardware of Temperature and Humidity Sensor Nodes

Select SHT10 as a sensor to collect the environmental temperature and humidity on the farmland. The hardware diagram is shown in Figure 5.

![Figure 5. Hardware diagram of temperature and humidity node](image)

The DATA and SCK of SHT10 are connected to MCU respectively, in order to let MCU collocate SHT10 to realize data communication between them. At the same time, MCU collocate CC1000 through P5.3, P5.1 and P5.0, including sending and receiving frequency, sending power, data rate and other parameters. Meanwhile, the MCU uses an interruption mode of P1 to write the data waiting to be sent or read the received data from CC1000 through P4.6 and P1.4.
3.3.2. Hardware of light intensity sensor node

Choose TSL230B as sensor collecting light intensity on the farmland. The light hardware diagram is shown in Figure 6. TSL230B has four configuration pins in total, S0, S1, S2 and S3, which are configured by MSP430F149. As the output of TSL230B, OUT is connected to MCU through P1.1, which can read the chip's calculating frequency, output signal, and Figure out the light intensity in the end.

3.3.3. Software of Sensor Node

After being powered on and initialized, if it is a new node, the system will apply for network access, or let sensor modules collect data. Compared with data in the last cycle, if they are different, record the new data. Next, start the ADC module to measure power, mark alarm data frame when it reaches the threshold value. In the current cycle, when the sensor nodes have data frames or alarm data frames needed to be sent, wait for two beacon frame's periods and receive one beacon frame. Then, the system turns off the wireless transmission module, enters into LPM3 Low-Power mode.

Figure 7. Main program flow chat of sensor nodes

Figure 8. Sink Node Hardware Structure Chart
After a short delay, the system wakes up and sends data when meets the specified time slots required to send data. Later, it re-enters the Low-Power mode and waits for the next cycle. The main program flow chart of sensor nodes is shown in Figure 7.

3.4. Implementation of Sink Nodes
3.4.1. Hardware of Sink Node
Since there is no requirement on Low-Power, the sink node is controlled by high-performance ARM processor, LM3S6918. The hardware mainly includes clock, RF, GPRS, external flash, power, serial port, watchdog and reset circuit, and LCD. The hardware structure of sink node is shown in Figure 8.

While the sink node is sending and storing data, it needs to record the current time, which is achieved by PCF8563 chip. It is controlled by MCU via I2C and powered by lithium batteries, which can be charged by CN3052A chip [8]. LM3S6918 offers two full-duplex synchronous or asynchronous serial ports. They are used as RS232 serial port, and RS485 serial port to connect to LCD and GPRS module.

3.4.2. Software of Sink Node
After being powered on and initialized, LM3S6918 enters sending state and sends a beacon frame. In this state, if the sink node receives applying frames or alarm frames from sensor nodes in the last cycle, it needs to reply an acknowledgment frame to the sensor node in the beginning. After that, the sink node starts to send the beacon frame to synchronize sensor nodes needing to send data in a network.

![Main program process of sink node](image)

After completing sending all beacon frames, the sink node turns into receiving state to receive data frames. Later, if it receives data from sensors, the sink node will read time information, stores it into external flash and forwards it to the information center through RS232. Processes are the same when the sink node receives applying or alarm data, and then it marks acknowledgment frames. Later, sink node enters the next cycle. The flowchart of main program is shown in Figure 9.

4. Results and Analysis
Experimental tests are carried out under the following conditions. RF transceiver’s frequency is 433.3MHz; sending gain of a node is 10dBm; data transfer rate is 9.6kbit/s; data encoding format is NRZ; and modulation is FSK.
4.1. Packet Loss Rate Test

Let 3 sensor nodes send different data to one sink node. Every node sends 3000 data packets. Based on the total number of data packets received by the sink node, packet loss rate of multi-point communication can be figured out, which is shown in Table 3. From the Table, packet loss rate of every node can remain within 1%, meeting the requirements of this network.

<table>
<thead>
<tr>
<th>Receiving Packets</th>
<th>Packet Loss Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Temperature</td>
</tr>
<tr>
<td>2985</td>
<td>2971</td>
</tr>
<tr>
<td>2986</td>
<td>2980</td>
</tr>
<tr>
<td>2988</td>
<td>2972</td>
</tr>
</tbody>
</table>

4.2. Power Consumption Test

Sensor node has four main types of states: transmitting, receiving, data collection and sleeping. Measured by experiments, the current of transmitting state, receiving state and active state is represented as 24.72mA, 12.74mA and 2.53mA. When sensor nodes of temperature and humidity collect data, the current is 3.20mA, and when sensor nodes of light intensity collect data, the current is 3.40mA. In the end, nodes’ current in sleeping state is 2.1 µA.

It needs 4.3ms or 4.6ms when RF turns sleeping to receiving or transmitting state. It is also tested that it costs 9.45ms or 7.95ms when sensor nodes receive beacon frames or send data frames. Meanwhile, temperature and humidity sensor costs 4.1ms monitoring an integrated data. But light intensity sensor spends only 100µs doing the same.

Since the system is powered by batteries, the average current determines the system life cycle. According to the formula of average current [9], \( I_{\text{avg}} \) equals to the quotient of total current and time. The former one refers to the sum of the product of working current and working time in the active state and product of sleep current and sleep time in sleep state. Suppose that the working cycle of a node is 2s, a node sends data every two cycles, every cycle has a data collection operation. Average working current of temperature and humidity sensor node can be calculated by the following formula.

\[
i = 0.0021 + \frac{3.2 \times 2 \times 4.1 + 2.53 \times (8.9 + 9.45 + 7.95) + (9.45 \times 2 + 4.3) \times 10.21/2}{4 \times 10^3} + \frac{(7.95 \times 2 + 4.6) \times 22.19/2}{4 \times 10^3} = 0.1118 \text{mA}
\]

The light intensity sensor needs far less time than temperature and humidity sensor when collecting data, so the average current is less than 0.1118mA. The working cutoff voltage of nodes is 2.7V. Assume the node is powered by two common lithium batteries with 1.5V voltage and 2700mAh capacity. According to the discharge characteristics of lithium battery [10], when battery discharges to 2.7V, the loss of battery capacity is about 2000mAh. Node’s life can be roughly estimated as 2000/0.118=17889h (745.4 days), which means that a sensor node can last for more than one year.

4.3. Maintenance Cost

In this proposed MPA-WSN, GPRS modules are only used in the design of sink nodes. The sensor nodes apply the proposed protocol, which do not need any maintenance cost. One sink node, together with \( n_i \) sensor nodes, consists of the \( i \) sub-WSN. If the system has \( m \) sub-WSN, the average number of sensor nodes in the system can be calculated by formula (3).

\[
n_{\text{ave}} = \frac{\sum_{i=1}^{m} n_i}{m}
\]

According to above formula, the proposed system only needs \( 1/n_{\text{ave}} \) times cost compared with typical system.
On the other hand, it is more convenient to add one new sensor node. According to the proposed protocol, it does not need any hardware or software to be changed when a new sensor node is added.

5. Conclusion

WSN’s Life-cycle is the key to its application. It is the normal and main measure to reduce power consumption in two aspects, hardware design and communication protocol. The low-Power MCU and RF can reduce power consumption of the nodes in activating state. Ultra-low power MCU can reduce average power consumption. Compared with the typical system, the MPA-WSN has much lower maintenance cost, good reliability and long life-cycle. Against the particularity of star structure in small-scale farm WSN, the improved MAC protocol, START-MAC, can further reduce power consumption and prolong the network life cycle. For medium-scale and large-scale farm WSN, the network structures and communication protocols should be studied and improved to meet the requirements of every WSN in precision agriculture.

References