A MAC Protocol for Chain-type Wireless Sensor Network Based on the Token

1 Lingling Wang, 1 Xijun Yan, 2 Yan Yan
1, 2 College of Computer and Information Engineering, Hohai University,
Focheng West Road of Jiangning, Nanjing 211100, China
1 Tel.: +86-013705165897, fax: +86-025-58099120
E-mail: yan_xijun@hhu.edu.cn

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Abstract: Currently, chain-type wireless sensor network (WSN) is widely used in many fields such as bridge structure and gas pipeline monitoring. To reduce the channel conflict and energy consumption of the network, a novel Media Access Control (MAC) protocol for chain-type WSN based on token is proposed. It takes the token in the beacon frame to control adjacent sensor nodes for communication. Message equipped mechanism is used to embed synchronization information into the routing protocol, which can realize coarse-grained time synchronization. To improve reliability, this paper proposes a novel transmission mechanism by sending redundant data packets through a single path. Experimental results show that the new protocol can improve stability and reliability in transmission, prolong life cycle and meet the application requirements of chain-type WSN. Copyright © 2013 IFSA.

Keywords: Chain-type wireless sensor network, Token, MAC protocol, Time synchronization, Low power consumption.

1. Introduction

WSN is a multi-hop and self-organized network system through wireless communication, which is composed of large numbers of sensor nodes in the monitoring area. Usually, it is used to monitor, collect and deal with the information and then send results to observers. Nowadays, WSN has been widely applied in industry, environment monitoring, healthcare, home automation, and traffic control [1].

The chain-type WSN is considered to be a kind of special network model as its monitoring area can be considered as line. Thus, it has a bright application prospect in intelligent transportation, mine, and bridge. Chain-type topology has the following characteristics [2]:

(a) Single path: In general WSN, nodes have multi-adjacent nodes, leading to multiple transmission paths. However, in chain-type network, every node has only two adjacent nodes with only one transmission path.

(b) Multi-hop routing: Usually dozens of sensor nodes are deployed along the linear area to form a multi-hop network. Due to the characteristic of single path, the information collected by sensor nodes must be forwarded to sink nodes through other nodes.

(c) Imbalance amount of information: Every node not only monitors and sends local data, but also processes data transmitted from adjacent node. Therefore, the amount of information is increasing along the transmission path, which means the closer to the sink node, the greater amount of information to be deal with.
To meet the application requirements of chain-type WSN, one appropriate MAC protocol responsible for allocation of the wireless channels among sensor nodes [3], is very important. Sensor nodes have limited features in energy, computing ability, communication distance and storage capacity. Therefore, some attributes should be taken into consideration during the process of designing the MAC protocol for WSN: saving energy, channel allocation, and network efficiency.

2. The Proposed Method

At present, the existing MAC protocols for WSN can be divided into two categories: MAC based on competition and MAC scheduling-based. However, these protocols usually assume that sensor nodes are deployed in a two-dimensional or three-dimensional space, which cannot be effectively applied to the chain-type WSN.

Currently, there are many researches focus on MAC protocols of chain-type WSN. Zhang proposes a fast data transmission protocol based on chain-type cluster [5]. In this protocol, nodes are distributed in clusters. The realization process is as follows:

At first, sink node broadcasts routing commands to the sensor nodes, and sensor node sends back a response frame after, which contains the received signal strength indication (RSSI). Sink node defines No. of node according to the RSSI value, and sends to the sensor node to complete time synchronization. After synchronization, sink node sends downlink commands hop-by-hop, which contains information of initiating nodes and the time that each cluster begins to upload data. Initiating nodes (No. 4, No. 8 and No. 12) start transmitting data at the given time in downlink commands. The next hop node continues to upload the data fused with last hop node. Finally it forms a data packet in the cluster and uploads data through the adjacent clusters directly until arriving at sink node, without data fusion with other clusters. The transmission process is shown in Fig. 1.

In this protocol, data fusion is combined with time synchronization, which reduces extra energy consumption and improves transmission efficiency and network scalability. However, all nodes are in active state in the process of data transmission. The nodes can only switch to sleeping mode until all data transmission is completed, thus it increases energy consumption of the nodes.

Ma proposes a linear cluster WSN protocol [6]. The linear region is equally divided into N observation areas, in each observation area, N sensor nodes are placed linearly aimed at forming a cluster. Each observation area defines a secondary cluster head. Besides, there is a primary cluster head outside the linear region. Members in the clusters transmit data to the secondary cluster head directly or through multi-hop. Secondary cluster heads and the primary cluster head form a star network, which transmit information directly. The linear clustering protocol is shown in Fig. 2.

![Fig. 1. The data transmission of the fast chain-type cluster protocol.](image1)

![Fig. 2. The linear cluster WSN protocol.](image2)
In this protocol, secondary cluster heads transfer data after being fused with other nodes in the cluster, which reduces data amount and saves energy to some extent. However, the protocol adopts the topology with one primary cluster head and secondary cluster heads, which cannot be fully applied to the chain-type WSN. Furthermore, the distances between primary cluster head and secondary cluster heads are relatively long in general, the energy consumption of data transmission is larger. It will affect life cycle of the whole network.

This paper proposes a novel MAC protocol for chain-type WSN based on token. Listen/sleep mechanism is the core of this protocol, which can reduce energy consumption by switching to sleeping mode timely. Message equipped mechanism is used to embed synchronization information into the routing protocol, and realize coarse-grained time synchronization. To improve reliability, a novel packets through a single path is proposed.

3. MAC Protocol Based on Token

According to existing MAC protocols, we design a chain-type MAC protocol based on token combining the idea of fixed time slot allocation. The protocol ensures that information collected by every node can be gradually transmitted upward. During data transmission, as soon as the nodes receive adjacent nodes’ access permissions, they can transmit data, while others are in the sleeping mode. In this way, it can reduce the energy consumption, and effectively prolong the life cycle of network.

3.1. Format of Frames

The protocol defines two main types of frames: beacon frame and data frame. Sink node broadcasts beacon frames cyclically, aiming to send out time synchronization information and assign the channel permissions for nodes in the whole network. Data frame is used for data transmission among adjacent sensor nodes.

Wireless RF chip follows IEEE802.15.4 [8] standard, therefore the frame follows its beacon frame format in MAC layer in this paper.

- Beacon frame.

Beacon frame is responsible for synchronizing adjacent nodes and assigning channel permissions, whose length is stably two bytes. The first one stores token information, and the other one stores the number of nodes in network. Token information differs in different period (Fig. 3).

- Data frame.

Besides uploading its own data, sensor node has to transmit other nodes’ data. So the length of data frame is changeable for different nodes. At the same time, it includes node’s ID and alarm information. Thus, the frame’s format is as below (Fig. 4).

3.2. Time Synchronization

Coarse-grained time synchronization algorithm [9] is adopted in the new protocol. Sink node periodically sends a certain number of beacon frames. After waking up from sleeping mode, sensor nodes in the network randomly receive one beacon frame containing time slice and token information, which can determine whether nodes get the communication authority. If getting the authority, nodes will finish time synchronization, and accomplish data transmission between adjacent nodes later. Otherwise, they will continue to sleep. In this way, the network can not only avoid data collision in data transmission, but also can reduce the power consumption.

Fig. 5 shows the node hierarchical rule in the chain-type network. The ID of sink node is 0, and the other nodes are incremented by 1. Solid lines represent the transmission process of beacon frames broadcasted by sink nodes. Dotted lines represent the process of data frames transferred by sensor nodes, which are transmitted one by one until they arrive to sink node.

Assume the whole chain contains N child nodes (except node 0). During one completed data transmission, the sink node has to broadcast N
periods' synchronization information. Each period contains M (0<M<256) beacon frames, whose token information is the same in one period. The relationship between token information and the nodes' state can be seen in Table 1.

Table 1. Relationship between token information and the nodes' state.

<table>
<thead>
<tr>
<th>Period</th>
<th>Token information</th>
<th>Synchronize working nodes &amp; the state after synchronization</th>
<th>Beacon frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>Node N: sending state</td>
<td>M</td>
</tr>
<tr>
<td>2</td>
<td>N-1</td>
<td>Node N-1: sending state</td>
<td>M</td>
</tr>
<tr>
<td>j</td>
<td>N-j+1</td>
<td>Node N-j+1: sending state</td>
<td>M</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>Node 1: sending state</td>
<td>M</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

The whole period of broadcasting is shown in Fig. 6. The broadcast period T contains $T_{a1}, T_{a2}, ..., T_{aN}$.

The time of a period is $T_{a}$ ($0 < j \leq N$). It contains two parts. When $0 < j < N$, $T_{a}$ consists of token transmission timeslot and idle timeslot. In the transmission timeslot, sink node transmits M beacon frames, and the token information is N-j+1. When $j = N$, $T_{a}$ consists of transmission timeslot, data receiving and processing timeslot. A period $T_{a}$ is shown in Fig. 7, in which t is the time of transmitting M beacon frames, $t_{i}$ is the time of transmitting one beacon frame, $\tau$ is buffer time. $\Delta \tau$ is set by users to adjust receiving time of period N based on time for processing, uploading and storing data.

Node i (i ≠ 0) receives a beacon frame randomly, the node gets three types of information: the current token information N-j+1; beacon frame number k; the number of the entire network nodes N.

According to the three types of information above, node i can concludes that: it is the beacon frame of period j, which can synchronize node N-j and node N-j+1 and the data are transmitted after synchronization. The scheduling figure is shown in Fig. 8.

The specific judgment of node i is as follows:

1. $j \neq N$:
   (a) $i > N - j + 1$ or $i < N - j$: Node i switches to sleeping state which lasts for $(M - k)\tau_{i} + \tau$, and then intercepts beacon frames after waking up.
   (b) $i = N - j$: Node i switches to the sleeping state which lasts for $(M - k)\tau_{i} + \tau$, then switches to receiving state. After receiving data or out of receiving time, it switches to sleeping state which lasts for t, and then intercepts beacon frames after waking up.
   (c) $i = N - j + 1$: Node i switches to sleeping state if there is data waiting for transmitting, it sleeps for $(M - k)\tau_{i} + \tau$, and then switches to transmitting state. After transmission, the node sleeps for $(N - 1)\tau_{i} + \tau + \Delta \tau$ or $(N - 2)\tau_{i} + \tau + \Delta \tau$ when $i = N$ or not, and then intercepts beacon frames after sleeping. If there is no data to transmit, the node sleeps for $(M - k)\tau_{i} + \tau + (N - 2)\tau_{i} + \tau + \Delta \tau$ when $i = N$ or not, and intercepts beacon frame after sleeping.

2. $j = N$:
   Node 1 switches to sleeping state which lasts for $(M - k)\tau_{1} + \tau$, and then transmits data, later the node switches to sleeping state. After $(N - 2)\tau_{1} + \tau + \Delta \tau$, it wakes up and intercepts beacon frames. Meanwhile, other nodes switch to the sleeping state which lasts for $(M - k)\tau_{i} + \tau + \Delta \tau$, and intercept beacon frames when wake up.

The communication process of four nodes is shown in Fig. 9, $K$ means the No. of beacon frame acquired by nodes. $t_{i}$ is the time for sending one beacon frame. $\tau$ is buffer time to avoid intercepting the last frames in period. $\tau$ can not affect the next period.
3.3. Reliable Transmission Mechanism

Usually, ACK message acknowledge or end-to-end retransmission mechanism are used to solve packet loss caused by channel conflict and data collision [10]. However, this method will increase time delay. It has to cache data packets on the node, which is not suitable for WSNs with low storage capacity and high real-time requirements. Besides, multi-path transmission mechanism is also widely used to solve the problem [11], which improves the transmission reliability by sending a plurality of packets through multiple paths. But in chain-type WSN, it has no multi-path because of the special geographical conditions. Thus, a novel reliable transmission mechanism is proposed which improves its reliability by sending redundant data packets through a single path [12].

The mechanism of forwarding redundant packet through single path in chain-type WSN is shown in Fig. 10.

Assume the probability of the data packets in partition i correctly reaching sink node is $P_{\text{reach-i}}$:

$$P_{\text{reach-i}} = \prod_{j=1}^{N} \left( 1 - e^{-\lambda j} \right)$$  \hspace{1cm} (1)
In this model, parameters and assumptions are identified as follows:

- \( h_i \): Amount of copy packets sent from partition \( i \) to partition \( i+1 \);
- \( \epsilon_{es} \): Average communication error rate;
- \( d_i \): Average distance from partition \( i \) to partition \( i+1 \) in the Z-axis direction;
- \( E_{elec} \): The energy consumption when sending or receiving information;
- \( \alpha \): The path loss;
- \( \epsilon_{amp} \): The energy consumption of the power amplifier.

For sending packets of size \( k \) from partition \( i \) to sink node, the energy consumption of the partition is:

\[
E_j = E_{elec} \times k \times h_{j-1} + E_{elec} \times k + \\
E_{elec} \times k \times (d^2 + D^2)^{\alpha} \times h_{j}
\]

(2)

The total energy consumption is:

\[
E_x = \sum_{j=1}^{N} E_{elec} \times k \times h_{j-1} + \sum_{j=1}^{N} E_{elec} \times k + E_{elec} \times k \times (d^2 + D^2)^{\alpha} \times h_j
\]

(3)

In which, \( j \in [i, N] \), \( h_{-1} = 0 \), \( h_{N+1} = 0 \).

It can be concluded from above analysis that \( P_{reach+1} \) is increased with \( h_j \). But at the same time, \( E_j \) and \( E_r \) become larger. So we should allocate \( h_j \) reasonably to receive the largest probability of packets arriving, when \( E_r \) is fixed.

According to formula (1), \( \epsilon_{es} \in [0,1] \) and \( h_j > 0 \), and based on the mean value inequality principle, we can get:

\[
\sum_{j=1}^{M} (1 - \epsilon_{es}^j) \leq \sum_{j=M-i+1}^{M} (1 - \epsilon_{es}^j)
\]

(4)

when \( 1 - \epsilon_{es}^k = 1 - \epsilon_{es}^{k+1} = \cdots = 1 - \epsilon_{es}^M \), we can get:

\[
\sum_{j=1}^{M} (1 - \epsilon_{es}^j) = \sum_{j=M-i+1}^{M} (1 - \epsilon_{es}^j)
\]

(5)

In which,

\[
h_j = \frac{h_i \log \epsilon_{es}}{\log \epsilon_{es}} = h_i \log_{\epsilon_{es}} \epsilon_{es}, j \in [i, M].
\]
Then:

\[ P_{reach-i-max} = \left(1 - \frac{(M-i+1)\log_{10}i}{M-i+1}\right)^{M-i+1} \]

\[ = \left(1 - \frac{h_j}{\sum \log_{10}e_{i,j}}\right)^{N-i+1} \]  

(6)

It can be found that:

when \( i = N \), partition \( i \) sends \( h_i \) data packets in total, and \( h_i = \sum_{j=1}^{N} h_j \). Thus, the largest probability of packets arriving is \( p_{reach-i} \).

\[ P_{reach-i-max} = \left(1 - \frac{h_i}{\sum \log_{10}e_{i,j}}\right)^{N-i+1} \]  

(7)

4. Implementation of the MAC Protocol

MAC protocol includes two parts, broadcasting beacon frames and uploading data. Sink node sends beacon frames periodically, and then enters into receiving state. After receiving beacon frames, adjacent sensor nodes transfer data according to the token information. Finally, the network finishes data transmission from the end to the head of the chain.

4.1. Sink Node

Powered by electric power lines, sink nodes have enough energy. The program running on the sink node is simple. Algorithm is as follows:

(a) Initialize sink node.
(b) Check token information in beacon frame, and get message \( N \) from token. Token is identified by a byte. There can be 127 token access messages at most.
(c) Sink node sends \( M \) beacon frames, with the token message \( X = N \).
(d) If \( X \neq 1 \), go to step (e); else go to step (f).
(e) Let \( X = X - 1 \), then sink node enters the idle mode. Delay \( t \) seconds, go to step (c).
(f) Token message changes to \( X = N \). Sink node enters receiving mode. After processing received and uploading data, go to step (c).

4.2. Sensor Node

Mostly, sensor nodes are in the sleeping mode, and listen to beacon frames only in some certain time. Then judge the working mode according to beacon frames received to avoid message conflict and reduce energy consumption. The algorithm of sensor nodes is as follows:

(a) Initialize sensor node \( i \).
(b) Sensor node collects environment data.
(c) Listen to beacon frames. If received, sensor node get token information \( N-j+1 \), beacon frame number \( k \), and the number of nodes in the entire network \( N \). If sensor node hasn’t received beacon frame till the time out, go to step (n).
(d) If \( j = N \), go to step (m).
(e) If \( i \neq (N-j+1) \cap i \neq (N-j) \), node \( i \) enters sleeping mode. After waking up, it goes to step (b). If \( i = N-j+1 \), go to step (g).
(f) Node \( i \) enters sleeping mode for \( (M-k)t_i + t \), then wakes up and enters receiving mode, after which it enters sleeping mode again. Delay for \( t \), go to step (b). If time is out, enter sleeping mode directly and then delay \( t \) seconds to go to step (b) (Because the time for receiving data is far less than (l)).
(g) If there is no new data to transmitted, then go to step (i).
(h) Node sleeps for \( (M-k)t_i + t \) and transmits data after waking up. If \( i < N \), node sleeps for \( (N-2)T_{\alpha} + t + \Delta \tau \), then go to step (b). Else node sleeps for \( (N-2)T_{\alpha} + t + \Delta \tau \) and then goes to step (b).
(i) If \( i = N \), node enters to sleeping mode for \( (M-k)t_i + t + (N-1)T_{\alpha} + t + \Delta \tau \), then go to step (b). Else enters to sleeping mode for \( (M-k)t_i + t + (N-2)T_{\alpha} + t + \Delta \tau \) and then go to step (b).
(j) If \( i = 1 \), go to step (m), else go to step (n).
(k) If \( i = 1 \) receives data, data goes to step (l). Else enters to sleeping mode for \( (M-k)t_i + t + \Delta \tau \) and then go to step (m).
(l) Node 1 enters sleeping mode and the state lasts for \( (M-k)t_i + t + \Delta \tau \), and then begins to transmit data. Later, it sleeps for \( (N-2)T_{\alpha} + t + \Delta \tau \) and then goes to step (b).
(m) All nodes except node 1 enter sleeping mode for \( (M-k)t_i + t + \Delta \tau \) and then go to step (b).

5. Results and Discussion

5.1. Analysis of Energy Consumption

The model of energy consumption is shown in Fig. 11. Data frame can be transmitted in one listening period, and there is only one node sampling data frame. Only one pair of adjacent
sensor nodes can simultaneously transmit or receive data every time and no data collide and retransmitted during transmission.

![Fig. 11. The model of energy consumption.](image)

In this model, Parameters and assumptions are identified as follows:
- \( \rho \): Nodes’ sampling rate;
- \( E_i \): Energy consumption of idle slot in one period;
- \( E_s \): Energy consumption of sending one data frame;
- \( E_r \): Energy consumption of receiving one data frame;
- \( E_{on} \): Energy consumption of opening wireless transceiver equipment;
- \( T_{aj} \): Observation period;
- \( E_{s} \): Energy consumption in sleeping mode for one period;
- \( N \): The number of nodes in the network;
- \( T_f \): Data interval.

The energy consumption of one standard chain network [12] is:

\[
E(n) = \rho \cdot T_f \cdot E_s(n) - 2 \rho \cdot T_f \cdot E_i(n) + E_{on} \cdot T_{aj}(n) + E_s \cdot T_f(n) + E_r \cdot T_f(n) + E_{on} \cdot T_{aj}(n) + E_s \cdot T_f(n)
\]

That is:

\[
E(n) = \rho \cdot T_f \cdot E_s(n) - 2 \rho \cdot T_f \cdot E_i(n) + E_{on} \cdot T_{aj}(n) + E_s \cdot T_f(n) + E_r \cdot T_f(n) + E_{on} \cdot T_{aj}(n) + E_s \cdot T_f(n)
\]

In which, \( E_s(n) = \rho \cdot T_f \cdot E_s / 2 \).

Calculate total energy consumption and the average is:

\[
E[E_s] = T_f \cdot \rho \cdot (\sum_{i=0}^{N-1} (E_s + E_r) - (N-1)T_f) \cdot \rho \cdot T_{aj} + N \cdot T_f \cdot E_{on} \cdot T_{aj} / 2T_f
\]

\[
(10)
\]

The new MAC protocol based on token for chain-type WSN is similar to the above model in energy consumption. It only adds a new element to idle listening period, which is the energy consumption in adjustment slot and is shown as follows:

\[
E(n) = \rho \cdot T_f \cdot E_s(n) + E_s / \frac{NT_f \cdot E_{on} \cdot NSLP / TBSP + NT_f / TBSP \times NSLP \times E_{on} \cdot T_{aj} / T_f}{2T_f + N \times E_{on} \cdot T_{aj} / T_f}
\]

Calculate the energy consumption of all nodes and get the average:

\[
E[E_s] = T_f \cdot \rho \cdot (\sum_{i=0}^{N-1} (E_s + E_r) - (N-1)T_f) \cdot \rho \cdot T_{aj} + N \cdot T_f \cdot E_{on} \cdot T_{aj} / 2T_f
\]

\[
(12)
\]

Comparing formula (10) and (12), we find out that the new protocol and standards chain protocols have the same energy consumption in transmitting and receiving data which is: \((N-1)T_f \cdot \rho \cdot T_{aj} \).

By reducing the opening time of RF module, the new protocol can save energy of \( NT_f, E_{on} \cdot NSLP / TBSP \) compared with the standard protocol. It can also reduce energy of \( NT_f \cdot TBSP \cdot NSLP \cdot \rho \cdot T_{aj} / 2T_f \) in idle listening. It shows that the new protocol is suitable for the chain-type WSN and more effective than the standard chain protocol concerning energy consumption reduction.

### 5.2. System Reliability Test

To test the correctness and reliability of multi-point communication test packet loss rate, six groups of experiments have been carried out, each of which measured 3000 completed cycles. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sending data packets</th>
<th>Correct receiving data packets</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>3000</td>
<td>2896</td>
<td>99.53</td>
</tr>
<tr>
<td>2.</td>
<td>3000</td>
<td>2984</td>
<td>99.47</td>
</tr>
<tr>
<td>3.</td>
<td>3000</td>
<td>2979</td>
<td>99.30</td>
</tr>
<tr>
<td>4.</td>
<td>3000</td>
<td>2981</td>
<td>99.37</td>
</tr>
<tr>
<td>5.</td>
<td>3000</td>
<td>2975</td>
<td>99.17</td>
</tr>
<tr>
<td>6.</td>
<td>3000</td>
<td>2983</td>
<td>99.43</td>
</tr>
</tbody>
</table>

From the above table, we can see the accuracy of multi-point communication is a little lower than the one of point to point communication But they are all above 99.17 %. The average data receiving correct rate is 99.38 %. The reliability of the system is quite well, which shows the feasibility of this protocol based on token.

On the premise of excluding interference, there should not be packet loss in theory. The main reason is: nodes synchronize time by the time synchronization information in beacon frames and the own clock information, which can cause synchronization error when small differences and drift of clock are existed.
6. Conclusion

MAC protocol is significant in WSN technology, as well as the key technology in application [13]. In this article, a novel MAC protocol based on token has been designed. Nodes in the network adopt listen/sleep mechanism, and transmit data only after receiving beacon frames, by which energy consumption can be reduced effectively. Meanwhile, the token is used as control message so that the control process from sink node to sensor node is simplified, no interference will occurred among nodes, and the channel is used in order. To improve reliability, we propose a novel reliable transmission mechanism by sending redundant data packets through a single path.

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