A New Wireless Sensor Network MAC Protocol: NSMAC

Yaoyao Zhang, Lingyun Jiang

Abstract: How to reduce energy consumption and improve the life cycle is one of the hot spot issues in current wireless sensor network research. Media Access Control (MAC) has an important impact on sensor network life cycle and performance. This paper proposes a new MAC protocol--NSMAC protocol. This protocol dynamically changes the length of the contention window and the size of the duty cycle based on the load on the network. It can effectively reduce energy consumption, improve network throughput capacity, and improve sleep time-delay in a multi-hop network environment when the network load is large. The experimental results also prove that this protocol has significant improvement in energy consumption, time-delay and throughput capacity compared to SMAC protocol and RCMAC protocol.

1. Introduction

Wireless Sensor Network (WSN) [1-2] plays an important role in many fields, such as environmental monitoring, biological activities, and smart transportation. The WSN consists of a number of micro-computing devices, and these devices typically have sensing capabilities. A large number of sensing nodes work in the monitoring area, and the collected data are uploaded to the Sink node. The node is mainly composed of an energy module, a sensing module, a wireless module, and a processing module [3].

The medium access control (MAC) protocol in the WSN protocol stack [4] determines the use of wireless channels, allocates limited wireless communication resources among sensor nodes, and builds the underlying infrastructure of the sensor network system for sensor networks. It is one of the key protocols to ensure efficient communication of wireless sensor networks.

At present, the MAC protocol of most wireless sensor networks saves energy by reducing nodes’ idle listening, such as SMAC [5] protocol, BMAC [6] protocol, and so on. However, these MAC protocols can save energy when the network load is constant, especially when the load is light. However, when the network load is dynamically changing, especially in heavy load, the MAC protocols working in these fixed modes are not suitable well. This paper proposes a new MAC protocol--NSMAC, which can adapt to this dynamic change of the network. According to the load of the network, switch the working mode of the network, which can achieve better energy-saving results.

Since the wireless sensor network is an energy-constrained network, the first consideration for the MAC protocol is energy consumption. The most widely used Bluetooth [7] or 802.11 [8] protocols are not directly applicable to wireless sensor networks, as neither of them has reduced energy consumption as their primary design goal. The existing wireless sensor network MAC protocol can be divided into two major categories according to its working mode: competitive MAC protocol and scheduling (non-contention) MAC protocol. In the contention-based MAC protocol, nodes compete for channels in CSMA/CA. In the TDMA-based contention-free MAC protocol, each node is assigned a specific time
slot, and the node can directly access the channel for data transmission without contention. There are four main sources of energy waste in sensor networks: idle listening, collision, crosstalk, and control overhead [9]. For the above four aspects, different MAC protocols give different solutions.

The main goal of the contention-based MAC protocol is to reduce energy waste and maintain the simplicity and scalability of the protocol, which is especially important in resource-constrained network environments such as WSN. By periodically contending for the radio channel between the active state and the idle state (sleep state), a duty cycle mechanism is used while reducing energy waste due to idle listen. In 2002, Wei Ye et al. proposed the SMAC (Sensor MAC) protocol, which was the first MAC protocol specifically for wireless sensor networks. It achieves the goal of reducing energy consumption through periodic work and sleep. However, the SMAC protocol also has some problems, such as the fixed duty cycle, which introduces a large sleep delay while reducing power consumption. At the same time, when multi-hop transmission, due to the queuing of data packets, it also leads to the throughput decreases and the delay increases.

In the TDMA-based contention-free MAC protocol, each node is assigned a contention-free time slot. TDMA-Wakeup (TDMA-W) in [10] is based on the TDMA-based MAC protocol. Its main feature is that if a node has data to transmit, it only needs to wake up to send data in the time slot assigned to it, and other times go into sleep.

In recent years, cross-layer MAC protocols have also been proposed by many studies. For example, the RCMAC [11] protocol adopts a cross-layer optimization method. By modifying the MAC layer frame structure, the routing information provided by the network layer is introduced in MAC layer, so that the node can be advanced knowing the path, realizing the reserved channel and shaking hands in advance, improving the transmission efficiency of the network.

In a world, different types of MAC protocols have their mechanisms to reduce power consumption, but they also have their limitations. This paper proposes a new protocol, which mainly solves the problems of high energy consumption, low throughput and large delay increase in a multi-hop network environment when network traffic is large.

2. The mechanism of SMAC protocol
SMAC is the earliest application in the wireless sensor network MAC protocol, using many measures to reduce node energy consumption. It uses a low duty cycle to transmit information in a multi-hop network, and uses virtual clusters to keep nodes within the cluster in the same scheduling period, thereby reducing the overhead of control information. At the same time, the SMAC protocol uses a fixed-size contention window, reducing the complexity of the protocol. The duty cycle of the SMAC protocol and the contention window mechanism are our improvements.

In a wireless sensor network, if there is no information exchange, the node will enter a long idle state. Because in the case of low network load, it is not necessary to keep the node listening all the time. The SMAC protocol reduces the node listening time through a periodic listening mechanism. Each cycle is divided into a listening and sleeping state. In the listening state, the node exchanges synchronization information and completes the RTS/CTS handshake. The listening state accounts for about 10% of the entire cycle. In the sleep state, the node turns off the transceiver module, let power consumption remains at a fairly low level. Simultaneous, in the protocol design, only the light load situation is considered, the node has only a small amount of time to send data, so the contention window is set to a fixed value, thereby reducing the complexity of the protocol.

3. Design of NSAMC Protocol
The SMAC protocol with a fixed duty cycle and fixed contention window is difficult to adapt to the dynamic changes of the network. Because when the load is heavy, the fixed contention window and the duty cycle make the collision of the data packet become serious, and the number of retransmitted data packets becomes more, resulting in a decrease in the throughput of the network. When the load becomes light, this fixed working mode will increase the idle listening of the node, resulting in a waste of energy, which is the primary factor considered in the design of the wireless sensor network MAC protocol. In
this paper, we propose a new MAC protocol--NSMAC protocol. It can control the contention window size and duty cycle of the node in real-time according to the load condition of the network.

First, we analyze the competition window mechanism. In the SMAC protocol, the node needs to wait for a DIFS and select a back-off time to send packets:

\[ BT = \text{rand}(0, CW) \times \text{slotTime} \]  

(1)

CW is the contention window and the value is \(2^n - 1\). In the SMAC protocol, CW is fixed. When the load is heavy, the probability that other nodes select the same back-off window will become larger, and the collision retransmission problem of data will also increase, causing an increase in power consumption.

In NSMAC we use two limit values \(CW_{\text{min}}\), \(CW_{\text{max}}\) and a basic value \(CW_{\text{basic}}\) as the interval for the contention window adjustment. The \(CW_{\text{basic}}\) is the size of the contention window in the SMAC protocol. The size of the contention window is adjusted based on the number of node’s cached packets. Assuming that the packet queue length is MaxQueueLength (MaxQL) and the node cache packet queue length is QueueLength(QL), then we make the following judgment:

- The CW of the node is initialized to \(CW_{\text{basic}}\).
- The CW of the node is initialized to \(CW_{\text{basic}}\).
- If QL is greater than 60% MaxQL, then let CW equal \(CW_{\text{max}}\).
- If QL is greater than 30% and MaxQL is less than or equal to 60% MaxQL, then let CW equal \(CW_{\text{basic}}\).
- If QL is less than or equal to 30% MaxQL then we let CW equal \(CW_{\text{min}}\).

And then we analyze the duty cycle mechanism. Figure 2 is a basic cycle of the SMAC protocol. \(T_f\) is the time of a sleep cycle, the value is:

\[ T_f = T_{\text{sleep}} + T_{\text{listen}} \]  

(2)

where the \(T_{\text{sleep}}\) is sleep time and \(T_{\text{listen}}\) is the listening time.

Duty cycle is defined as [5]:

\[ D = \frac{T_{\text{listen}}}{T_f} = \frac{T_{\text{listen}}}{T_{\text{sleep}} + T_{\text{listen}}} \]  

(3)

In the SMAC protocol, the size of the duty cycle \(D\) is fixed. This brings up a problem, the node cannot adapt to the dynamic load of the network. As a result, the network has a high delay when the network load is heavy.

Then analyze the relationship between delay and duty cycle. The delay of the node at n hop is:

\[ D_n = t_{t,n} + t_{c,n} + t_{s,n} \]  

(4)

Where \(t_{t,n}\) is the transmission delay; \(t_{c,n}\) is the carrier sense delay and \(t_{s,n}\) the sleep delay.

The sleep time of the \(n\)th hop period is:
\[ T_f = t_{cs,n-1} + t_{tx} + t_{s,n} \]  

From (5) we can get the sleep delay \( t_{s,n} \):

\[ t_{s,n} = T_f - (t_{cs,n-1} + t_{tx} + t_{s,n}) \]  

The total delay for getting the \( n \)th hop in (4) is:

\[ D_n = T_f - t_{cs,n} - t_{cs,n-1} \]  

Then the total delay of the \( N \) hop is:

\[ D(N) = D_1 + \sum_{n=2}^{N} D_n = t_{s,1} + (N-1)T_f + t_{cs,N} + t_{tx} \]  

Then the average delay of the \( N \) hop can be obtained by expecting (8):

\[ E[D(N)] = E[t_{s,1}] + (N-1)E[T_f] + E[t_{cs,N}] + E[t_{tx}] \]

\[ = T_f/2 + (N-1)T_f + t_{cs} + t_{tx} \]

\[ = NT_f - T_f/2 + t_{cs} + t_{tx} \]  

When the duty cycle is low, \( T_f \) much larger then \( (t_{cs} + t_{tx}) \), so when the number of hops increases, the delay can be reduced by \( T_f \) reduced, that is to shorten long cycle time and increase the duty cycle.

In the SMAC protocol, the duty cycle of the node is fixed at 10%, and the period of a cycle is approximately 1.443s. In a cycle, each sensor node can only process one packet, and the rate of the node to process the packet no more than 1 packet/s. In the actual sensor network, the load of the network changes at any time, that is, the data packet cached in the queue of the node changes. In the NSMAC protocol, we introduce a new metric--the node packet growth rate. Of course, the growth rate here is the Average Growth Rate (AQR). That is, measuring the growth rate three times over a continuous period:

\[ AQR = \sum_{i=0,1,2,3} (Q_{i+1} - Q_i) / 3 \]  

Then dynamically change duty cycle based on the average growth rate. Because the increase in duty cycle means that the energy consumption will increase, so the duty cycle cannot be increased without control. Considering the energy consumption, delay and throughput, we set the MaxDutyCycle to 40% is reasonable. The duty cycle will be set to 10%, 20% and 40%.

The duty cycle is adjusted as follows:

- First, to ensure that the adjustment of the competition window is performed before the execution, the initial value of the duty cycle is set to 10%.
- If \( CW = CW_{\text{min}} \), the duty cycle remains unchanged at 10%.
- If \( CW = CW_{\text{basic}} \), determine the average growth rate. If \( AQR > 1 \), the duty cycle is doubled; if \( AQR < 0 \), the duty cycle is doubled; the others remain unchanged.
- If \( CW = CW_{\text{max}} \), judge the average growth rate. If \( AQR > 1 \), the duty ratio is adjusted to 40%; if \( AQR < 0 \), it is doubled; the rest remains unchanged.

![Figure 3. Adjustment of duty cycle](image-url)
4. Simulation

This paper uses the linear network topology diagram consisting of 10 nodes as shown in Figure 4. The simulation time is 1000s, where node 0 is the source node and 9 is the sink node. The node can only communicate with neighboring nodes to ensure that data can only be transmitted in single-hop. We use NS2 to simulate the N-SMAC protocol. The parameters are set as follows:

| Parameter             | Value            |
|-----------------------|------------------|
| bandwidth             | 20kpbs           |
| cbr packet size       | 50bytes          |
| CWmin                 | 7                |
| CWmax                 | 255              |
| initial energy        | 1000J            |
| SMAC duty cycle       | 10%              |
| maximum queue length  | 50               |
| node communication distance | 250m       |
| node distance         | 200m             |

The transmission interval of the data packet is from 1s to 10s, which is used to simulate different load conditions of the network. When the interval is 1s, the load is heavy, when it is 10s, the load is light, and the node sends 50 data packets.

4.1 Energy consumption

First, we look at the average energy consumption of the network. The average energy consumption is the total initial energy of the network minus the total energy at the end of the simulation, then divided by the number of nodes.

As can be seen from the figure, the power consumption of the RCMAC protocol and the SMAC protocol are not much different, mainly because the RCMAC protocol sacrifices energy consumption to obtain delay and throughput. Even when the load is light, this protocol cannot adapt to the dynamic changes of the load in the network, so it consumes more energy than NSMAC and SMAC. When the packet interval is reduced from 4s to 1s. The load of the network gradually increases, and the collision retransmission of data packets between nodes becomes serious. Therefore, the effect of changing the CW is more obvious. The probability that the node selects the same contention window when transmitting the data packet is greatly reduced, so the collision problem gets mitigation. At the same time, as the number of data packets cache in the node increases, the listening time of the node will also increase, and the dynamic adjustment of the duty cycle enables the node to send more data packets in the basic period of a SMAC protocol, saving the overhead of sync frames. They cooperate to make the network achieve lower energy consumption when the load is higher.
4.2 Average end-to-end delay
The delay in this paper refers to the end-to-end average delay, which means that all data packets are averaged in the application layer of the source node to the application layer of the destination node to successfully receive the time difference between the packets.

We set the data packet interval of the network to 1s, which means that the network load is heavy. In the SMAC protocol, due to the fixed duty cycle, the rate of node processes data packets is limited, and packets are too late to be sent are queued in the cache queue of the node. The queue delay increases and because the CW is fixed, the data collision is serious, some data packets will be retransmitted, and the delay will increase accordingly.

From Figure 6, we can see that as the hop increases, the delay also increases. The RCMAC protocol has some improvement over SMAC, but it sacrifices energy consumption. After adopting the NSMAC protocol, the CW and duty ratio are dynamically changed according to the number of cached packets and the growth rate of the nodes. When the traffic in the network is heavy, the node increases the duty cycle and transmits more data packets in one basic period, which reduces the dwell time of the data packet in the network. As the number of hops increases, the end-to-end delay of the NSMAC protocol is more advantageous than the SMAC protocol and the RCMAC protocol.

4.3 Network Throughput
The average throughput of the network refers to the total data packets received by the node over a period. The indicator used in this paper is the average throughput, which is the ratio of the amount of data received by the node to the total amount of time.

In the simulation, the source node sends a total of 50 data packets, each of which has a size of 50 bytes, so the total amount of data is 2500 bytes. The total time can be calculated from the simulation trace file of NS2.

In SMAC protocol, because the energy consumption is taken care of, the node is in idle state for most of the working time to save energy, which results in it has few opportunities to send data packets in a multi-hop environment, so the end-to-end throughput will be greatly affected. As shown in Figure 7, network throughput decreases with the increase of packet spacing in the multi-hop network environment due to data collision. As can be seen from the figure, the throughput of SMAC protocol does not change significantly with the increase of packet interval, mainly due to the influence of a fixed duty cycle. In RCMAC protocol, because it sacrifices energy consumption and adds routing information at the same time, the throughput improves significantly compared with SMAC protocol, but with the change of load. Compared with NSMAC, its throughput decreases more obviously. In NSMAC protocol, the node can
dynamically change the duty cycle according to the cache queue and increase the value of the contention window CW. Therefore, the nodes can adapt well to different levels of load; even load is heavy.

Figure 7. Comparison of three protocol throughputs

5. Conclusion
The SMAC protocol uses periodic sleep and message transmission mechanisms to save energy. However, due to its fixed contention window and duty cycle, it is difficult to adapt to the flexible load conditions in the network. Therefore, this paper proposes a new wireless sensor network MAC protocol, which can dynamically change the size of the contention window according to the packet situation in the queue length, and it can also dynamically adjust the duty cycle according to the growth rate of the queue packet. The RCMAC protocol does not consider power consumption while ensuring latency and throughput. It can be seen from the simulation that the NSMAC protocol ensures a certain degree of improvement in delay and throughput while reducing power consumption.

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