Medium Access Control Protocol with Dynamic Duty Cycle in Wireless Sensor Network

Ziqiang An

Abstract—**Lowering the energy consumption may result in increase of time delay from end to end in Wireless Sensor Network (WSN). To address the tradeoff between energy consumption and time delay, this paper proposes a Media Access Control (MAC) protocol based on dynamic duty cycle. It adjusts duty cycle dynamically through computing node utilization rate, average sleeping delay, and the upper and lower bound of duty cycle, to adapt the network real-time communication flow. Experimental results show that MAC protocol saves energy about 52 % and reduces latency time 35 % than S-MAC in linear topology. In the reticular topology, it achieves 68 % energy saving and 46 % latency reduction than S-MAC.**

Index Terms—**Wireless sensor network (WSN), media access control (MAC) protocol, duty cycle, average delay.**

I. Introduction

Wireless Sensor Network (WSN) [1] as a new technology, has been used in many occasions to perceive and gathering the data in the environment. Sensor network is composed by a large number of sensor nodes. Sensor nodes rely on battery power, through their own processor to do simple data processing. Therefore, the sensor nodes will transfer the collected data to gathering nodes; the nodes are responsible for gathering data and processing.

The sensor nodes rely on battery power supply, so energy efficiency is the main considered goal in the design [2]. Sensor MAC [3] (S-MAC) protocol is based on 802.11 MAC protocol, aiming to the saving energy demand of sensor network and puts forward the sensor MAC protocol. S-MAC uses monitoring and sleeping regulation mechanism to ensure energy efficiency. But there is a problem, if message transmission is ensured reliable and timely, the activities time of nodes must adapt to the highest communication load. The network load dynamically changes, thus the fixed duty cycle of S-MAC cannot make node's activity time reflect the data transmission requirements in network, which will result in the increase of end-to-end delay.

Aiming to this problem, many protocols conduct the improvement based on S-MAC. Timeout MAC [4] (T-MAC) protocol keeping period length constant, defines 5 kind of events and a timer TA to determine the end time of work stage. Although the wasted energy in free monitoring is reduced, the protocol still has early sleeping problem. Data-gathering MAC [5] (DMAC) puts forward the swinging-to-awaken strategy to solve the data delay problem in S-MAC, which adjusts the nodes work cycle of each layer in the tree, to make the sending time of child nodes coincide with the receiving time of father nodes. But DMAC protocol needs the strict time synchronization among nodes. Dynamic Sensor MAC protocol [6] (DSMAC) according to the current network traffic, adaptively adjusts node's duty cycle to improve delay problem. DSMAC according to node delay and queue cache length increases double or decreases half of the duty cycle. But the amplitude of duty cycle is fixed which is adjusted by DSMAC, this can't fully embody the advantages of adaptive flexible adjustment.

In order to make the duty cycle of S-MAC adapt to the network load much better, this paper puts forward Adaptive Duty Cycle SMAC (ADC-SMAC). ADC-SMAC mainly improves two aspects of S-MAC: variable duty cycle mechanism is used to realize the distribution of different duty cycle for different task nodes; node's independent calculation is suitable for their own duty cycles. As same as DSMAC, ADC-SMAC also sets a variable duty cycle for nodes. But different with DSMAC fixed duty cycle to change amplitude, the flexible duty cycle regulation mechanism of ADC-SMAC has greater advantages.

II. S-MAC Protocol

A. S-MAC Protocol Design

S-MAC work mechanism is shown in figure 1 below. The upward arrow represents sending messages, down arrow represents receiving messages, the above information flow represents sending and receiving sequence of messages while nodes always being in the monitoring state, the under information flow represents the sending and receiving sequence of message adopting S-MAC protocol.

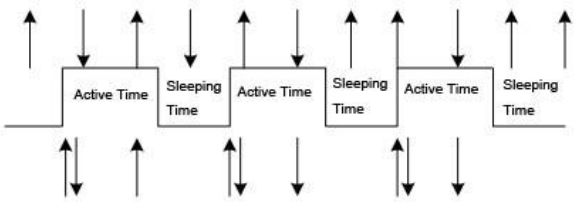

Fig. 1. S-MAC work mechanism

Design features of S-MAC protocol:

- Periodic monitoring and sleeping mechanism. In the application environment the load flow of many sensors is not so large, that is, sensor nodes are in the idle monitoring state most of time. The energy consumption in the idle monitoring state is the main

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reason of invalid energy consumption for nodes. S-MAC leads into periodic monitoring and sleepingmechanism in order to solve the idle monitoring problem. A complete monitoring and sleeping cycle is called one frame; the monitoring part in one frame is called the active time. Before nodes sending data, they will broadcast their scheduling list to their neighbor nodes, and take the same monitoring and sleeping scheduling node to form a virtual cluster.

- Avoid crosstalk. In the traditional IEEE 802.11 network, the nodes monitor all the data sent from neighbor nodes, even if they are not the target nodes of packets. To avoid this crosstalk problem, S-MAC puts forward when the received destination node is not their RTS or CTS packet, the node will go into the sleeping state until the data transmission is over.
- Data transmission. In 802.11 networks, a piece of long data will be separated into several short data; the transmission of each short data is need through the handshake process of RTS/CTS/DATA/ACK. This process will lead to the cost of control information and a higher price. After S-MAC does once shake hands, it transmits all short messages to solve the problem.

B. S-MAC Protocol Problems

Though S-MAC improved the energy consumption problem of IEEE 802.11, but its own use also has many defects.

- United duty cycle. In a typical sensor network, different nodes may undertake different tasks, such as data source node, relay node, and gathering node. In S-MAC, unified fixed duty cycle is set in whole network. While the flow load is small, unified fixed duty cycle will lead into the increase of monitoring energy consumption in idle state, while the flow load is large, unite fixed duty cycle can lead to the increase of queuing delay for nodes. As shown in the linear topological structure in figure 2, node 0 is a source node, while the duty cycle is 20%, invalid energy consumption is the minimum; node 2 is taken as relay node, while the duty cycle is 35%, invalid energy consumption is the minimum. From here the problem of unit duty cycle can be found.

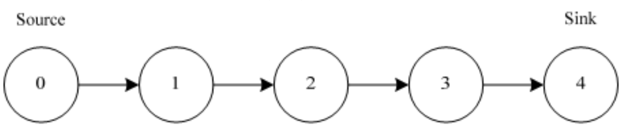

Fig. 2. Linear topology

- Delay. In some sensor applications, such as environmental monitoring, the required data delay from source node to destination node is in a certain range. In S-MAC, in order to ensure low energy consumption, usually node is set as low duty cycle. By the average delay of node in expression (1), the periodic dormancy mechanism with fixed duty cycle of S-MAC protocol cannot dynamically adjust duty cycle according to change of business in the network, there exists the conflict between delay and energy consumption.

$$
\begin{aligned}
E[D(N)] &= E\left[T_{s,N} + T_{c,N} + T_{tr} + (N-1)T_f\right] \\
&= \frac{1}{2}T_f + T_{tr} + E\left[T_{c,N}\right] + (N-1)T_f \\
&= \left(N - \frac{1}{2}\right)T_f + T_{tr} + T_c
\end{aligned}
\tag{1}
$$

Among the expression, $D(N)$ represents the total delay after N hop for forwarded packets; $T_{s,N}, T_{c,N}, T_{tr}$ represent the total dormancy delay, total competition delay, and total transmission delay; T_f represents the time length of one frame.

III. DESCRIPTION OF ADC-SMAC ALGORITHMS

Please acknowledge collaborators or anyone who has helped with the paper at the end of the text.

To solve the above two problems in S-MAC, this paper proposes ADC-SMAC protocol, the specific description is as follows:

Firstly, in order to reflect the change of different flow load, while sending the sync packet, node calculates the node utilization rate U in last period and the average sleeping delay $\overline{D}$, and according to the network status parameters, adjusts its duty cycle, and send the new scheduling in the form of broadcast to neighbor nodes, the specific algorithm is as follows:

Step 1. Computing the node utilization rate U of in last cycle:

$$U = \frac{T_{rx} + T_{tx}}{T_{rx} + T_{tx} + T_{idle}} \tag{2}$$

Among them, T_{rx} represents total receiving time; T_{tx} represents total sending time; T_{idle} represents total free time.

Step 2. Computing the average sleeping delay of last cycle:

$$\overline{D} = \frac{D}{packet\ count} \tag{3}$$

In the expression, D is the accumulation for sleeping time delay; packet count represents the accumulation number of packets.

Step 3. Adjust the duty cycle, using the code to describe:

If $U > U_{high}$ and duty $cycle > DC_{\max}$ then duty cycle = duty cycle + n% else if $U > U_{low}$ and duty $cycle < DC_{\min}$ and $\overline{D} < D_{\max}$ then duty cycle = duty cycle-n%

end if

In the expression, U_{high} *and* $U_{\min}$ represents the upper and lower bound of node utilization; $D_{\max}$ represents the maximum tolerable sleeping delay; $DC_{\max}$ *and* $DC_{\min}$ represents the upper bound and lower bound of duty cycle; n represents the adjustment amplitude of duty cycle.

Step 4. D=0, packet count = 0.

As shown above, node at first calculates the utilization rate U. If a node utilization U is very big, in the current scheduling mechanism, the node load is heavy. Therefore, increasing duty cycle adapts to such a load. In this algorithm, U_{high} represents heavy load. When the node utilization rate U is greater than U_{high}, the node duty cycle needs to increase n%. Appropriate n value not only can make node adapt the change of flow as soon as possible, but also can prevent the excessive changes of duty cycle. In order to prevent the endless change of duty cycle, the algorithm puts forward $DC_{\max}$ *and* $DC_{\min}$ as the upper bound and lower bound of duty cycle regulation.

Considering the delay, this paper proposed the concept of biggest tolerable sleeping delay $D_{\max}$. When average delay *D* is close to $D_{\max}$, node's duty cycle needs to stop the decrease.

Secondly, the following description is about the algorithm, which updates sleeping delay *D* after sending data packets each time, the specific content is as follows:

Step 1. Pick out of the value of delay character in data packet, and assign to variable d. Single sleeping delay d is the time that MAC layer receives packet from upper layer to successfully sending RTS.

Step 2. Computing accumulated sleep delay D; update the number of successful sending packets

$$D=D+d \tag{4}$$

Packet count=packet count +1 (5)

IV. Simulation and Analysis of Experimental Results

A. The test Environment and Explanation

The simulation experiment in this paper is conducted on ns2.29 [7] simulation platform to compare S-MAC, DS-MAC, ADC-SMAC. But the implementation mechanism between DS-MAC and ADC-SMAC is different. The adjusting mechanism of DS-MAC depends on queue length and delay, ADC-SMAC depends on node utilization rate, average sleeping time delay, and the upper and lower bound etc. adjustment parameters.

B. Experiment Topology

The simulation experiment using topological 1 is shown in figure 3 below. Node 0 is source node. Node 4 is gathering node, the data starts from node 0, through the relay of node 1, 2 and 3, eventually sends to node 4.

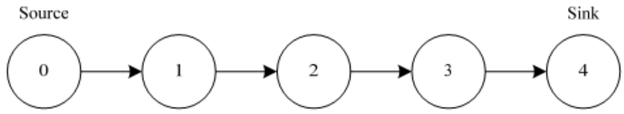

Fig. 3. Linear topology

The simulation experiment using topological 2 is shown in figure 4. Node 0, node1 are respectively as source nodes, node 3, node 4 are respectively as a gathering node, data produces from node 0 and node 1, relaying through node 2 and being sent to node 3 and 4. The design purpose of topological 2 is causing heavy load at node 2.

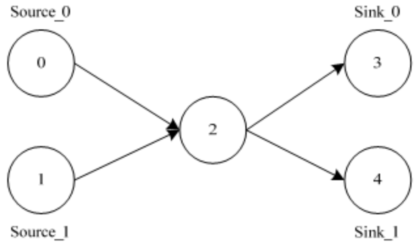

Fig. 4. Mesh topology

C. The analysis of Experimental Results

1) Analysis of experimental results under linear topological

Figure 5 shows the total energy consumption all nodes in topology 1.

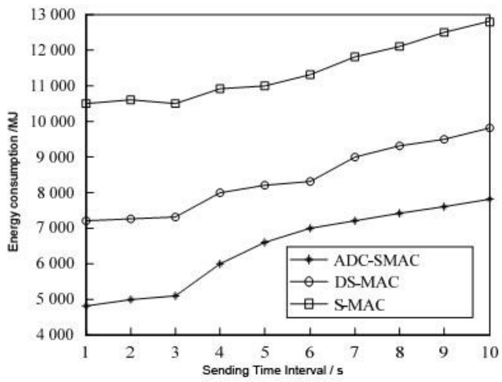

Fig. 5. The comparison results of average energy consumption under linear topology

Comparing with S-MAC in the figure, the energy saving effect of ADC-SMAC is very obvious, especially when the node load is heavy. When data sending interval is 1s, ADC-SMAC's energy consumption is 49% of s-MAC, at this time the network has been in a saturated state. When data sending interval is 4s, ADC-SMAC's energy consumption is 55% of MAC. The average energy consumption of ADC-SMAC is 52% of S-MAC. Comparing with the simulation results of DS-MAC and ADC-SMAC, the energy consumption of ADC-SMAC is lower than DS-MAC, this shows that the duty cycle mechanism taken by ADC-SMAC is more reasonable than DS-MAC.

As shown in figure 6, in topology 1 aiming to the average end-to-end delay of data packets, average delay of ADC-SMAC is less than S-MAC and DS-MAC. When data sending interval is 4s, the average delay of ADC-SMAC is minimum, which is 16% of s-MAC. DS-MAC can also improve delay to a certain extent, especially to heavy traffic load; the improvement degree is almost same with ADC-SMA. But when flow load is light, ADC-SMAC can still keep good delay status, but DS-MAC effect is not pretty. When data sending interval is 8s, average delay of ADC-SMAC is 57% of s-MAC, the average delay of DS-MAC is close to s-MAC, it is 97% of s-MAC. In the whole simulation stage, the average value of delay of ADC-SMAC is 35% of S-MAC.

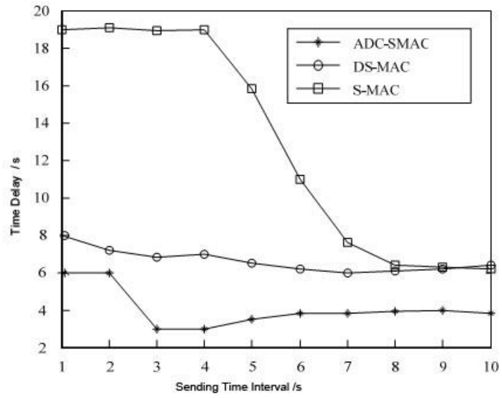

Fig. 6. The results of average delay comparison under linear topology

2) The analysis of experimental results under mesh topology

Figure 7 and figure 8 reflect in topology 2 the energy consumption and the average time delay of node 2 in S-MAC, DS-MAC and ADC-SMAC. It is shown that comparing with S-MAC and DS-MAC, ADC-SMAC still shows a good energy consumption status and delay condition. In figure 7, average energy consumption of ADC-SMAC is 68% of S-MAC. In figure 8, the average delay of ADC-SMAC is 46% of S-MAC.

V. LAST WORD

Wireless sensor networks have different application environment, some only require lower energy consumption, some only require lower time delay, and some needs both. Therefore, this article puts forward ADC-SMAC to solve in different application background the balance problems between energy consumption and time delay. In order to solve this problem, the mechanism proposed in this paper mainly according to the node utilization rate, the average sleeping delay and the lower and upper bound of duty cycle etc. adjustment parameters, dynamically adjust the duty cycle of nodes, the purpose is in certain degree to ensure low energy consumption and low delay. In linear topology and mesh topology, comparison experiment is done to S-MAC, DS-MAC, and ADC-SMAC, the results proves in these two topologies, the energy consumption and time delay of ADC-SMAC have great improvement than that of S-MAC and DS-MAC.

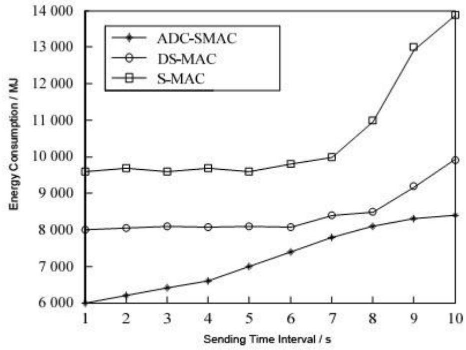

Fig. 7. The comparison results of average energy consumption under mesh topology

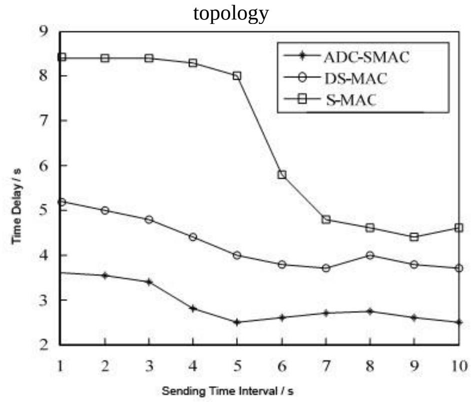

Fig. 8. The comparison results of average delay under mesh topology

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