MDA-SMAC: An Energy-Efficient Improved SMAC Protocol for Wireless Sensor Networks

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Abstract

In sensor medium access control (*SMAC*) protocol, sensor nodes can only access the channel in the scheduling and listening period. However, this fixed working method may generate data latency and high conflict. To solve those problems, scheduling duty in the original *SMAC* protocol is divided into multiple small scheduling duties (micro duty *MD*). By applying different micro-dispersed contention channel, sensor nodes can reduce the collision probability of the data and thereby save energy. Based on the given micro-duty, this paper presents an adaptive duty cycle (*DC*) and back-off algorithm, aiming at detecting the fixed duty cycle in *SMAC* protocol. According to the given buffer queue length, sensor nodes dynamically change the duty cycle. In the context of low duty cycle and low flow, fair binary exponential back-off (*F-BEB*) algorithm is applied to reduce data latency. In the context of high duty cycle and high flow, capture avoidance binary exponential back-off (*CA-BEB*) algorithm is used to further reduce the conflict probability for saving energy consumption. Based on the above two contexts, we propose an improved *SMAC* protocol, micro duty adaptive *SMAC* protocol (*MDA-SMAC*). Comparing the performance between *MDA-SMAC* protocol and *SMAC* protocol on the *NS-2* simulation platform, the results show that, *MDA-SMAC* protocol performs better in terms of energy consumption, latency and effective throughput than *SMAC* protocol, especially in the condition of more crowded network traffic and more sensor nodes.

Keywords: Wireless sensor networks, SMAC protocol, micro-duty, traffic adaptive duty cycle, back-off algorithm

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1. Introduction

Saving energy of nodes is a vital issue when designing and deploying wireless sensor nodes (*WSNs*) applications due to *WSNs* are usually deployed in wide, special environment with limited energy. Sensor medium access control(S*MAC*) protocol [1] determines the way of sensors to access the channel and directly controls the communication module with most energy consumption of the deployed nodes. Therefore, the design of energy-efficient *MAC* protocol is one of the main research directions in the field of *WSNs*. Current researchers in *MAC* protocol for *WSNs* are doing researches in this field, and have achieved some results [1][2][3]. However, there is no uniform standard for classifying *MAC* protocol for *WSNs*. According to the number of occupied channels, *MAC* can be divided into multi-channel and single-channel *MAC* protocol. According to data communication types, it can be divided into unicast and multicast *MAC* protocol[4]. According to the variability of nodes transmission power, it can also be divided into fixed and variable power *MAC* protocol[5]. Based on the node access channel method, the most wildly used classification schema divides the *MAC* protocol into three classifications, *MAC* protocol based on channel allocation mechanism, hybrid *MAC* protocol and *MAC* protocol based on competition mechanism. In the paper, we research *MAC* protocol based on competition mechanism. This method has the following advantages (1) Better adaption to network topology changes. (2) No centralized control of a large number of scattered sensor nodes. (3) Channel is used only when data transmission occurs, otherwise, it will turn into sleep or low power state, dramatically reducing the energy consumption.

Due to its inherent flexibility, scalability, and the advantage of tackling the problem of data fluctuation, competition-based *MAC* protocol is widely used with high research value. *SMAC* protocol [3][6][7] is a typical completion-based protocol in *WSNs*. Most of competition-based *MAC* protocols are based on this protocol. *MAC* protocol IEEE802.11[8] based especially is proposed for solving the problem of limited energy storage of sensor nodes in wireless sensor network. It achieved a better energy efficiency effect with assumptions that the network can tolerate a certain delay and allowance for node sleep periodically. *SMAC* protocol has good scalability due to the competitive mechanism for accessing channel. The main mechanism applied in the *SMAC* protocol is timing synchronization, flow adaptive listening, cross talking and fragment messages transmitting. But nodes use a fixed duty cycle to work, which cannot adapt to changes of network traffic. This approach leads to a less node working time, long sleep time, wasting a lot of time resources, and large network latency. During the stage of listening, all nodes try to get access to the channel and in this situation, when network traffic flow is large or in a dense *WSNs* environment, the conflict between the nodes will exacerbate, which will lead to multiple nodes retransmission back-off, and more energy waste. Energy saving and energy efficiency in the next generation wireless communication, especially in 5G network, some literatures are available in [9][10][11] [12]**.** [9]proposed a computation power model for 5G small cell networks. Considering that the massive MIMO and millimeter wave technologies are adopted at small cell BS’s, the impact of the number of antennas and bandwidths on the computation power of 5G small cell networks is investigated. They concluded that the energy efficiency optimization of 5G small cell networks should consider computation and transmission power together. [10] proposed the distributed architecture of ultra-dense cellular network with single and multiply gateways, which can be deployed in all 5G cellular scenarios. Meanwhile, the impact of different numbers of small cell BSs on the backhaul network capacity and the backhaul energy efficiency of ultra-dense cellular networks was investigated. [11] proposed a 5G wireless network solution for reducing the transmission delays and system energy consumption in AR/VR applications. The SEEM algorithm was designed to minimize the network energy consumption while guaranteeing that the delay is less than a given threshold by adopting the MCR scheme. This idea and algorithm give us some guideline and the algorithm will be adopted in our future research. In [12] a new OAM spatial modulation scheme was proposed for multi-antenna millimeter wave communication systems. Those research results give our research some new good idea and some inspiration. Meanwhile, those studies will offer a fresh perspective on energy efficiency in this context. We will apply some research result as our research method. [13] identified three major energy-exhausting attacks in MAC protocols in WBANs. It also showed the attacks can cause energy exhaustion in different MAC protocols. The research result can be as the prevention mechanisms for energy consuming attacks.

The rest of this paper is organized as follows. In Section 2, related work on energy optimization *MAC* protocol and related questions are presented. In Section 3, the theoretical basis and adaptive mechanism for traffic duty-cycle and micro-duty are studied. In section 4, flow-adaptive back-off algorithm is proposed. Followed by experiments and evaluation**,** results are presented for our proposed approaches in Section 5. Finally, we conclude the paper with a summary.

2. Related Work

Wireless sensor networks are widely used in environmental monitoring, smart spaces, medical systems and many other areas. In such networks, sensor nodes with battery-operated are one of the most important design criteria because it determines the network lifetime [2]. Paper [3] introduced medium access control (*MAC)* protocols for wireless sensor networks which faced many challenges, including energy-efficient operation and robust support for varying traffic loads. This protocol addresses these challenges through the introduction of novel mechanisms for adaptive receiver-initiated multichannel rendezvous and predictive wake-up scheduling. [14] presented a mechanism to evaluate the *PW-MAC* (Predictive-Wakeup MAC), which is an energy-efficient asynchronous duty-cycling *MAC* protocol for sensor networks. [15] adopted scheduled access mechanism to ease the coordination of nodes which are dynamically switched their interfaces between channels and made the protocol to operate effectively the collisions during peak traffic. [16] introduced opportunistic flooding (*OF*), a novel design tailored for low-duty-cycle networks with unreliable wireless links and predetermined working schedules. The key idea is to make probabilistic forwarding decisions at a sender based on the delay distribution of next-hop nodes. Only opportunistically early packets are forwarded using links outside the energy optimal tree to reduce the flooding delay and redundancy in transmission. [17] researched the slotted duty-cycled *MAC* protocols. In the paper, sensor nodes periodically and synchronously alternate their operations between active and sleep modes. The sleep mode allows a sensor node to completely turn off its radio and save energy. [18][19] proposed a medium access control (*MAC)* protocol named Directional CR-aware *MAC* (*DC-MAC*) for CRSNs. [20] is a hybrid of both global common control channel (*GCCC*) and non-GCCC *MAC* protocols in order to increase the performance and security. [21] introduced emergency response sensor medium access control (*ER-MAC*), a novel hybrid *MAC* protocol for emergency response wireless sensor networks. It tackles the most important emergency response requirements, such as autonomous switching from energy-efficient normal monitoring to emergency monitoring to cope with heavy traffic, robust adaptation to changes in the topology, packet prioritization and fairness support. Time-Division Multiple Access (*TDMA*) [22][23] is a schedule based *MAC* protocol that controls the access to the channel by scheduling when a node should transmit, receive, or sleep to conserve energy. Schedule-based protocols support fairness by scheduling when a node can get access to the channel. Due to the inability to maintain the schedule when the traffic and topology changes are major problems of this kind of protocol, *TRAMA* [24] [25] and *FLAMA* [26][27] utilize *CSMA*[28][29] periods to allow new nodes to join the network, while *VTS* [30][31] adaptively adjusts super frame length according to the number of nodes in range. To cope with heavy traffic, nodes of *TRAMA* and *FLAMA* release their unused slots, while *VTS* reduces the sleep interval.

3. Study of MDA-SMAC Protocol

In this section, we present the theoretical basis of micro-duty mechanism, mechanism of micro-duty division, methods of selection and setting state for micro-duty and an adaptive mechanism for traffic duty-cycle.

3.1 Theoretical Basis of Micro-duty Mechanism

SMAC and time out-medium access control (*T-MAC)* protocols adopt conflict resolution strategies of *IEEE802.11 MAC* to solve the confliction occurrence among nodes. It means that both protocols use a kind of back-off algorithm to postpone node to access the channel. Combining the two typical back-off algorithms, their general formula is given as below.

$$\mathrm{CW_{i+1}} = \begin{cases} \min(\mathrm{m_i} \times \mathrm{CW_i}, \mathrm{CW_{max}}) \\ \max(\mathrm{r_i} \times \mathrm{CW_i}, \mathrm{CW_{min}}) \\ \min(\mathrm{CW_i} + \mathrm{l_i}, \mathrm{CW_{min}}) \end{cases} \tag{1}$$

Formula 1 shows the most commonly back-off algorithms based that change the current contention window ($\mathrm{CW_i}$) value according to the accessing state of nodes. $\mathrm{CW_{i+1}}$ is the next contention window selected by the different conditions. $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$ stand for the minimum and maximum contention window sizes respectively. It means that if the state is in success, the window value will be reset by a coefficient $\mathrm{m_i}$ and the contention window will be reset the minimum between $\mathrm{m_i} \times \mathrm{CW_i}$ and $\mathrm{CW_{max}}$. If the state is in conflict state, the window value will be multiplied by a factor $\mathrm{r_i}$ and the contention window will be reset the maximum between $\mathrm{r_i} \times \mathrm{CW_i}$ and $\mathrm{CW_{min}}$. If the channel is busy, the window value will be linearly changed by a factor $\mathrm{l_i}$ and the contention window will be reselected the minimum between $\mathrm{CW_i} + \mathrm{l_i}$ and $\mathrm{CW_{min}}$. On the basis of the algorithms Markov chain model in [32][33], we propose a theoretical analysis procedure of these algorithms. Supposing there is a current node in the network, each node will definitely send data after a period of channel competition. We set $\mathrm{W(t)}$ as the back-off counter size at time t (a discrete-time set here). t and $\mathrm{t+1}$ are two consecutive time slots, and T is the size of a time slot. After $\mathrm{W(t)}$ is selected by the node, according to the back-off algorithm, the back-off window value of the node is knowable during the period of $\mathrm{W(t)}$ and retreat to 0. Therefore a Markov chain model could not be constructed. For solving above question, another stochastic process $\mathrm{R(t) = k}$ is set to indicate the number of nodes collision times at slot time t. According to the given stochastic process, the formulas 2 to 5 are listed, where ρ denotes the possible collision probability of data transmission in the channel, and k denotes the frequency of node accessing channel. m is the maximum back-off stages. **Fig. 1** presents the Markov chain model of the back-off algorithm. Horizontal coordinate stands for contention windows change, and vertical coordinate represents the back-off stages change. In **Fig.1**, the transmission probability is decided by the possible collision probability of data transmission in the channel and the contention window W sizes. At the first transmission of a contending node, if the channel is idle for more than a time t, a contending station can transmit immediately. If the channel is busy, the contending station will generate a random contention window sizes. At the first transmission, the contention window size is selected equal to a minimum contention window sizes. After that, the contention windows sizes are decreased from the slot by slot during the idle period more than a given time. If the transmission is unsuccessful or the collisions happen, the contention window size is doubled for every transmission failure until it reaches the maximum contention window sizes. During countdown process in the back-off procedure, the contention window will pause if the channel is in the sensed busy state. If a destination or a receiver does not receive an acknowledgment frame within an acknowledgment timeout period after a data frame is transmitted, it will continue to retransmit the data frame according to the back-off algorithm. After a successful transmission, the contention window size is reset to the initial value.

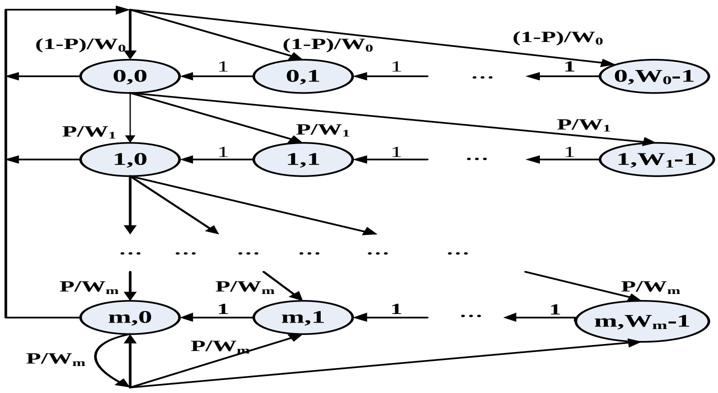

Fig. 1. The Markov chain model of the back-off algorithm

$$P\{i,k|i,k+1\} = 1 \quad k \in (0,W_i - 2), i \in (0,m) \tag{2}$$

Equation 2 expresses that for each time i and the frequency of node accessing channel k, when a node enters into a new time slot $k+1$ (i.e., the channel being listened to be as an idle state) its back-off timer value will be decreased by 1. In **Fig. 1**, we use equation 2 to describe the states transition probability from right to the left according to the horizontal coordinate.

$$P\{0,k|i,0\} = (1 - \rho)/W_0 \quad k \in (0,W_0 - 1), i \in (0,m) \tag{3}$$

In **Fig. 1**, equation 3 shows that after the packet transmission, the number of its current collision time is set to be zero, and the back-off window value will be re-selected. In **Fig. 1**, $k \in (0,W_i - 1)$ is the stationary distribution of the chain. Equation 4 denotes that if the node collision occurs, the number of collisions will be added by 1, and the back-off window value will be re-selected.

$$P\{i,k|i-1,0\} = \rho\ /W_i \quad k \in (0, W_i\ -1), i \in (0,m) \tag{4}$$

Equation 5 states that once the collision time reaches the upper limit, the node will reset the contention window by probability $\rho/\ W_m$.

$$P\{m,k|m,0\} = \rho/\ W_m \quad k \in (0, W_m - 1) \tag{5}$$

According to the formulas from 2 to 5, limiting distribution can be expressed as formula 6.

$$Q_{i,k} = \lim \rho\,\{W(t) = i, \qquad R(t) = k\} \tag{6}$$

According to Kolmogorov-Chapman (*KC*) equation, the conclusion can be drawn as follow in formula 7.

$$Q_{i,0} = \rho^i \cdot Q_{0,0} \quad i \in (0,m) \tag{7}$$

By applying equation 8, the system can derive the steady state conditions of the collision probability of the node, $Q_{0,0}$ is finally determined by imposing the normalization condition, that simplifies as follows.

$$Q_{0,0} = \frac{2(1-2\rho)(1-\rho)}{(1-2\rho)(W+1) + \rho W[1-(2\rho)^m]} \tag{8}$$

On the basis of formula 8, the following equation 9 is given. τ expresses the probability that a station transmits in a randomly chosen slot time. As any transmission occurs when the back-off time counter is equal to zero, regardless of the back-off stage.

$$\tau = \sum_{i=0}^{m} Q_{i,0} = \frac{1}{1-\rho} \cdot Q_{0,0} = \frac{2(1-2\rho)(1-\rho)}{(1-2\rho)(W+1) + \rho W[1-(2\rho)^m]} \tag{9}$$

The relationship between the collision probability and the node can be drawn from the condition probability shown in formula 10. In general, τ depends on the conditional collision probability ρ, which is still unknow. To find the value of ρ it is enough to notice ρ that a transmitted packet encounters a collision. In a time slot, at least one of the $n-1$ remaining stations transmits. At steady state, each remaining station transmits a packet with probability τ.

$$\rho = 1-(1-\tau)^{n-1} \tag{10}$$

[34] solves this kind of problem by applying another Markov chain model, and derives the

following formula.

$$n = 1 + \frac{\log_2(1 - p)}{\log_2\{1 - \frac{2(1 - 2p)}{\{(1 - 2\rho)(W + 1) + \rho W[1 - (2\rho)^m]\}\}}} \qquad (11)$$

As can be seen from the above two formulas, the probability of data transmission depends on the collision probability ρ, which has a close link with the number of nodes in the current conflict region.

Formula 11 means when the network load is light, less number of nodes will get access to the channel, and less conflict will occur among node and less energy will be consumed. When the network load is heavy, a large number of nodes will compete for the channel, and more conflicts will be aroused within the same time, and more energy will be consumed. *SMAC* protocol is thoroughly studied in [35]. In the paper, the numbers of nodes in the network are not changed and steady, but the probability of conflict between the nodes and energy consumption can be reduced by controlling the arrival time of node for the channel competition. It means different nodes can access channel in different time periods. The improved method of virtual nodes within a cluster of *SMAC* protocol dispersedly competing for the channel is given. In this manner, nodes are dispersed at different time intervals to contend for the channel, thus can reduce the probability of collision. Meanwhile in a large duty, nodes and data communications can be carried out repeatedly in a manner similar to *TDMA*[31] and reduces data latency.

In order to achieve the objective of decentralized nodes, multi-period and multi-node communication within the mission ring, this paper presents a new scheduling duty and names it as a micro duty. Nodes in *SMAC* protocol formed a virtual cluster with the same scheduling period, and consisted of multiple virtual clusters throughout the network. Similarly, micro-cluster is smaller than the virtual cluster, and is set as the synchronous scheduling unit for each node in *SMAC* protocol. Nodes working in the same micro-duty compose the smaller micro-clusters, and micro-clusters constitute the virtual clusters in *SMAC*.

Definition 3.1 The number of micro-clusters is equal to the number of micro duty.

Proof Nodes working in the same micro-duty only belong to the same micro-cluster. One scheduling duty in *SMAC* protocol can be split into *n* micro-duties. Therefore, the number of micro-clusters is also *n*.

3.2 Micro-duty Division

In *SMAC* protocol, synchronization, listening, and sleeping constitute a complete scheduling period and a task loop (micro-duty). Within each task loop, nodes firstly synchronize, listen and send data, meanwhile shift to the sleeping mode when sleeping clock arrives, as shown in **Fig. 2**.

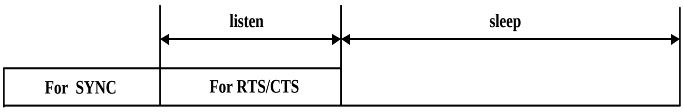

Fig. 2. The schedule of SMAC

The listener/sleep stage of a task loop in the original *SMAC* protocol is divided into multiple independent continuous listening and shorter sleep stages. For nodes, after the data are transmitted at each micro-listener stage, it will turn into sleep state to conserve energy at each micro-sleep stage. Multiple successive micro-duties constitute the micro listener/sleep duty of the original *SMAC* protocol. The procedure is shown as in **Fig. 3**.

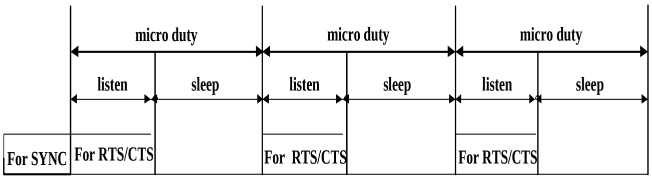

Fig. 3. Successive micro-duty

3.3 Selection and Setting State for Micro-duty

In *MDA-SMAC* protocol, nodes firstly need to determine the number and status of their own micro-duty, adjust its duty cycle according to network traffic micro-duty. It is the primary task that how to choose the number of micro-node duty and set the status of each micro-duty. For keeping the energy conservation, data transmission is permitted to have a certain delay. To solve this problem of energy-constrain, [6] [7] proposed a clustering protocol based on residual energy. Therefore, in the paper, we propose an approach to select the number of micro-duty based on the remaining energy and set the state of the micro-duty.

Task loop can be divided into *10* micro-duties with *10%* duty cycle. The initial energy of the node is E_{init} and after a period of operation, the residual energy is $E_{residual}$. The number of micro-duties of a node can be deducted according to formula 12, where M represents the number of the divided micro-duty. It means the result of the n state is decided by the number of the divided micro-duty M and the ratio between the $E_{residual}$ and E_{init}.

$$n = \begin{cases} 1 & \frac{E_{residual}}{E_{init}} \times M \leq 1 \\ \left\lceil \frac{E_{residual}}{E_{init}} \times M \right\rceil & \frac{E_{residual}}{E_{init}} \times M > 1 \end{cases} \qquad (12)$$

The number of micro-duty n is calculated according to the formula 12. Node is set to work that only the first n states are in *10* micro-duty and the rest of the micro-duty is in sleep state. It means that the smaller the residual energy of nodes is, the fewer the number of its access channel is. Nodes in the network can balance the energy consumption and prolong the network life duty by judging residual energy. For example, assuming the initial energy of a node is *1000J*, and when the residual energy is less than *100J,* that is that the ratio between residual energy and initial energy ratio is less than *1*. It is necessary to perform further calculations. The node n is calculated according to the formula 13.

$$n = \begin{cases} 1 & \frac{E_{residual}}{E_{init}} \times M \leq 0.1 \\ \left\lceil \frac{E_{residual}}{E_{init}} \times M \right\rceil \times 10 & 0.1 < \frac{E_{residual}}{E_{init}} \times M < 1 \\ \left\lceil \frac{E_{residual}}{E_{init}} \times M \right\rceil & \frac{E_{residual}}{E_{init}} \times M > 1 \end{cases} \qquad (13)$$

After completing the selection of the numbers of micro-duty, nodes need to set the status of each micro-duty. Node chooses a random numbers from$\{1,2,3 \cdots n\}$, and each random number is used to represent the number of micro-duty of a node. Node status in each micro-duty is determined by the following rules. When the random number is greater or equal to the threshold value, the node is in listening state within the micro-duty. When the random number is less than the threshold value, the node is in sleeping state.

Threshold value is readjusted by considering the residual energy of the node. This paper combines the threshold value with the number of micro-duties of the node as a standard to compute. The threshold value is set according to the formula 14.

$$F = \lceil n/2 \rceil \tag{14}$$

Formula 14 shows that it is feasible for a node to listen to the channel within half of the micro-duty $\lceil n/2 \rceil$, and to sleep within the other half micro-duty $\mathrm{n} - \lceil n/2 \rceil$. In this way, the nodes extend the sleep time, and the energy consumption will be reduced. By setting the state of micro-duty, the node can use a plurality of micro-duties for communication to achieve the goal of multiple nodes communicating over a large period of the duty. Due to the random selection trait, nodes are dispersed in different micro-duties. When the number of nodes that compete in each micro-duty is less than the number of nodes of contention channel in *SMAC* protocol, collision probability of the data is decreased, and more energy is saved. The threshold value determines whether the node should get access to channel within the micro-duty. For a single node, no access to channel means the longer of sleep time of node, lower energy consumption, and longer network lifetime.

3.4 An Adaptive Mechanism for Traffic Duty-cycle

In the paper, length of buffer queue Q_{length} is adopted as a key factor for assessing network traffic. Meanwhile, the duty-cycle (DC) of *MDA-SMAC* protocol is dynamically changed. In *MDA-SMAC* protocol, when the buffer queue length Q_{length} is greater than the given threshold value, the duty-cycle (DC) of the node will be increased. This is the reason that more packets need to be transmitted and may incur more crowded network traffic. According to many researches[36][37][38], we consider that the current network traffic is large when the buffer queue length is over 35 and nodes need to expand the duty-cycle (DC). Therefore, we use buffer length $Q_{length} = 35$ as the duty-cycle threshold. [18] [39] proposed dynamic duty strategy on basis of *SMAC* protocol. They further studied the dynamic duty cycle mechanisms in these protocols, where the node still competed in a unified listening period for channel, causing larger conflict probabilities between nodes. In *MDA-SMAC* protocol, nodes use micro-cycle to schedule and work in a distributed manner within the micro-duty, so the probability of confliction between the nodes is significantly reduced. Therefore, adaptive duty-cycle means to dynamiclly adjust the duty-cycle of the micro-duty in *MDA-SMAC* protocol. In the *MDA-SMAC* protocol, nodes use Formula 15 to adjust the duty cycle of micro-duty. The formula means when the $Q_{length} \geq 35$ is true, the new duty-cycle is assigned the smaller values of $2 \times \mathrm{DC_{old}}$ and $\mathrm{DC_{max}}$. If $Q_{length} \geq 35$ is false, the new duty-cycle is equal to the original duty-cycle.

$$\mathrm{DC_{new}} = \begin{cases} \min(2 \times \mathrm{DC_{old}}, \mathrm{DC_{max}}) & Q_{length} \geq 35 \\ \mathrm{DC_{old}} & Q_{length} < 35 \end{cases} \tag{15}$$

4. Flow-adaptive Back-off Algorithm

SMAC protocol is a *MAC* protocol based on binary exponential bac-koff (*BEB)* algorithm with regardless of the current network traffic condition. *BEB* algorithm stipulates different upper limitation for retransmission and in general, the upper limitation of the retransmission of the node is *7*[40]. The corresponding range for the back-off window size CW is $[0{,}128]$. If the *RTS/CTS* mechanism[41][42] are adopted, the upper limit is *4*, corresponding to the back-off window value interval $[0{,}16]$. In *SMAC* protocol, the maximum back-off window is set to be *63* in *NS2* [43][44]. However, fixed setting method for window back-off interval is not suitable for the dynamically changing trait of wireless sensor networks, and therefore the development of a flow-adaptive back-off algorithm is a direction for improving *SMAC* protocol. All back-off algorithms contain two fields $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$, representing minimum back-off window value and maximum back-off window value respectively. Back-off window value is randomly selected in the two digits. Therefore, one of the key points for flow-adaptive back-off algorithm changes dynamically the size of $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$ into $\mathrm{CW_{newmin}}$ and $\mathrm{CW_{newmax}}$. On this basis, we propose two improved *BEB* algorithm, *F-BEB* and *CA-BEB*.

4.1 F-BEB Algorithm

In the paper, threshold L_{rate} is set as buffer utilization rate. After several experiments, we can conclude when the buffer queue length becomes less than *10*, it indicates lower network traffic, and L_{rate} is set to be 20%. The back-off window range is modified according to formula 16 and 17

$$\mathrm{CW_{newmin}} = \lceil (1 + Buffer_{rate})/2 \times \mathrm{CW_{min}} \rceil \tag{16}$$
$$\mathrm{CW_{newmax}} = \lceil (1 + Buffer_{rate})/2 \times \mathrm{CW_{max}} \rceil \tag{17}$$

It means that if the utilization rate is lower, fewer data will be sent. Associating the back-off window interval of standard duty-cycle with the current buffer utilization rate, back-off window range of the node can be dynamically reduced. That is if the back-off window size selection is the smaller value $\mathrm{CW_{newmin}}$, the less back-off time of the node will be adopted and which means fast accessing the channels. Therefore, under the standard duty cycle, if the buffer utilization rate is less than L_{rate}, the node will use *F-BEB* algorithm for channel competition. *F-BEB* back-off algorithm is described as follows.

1) For the newly added node, the back-off window value chosen from $\lceil \mathrm{CW_{newmin}}, \mathrm{CW_{newmax}} \rceil$ is as the initial back-off window value $\mathrm{CW_{init}}$.
2) When node accesses channel for listening, it will check the state of the channel. If the channel is in the idle state, the value of back-off window will be subtracted by 1. If the node continuously listens to idle intervals, the back-off window value will be halved.
3) If the channel is in busy state, freezing back-off timer, and the node turns into the corresponding length of sleep mode according to *NAV* field.
4) If a conflict occurs, the node will linearly increase its back-off window value by 1.
5) If the data has been successfully sent, the node will select a new back-off window value.
6) Repeating steps 1)-5).

4.2 CA-BEB Algorithm

First, node will alter its back-off window range $\lceil \mathrm{CW}_{\mathrm{newmin}}, \mathrm{CW}_{\mathrm{newmax}} \rceil$ according to the formula 18 and 19.

$$\mathrm{CW}_{\mathrm{newmin}} = \lceil (1 + Buffer_{rate}) \times \mathrm{CW}_{\mathrm{min}} \rceil \tag{18}$$
$$\mathrm{CW}_{\mathrm{newmax}} = \lceil (1 + Buffer_{rate}) \times \mathrm{CW}_{\mathrm{max}} \rceil \tag{19}$$

In *CA-BEB* algorithm, nodes change the back-off window interval according to its current buffer utilization, which provides two main benefits.

1) Although the duty cycle has been adjusted due to a larger number of nodes in the network, in most cases, only part of the nodes has more data to be sent with different buffer utilization rate. According to the buffer utilization, when window interval is set, node with high buffer utilization rate will be arranged a larger range of the back-off window interval. It covers longer length of the back-off interval, provides more back-off value for choosing, and brings the relatively low conflict probability between nodes. For node with low buffer utilization rate, its back-off window interval is set to be a smaller number for prompting data transmission.

2) Node dynamically changes its back-off window interval according to the current buffer utilization rate, rather than simply doubling the node back-off window interval. Hence, the size of back-off window interval could properly be controlled, avoid over-sized window problem, and take into account the competing fairness of channel access as well. In *CA-BEB* algorithm, a middle threshold value CW_{mid} is set according to formula 20.

$$CW_{\mathrm{mid}} = \frac{(CW_{\mathrm{max}} + CW_{\mathrm{min}})}{2} \tag{20}$$

In the process of data transmission, if there is a conflict to occur, the current window values CW and CW_{mid} will be compared to be selected. If the current back-off window value is less than CW_{mid}, back-off window value will be increased linearly by formula 21. It aims at reducing the idle listening frequency of the node with smaller back-off window value, and boosts the data transmission. If the current back-off window value of the node is larger than CW_{mid}, method of doubling window size in *BEB* algorithm will still be adopted for their window value change.

$$CW_{\mathrm{new}} = \lceil CW + CW \times Buffer_{rate} \rceil \tag{21}$$

In *CA-BEB* algorithm, after data has been successfully transmitted, the node resets its back-off window value (usually assigning a smaller value). In the case of high network traffic, this resetting method can easily lead to a high probability of conflict. Hence the resetting method needs to be changed according to the selection of the next back-off window value. *CA-BEB* improved the resetting mechanism by comparing the back-off window value CW and CW_{mid}. If CW is greater than CW_{mid}, the back-off window value of the node will belong to a high value area meanwhile a number of retreat will occur before the data successfully being sent. In this case, if a smaller value is reset to the back-off window value, more conflicts will be created. Each conflict may lead to multiplied value, which may result in notably waste of energy for channel listening and data retransmission. In such situation, when the back-off window value is required to reset, the node is needed to set a larger value which is selected from CW_{mid} to CW_{max}.

5. Experiments and Analysis

5.1 Single-hope Simulation

One hop topology for simulation is adopted in the experiment. In *NS-2* platform, node positional relationship is shown in **Fig. 4**. *21* nodes are deployed in the 100m × 100m area with node 0 located in the center and acted as *Sink* nodes to receive data. Other 20 nodes are located around the node *0* to send data to *Sink* node.

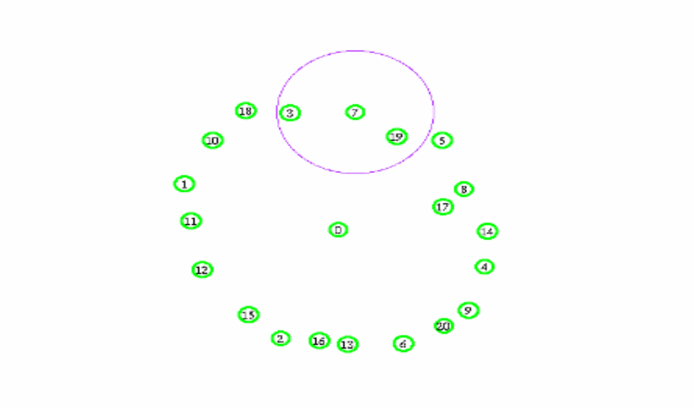

Fig. 4. Topo of Single Hop

Table 1. Some simulation parameters of experiment

Parameter(s)	Value(s)
Upper layer routing protocol	AODV
Region size	100m×100m
Communication bandwidth/kbps	20
Sending power consumption/mW	200
Receiving power consumption/mW	200
Sleeping power consumption/uW	1
Node primary power/J	100
Nodes number	21
Max length of buffer queue	50
Communication radius/m	100

MDA-SMAC protocol decides which micro-cycle to be selected and to be listened by using random manner, so the selected results may be different. For decreasing the random property, this paper uses the average value of multiple experiments as simulation results. Data is sent in *10* seconds, and lasts 50 seconds. In the simulation process, nodes access channel at different times, meanwhile, we simulate the size of the network traffic by changing packet transmission time intervals. The smaller transmission interval means the more nodes sending packets to stimulate larger current network traffic. The larger the transmission interval indicates the fewer nodes sending packets to stimulate less network traffic. In simulation process, data packet transmission interval ranges from *1s* to *10s* with each interval under *10* tests and takes the average value of *10* times as the final results. In this paper, average energy consumption of nodes of the two protocols during each interval of data sending is compared as benchmarks. simulation parameters of the experiment are shown in **Table 1**. **Fig. 5** shows the comparison of average energy consumption of the two protocols. In this line chart, blue line stands for the energy consumption of *SMAC* with the increasing of the interval. Red line represents the energy consumption of *MDA-SMAC* with the increasing of the interval. As can be seen from **Fig. 5**, energy consumption in the *MDA-SMAC* protocol for sending a packet of node in each transmission interval is less than the *SMAC* protocol. When there is larger traffic of the network, the conflict probability between the nodes in *SMAC* protocol also increases. Nodes may require multiple back-off cycles to retransmit, and therefore consume more energy. *MDA-SMAC* disperses nodes into the micro cycle, reducing the probability of conflict. While *CA-BEB* algorithm at high flow period can further reduce the probability of conflict between nodes, so the energy consumption is less than that of *SMAC* protocol. With the gradual increasement of the transmission interval, the network traffic will decrease, and the energy consumption of the two protocols is also reduced. Overall, the energy consumption by *MDA-SMAC* protocol is less than *SMAC* protocol.

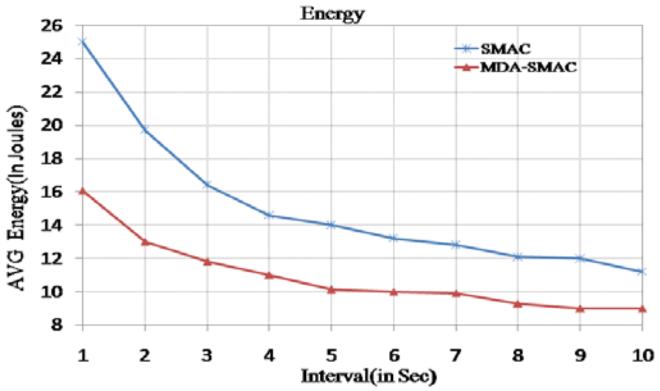

Fig. 5. The comparison of average energy consumption

Fig. 6 shows the relation between intervals and delay. As shown in the **Fig. 6**, when the network traffic is high, fixed duty cycle and higher collision of *SMAC* protocol result in higher data delay. *MDA-SMAC* protocol applies micro-cycle as the scheduling period, in which node can transmit data in a plurality of micro-cycles with node using adaptive duty cycle flow mechanisms and *CA-BEB* algorithm to reduce conflict. Hence, data latency of *MDA-SMAC* is less than that of *SMAC* protocol. With the gradual reduction of network traffic, the data transmission delay in both protocols is decreasing. However, due to the *F-BEB* algorithm is based on *MDA-SMAC* protocol, when the network traffic is low, the data latency is still less than that of *SMAC* protocol.

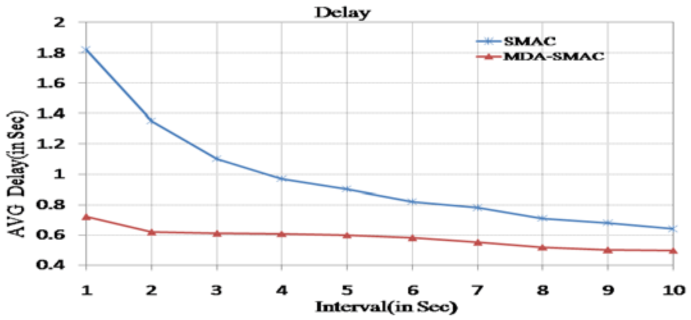

Fig. 6. The comparison of average delay

As shown in **Fig. 7**, effective throughput of the two protocols is compared. As can be seen from the figure, when the network traffic is larger, *SMAC* protocol may cause a large amount of data packets aggregation in the buffer. This aggregation problem may result in a higher probability of collision between nodes and smaller effective throughput. In *MDA-SMAC* protocol, data transmission can be repeated within a scheduling period, and the duty cycle of the micro-cycle can be adjusted according to buffer queue length. Thanks to the adaptive back-off algorithm, the effective throughput of *MDA-SMAC* is higher than *SMAC*. When the network traffic is small, there are less number of packets in the network with small conflict probability between the nodes and there is little difference in terms of effective throughput for both *SMAC* protocol and *MDA-SMAC* protocol.

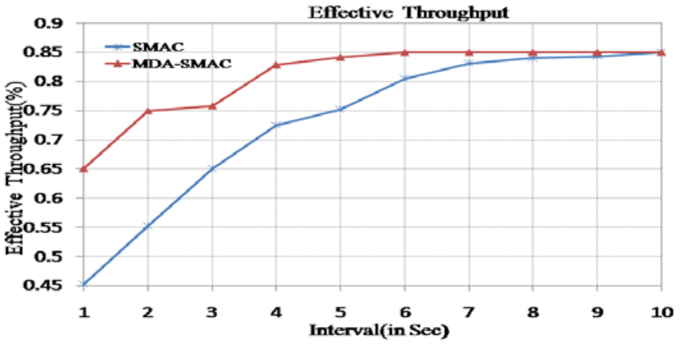

Fig. 7. The comparison of effective-throughput

5.2 Multi-hop Simulation

Experiment scenarios for multi-hop simulation are shown in **Fig. 8** with *40* nodes located in a *100m* × *100m* area. Those *40* nodes are located separately in two clusters (in this case, cluster refers to all nodes are in the single-hop range). Node *0* belongs to two clusters, and *Sink* node is responsible for data transmission.

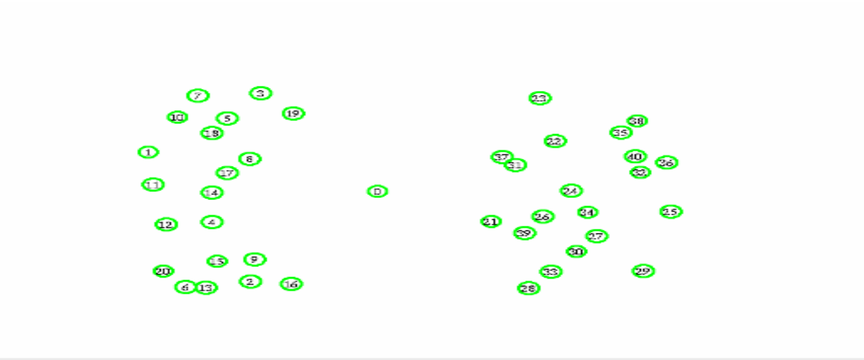

Fig. 8. The topo of two hops

To ensure data transmission in the way of hop-by-hop, the sending power and the receiving power of nodes are reduced to *150mw*, and the communication radius for nodes is *50m*. Experiments are conducted *10* times under the two-hop environment during each interval of data sending. The average value of 10 experiments is taken as a simulation result, which takes *50* seconds (nodes within two clusters access channel at different times). Detailed experiment data are presented in **Table 2.**

Table 2. Some simulation parameters of experiment II

Parameter(s)	Value(s)
Routing protocols for upper layers	AODV
Area size	100m×100m
Communication bandwidth/kbps	20
Sending power consumption/mW	150
Receiving power consumption/mW	150
Sleeping power consumption/uW	1
Node initial power/J	100
Number of nodes	41
Maximum of buffer queue length	50
Communication radius/m	50

In the two-hop scenario, the energy consumption comparison of the two protocols is shown as in **Fig. 9**. Due to the two-hop scene is adopted and deployed (number of nodes than in experiment one), the conflict probability between nodes increases. It can be seen from **Fig. 9**, in each contract interval, the energy consumed by *MDA-SMAC* protocol is still less than that of the *SMAC* protocol. In larger network traffic with increasing intervals of packet sending, energy consumption for both protocols are reduced.

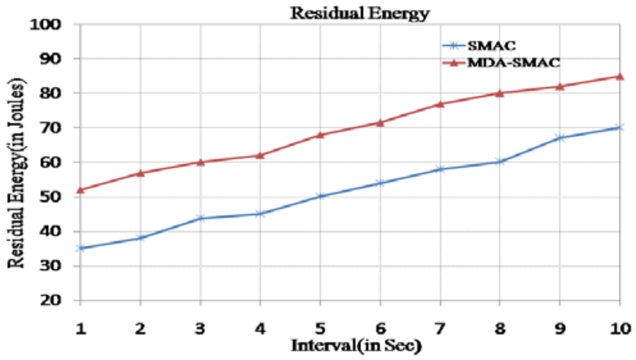

Fig. 9. The comparison of residual energy of nodes

Data latency comparison under the two-hop scene in *MDA-SMAC* protocol and *SMAC* protocol is shown in **Fig. 10**. As can be seen from the figure, the transmission delay is increased. In the high network traffic, compared with the *SMAC* protocol, due to *MDA-SMAC* protocol uses an adaptive duty cycle and an adaptive back-off algorithm which can reduce the impact of conflict on data transmission, so data latency is less than *SMAC* protocol. With increasing intervals, both of them can reduce delays, but the delays of *MDA-SAMC* protocol is still less than the *SMAC* protocol.

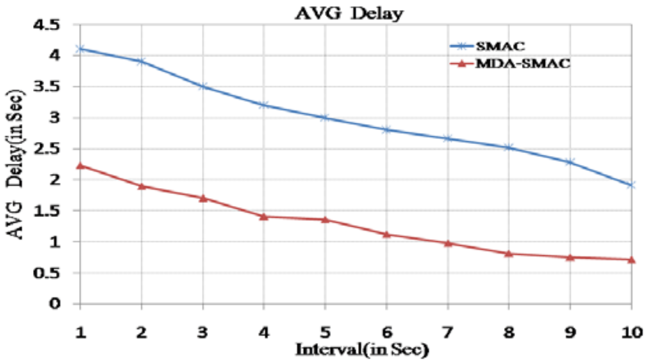

Fig. 10. The average delay of two hops

5. Conclusion

In the paper, we study the competition-based *MAC* protocol in wireless sensor networks, analyze its key technologies, related algorithms. The classic *SMAC* protocol is studied detailed, and its performance and shortcomings are analyzed. An improved *SMAC* protocol is proposed with following innovations. (1) We propose a new scheduling cycle, *the micro-cycle*, which divides a whole listening/sleep time into several small listening/sleep cycle. The number of micro-duties depended on the residual energy with different states set scattering inside each micro-cycle. Channel competing level is reduced by scheduling contention in each micro-cycle. By reducing the competing level, the schema can reduce the probability of conflict and save node energy. Meanwhile, nodes working in multiple micro-cycles transmit data in a similar *TDMA* manner, which decreases data latency of the network. (2) To solve the problem that *SMAC* protocol cannot properly adapt to the traffic dynamic change due to its fixed duty-cycle in *WSN*, we propose a traffic self-adaptive duty cycle mechanism for micro-cycle. Duty cycle is adjusted according to its buffer queue length, which means that the duty cycle of the micro-cycle will be multiplied if the buffer queue length is larger than the threshold value. We also studied the adaptive back-off algorithm. For different duty-cycle, different back-off algorithms will be selected correspondingly based on the buffer utilization. For standard duty cycle, if the buffer utilization is less than 20%, the F-BEB fast back-off algorithm will be applied for reducing data latency. For double duty cycle, *CA-BEB* algorithm will be used to reduce the conflict probability as much as possible, and further conserves node energy.

MDA-SMAC protocol is proposed by applying micro-cycles, adaptive micro-cycle duty cycle mechanism and adaptive back-off algorithm in the original *SMAC* protocol. Comparing the simulation results for both protocols, it is obvious that, *MDA-SMAC* protocol performs better in terms of energy consumption, delay effective throughput than *SMAC*, especially in high-flow state.

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