An Adaptive MAC Protocol Based on Spatial and Temporal Correlation in Wireless Sensor Networks

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***Abstract*—The correlation between neighbor nodes is a key factor in wireless sensor networks. It has a crucial impact on network load. But few researches refer to it. This paper discusses the correlation effect on network load firstly, and then presents DOSC and DOTC as parameters to quantify the spatial and time correlation of the neighbor nodes respectively. Based on these, the paper proposes STCAS-MAC. STCAS-MAC is evolved from AS-MAC by improving its adaptive scheduling and considering the validity period of information. Simulation results show that compared with the AS-MAC, the proposed protocol improves greatly in several performances. Especially when the network load is heavy or variable, the STCAS-MAC protocol can improve the delivery ratio effectively or adaptation obviously.**

***Index Terms*—wireless sensor networks, medium access control, adaptive scheduling, spatial and temporal correlation**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have gained world-wide attention in recent years. As sensor nodes are generally battery-powered devices, low energy consumption has become the main intent of the researchers of WSNs[1][2][3][4]. With the further advance of WSN, some other network performances such as low transmission-delay, high adaptation, etc. also have been brought into attention[2][3][4].

Sensor node is a tiny device consists of three components: a sensing subsystem, a processing subsystem and a wireless communication subsystem which is the most energy savings part[1][2]. One of the ordinary manners is the design of networking protocols. MAC protocol is responsible for controlling the operational modes of the transceiver[2], so MAC protocol plays a significant role in decreasing the energy-consumption and end-to-end delay.

Literature[5] gives the definitions of spatial and temporal correlation. Studies[6][7] show that spatial correlation has a significant impact on the performance of channel contention and QoS. However, they have not noted the real reason to the effect of spatial and temporal correlation on the preference of WSN protocols. Meanwhile, they have not given parameters to quantify the spatial correlation and temporal correlation. This paper will discuss the relationship between correlation and network load in detail and then introduce an advanced MAC protocol to reduce energy consumption and end-to-end delay.

Recently literatures[1][2][8] indicate that the primary situations of energy waste include idle listening， overhearing, control-packet overhead and collision. In any case, overhearing and collisions waste energy because they add communication overhead(i.e., overhearing is an extra reception and collision inevitably leads the following retransmission). How to reduce idle listening and communication time becomes the guide in MAC-designing. Evolved from AS-MAC, this paper proposes STCAS-MAC, which aims at decreasing collision and unnecessary communication.

In this paper, we introduce DOSC(degree of spatial correlation) and DOTC(degree of temporal correlation) as parameters of spatial and temporal correlation respectively. Integrating DOSC and DOTC, a new adaptive schedule is proposed for adjusting to variable traffic of the network. Then a Time-Determination is brought to make sure every message received is valid. The STCAS-MAC can achieve lower energy consumption, lower latency, higher effective delivery ratio and better adaptation than AS-MAC.

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This paper is organized as follows: Section II discusses the related works of STCAS-MAC. Section III describes the problem in AS-MAC. Section IV describes the detailed design of STCAS-MAC. Simulation design and results are analyzed comparing with AS-MAC in Section V. At last, Section VI concludes this paper and states the future work.

II. RELATED WORKS

S-MAC[8] proposes the schedule mechanism to adjust the duty cycle, and reduces the energy consumption resulted from idle listening. But the constant schedule mechanism is not adaptive to the network of variable traffic load. Using the time-out timer to end the active period, T-MAC[9] outperforms S-MAC. T-MAC can achieve significant energy savings by reducing idle listening when load is light. However, although Future Request-To-Send and Full-Buffer Priority decrease the possibility of early-sleeping problem which is caused by T-MAC, end-to-end delay caused by early-sleeping problem is still serious. The FRTS and DS packets consume additional energy, and the probability of collision is also increased.

DW-MAC[10] is a novel protocol based on demanding wakeup mechanism, it leads in SCH(scheduling frame) and divides the duty cycle into three parts: T_{sync} for network synchronization, T_{data} for SCHs delivering and T_{sleep} for data packets transmission (i.e. it divides communication into two parts: channel contention and data transmission). DW-MAC uses the method of transmitting with a small control packets in T_{data} period to simulate the practical data which can establish the transmit-time of practical data in T_{sleep} period. DW-MAC obtains a better performance than S-MAC and T-MAC. AS-MAC[11] is a improvement of DW-MAC, just as T-MAC development with S-MAC. The difference is that AS-MAC brings T_{as} instead of T_{data}. On the other hand, AS-MAC increases the SCH frame a bite sizes to cut down the time cost of changing SCH messages in T_{as}. Both DW-MAC and AS-MAC have no early-sleeping problem. Because the SCH message, which transmits in T_{data} period of DW-MAC or T_{as} period of AS-MAC, is short enough, for max_hop transmit in T_0. By the adaptive scheduling, AS-MAC can minimize idle listening. AS-MAC outperforms DW-MAC, especially in the situation of heavy traffic loads. However, the adaptive schedule in AS-MAC is not perfect, and there are great potentials for further performance enhancement. The network load it can sustain is still limited.

Sift[6] was designed for event-driven wireless sensor network. It reduces the number of messages that the node need to transmit successfully in a short time when an event happen. QS-Sift[7] gives high-priority to high-quality monitoring data, and inhibit the transmission of low-quality monitoring data, in order to reduce the number of nodes which need to send monitoring data. Thus QS-Sift reduced energy consumption, and lowered network latency. In HS-Sift[12], the sense region was divided into three sub-regions. Each region has a different channel access method, when HS-Sift remove spatial redundancy of monitoring data among neighboring sensor nodes, it tries to fusion TDMA and CSMA to improve the performance of system. Literatures[6][7][8] take into account spatial correlation, and obtain low energy consumption, but they hadn't given an exact connection of the correlation.

Inspiriting from [6][7][8], this paper propose STCAS-MAC which is evolved from AS-MAC. STCAS-MAC was designed for event-driven network. It reduces energy consumption, end-to-end delay and also provides a better adaptation.

III. PROBLEM DESCRIPTION

To better analyze AS-MAC, we perform AS-MAC with heavier network load again. As in [11], sensing range in our test is between 100m and 500m, but the increment is increased to 100m for simplifying our analyze. The difference is that event interval(EI) is 200s in [11], but in our test, we set EI to be different values from 2s to 200s, as 2s, 3s, 4s, 5s, 6s, 8s, 10s, 15s, 30s, 100s, 200s.

The test result shows that When EI > 10s, as sensing range extends, the delivery ratio is perfect and the energy consumption is low, which is because the net can sustain the network load and the timeout mechanism minimize energy consumption, the end-to-end delay is stable which is because idle listening plays an important role in it and the influence of Sensing range has been covered up, as shown in Fig.1(a), T_3 is unavailable. When EI□10s, the influence of Sensing range on the net has been strengthen. As the sensing range increases, the delivery ratio decreases, the energy consumption, the average and maximum end-to-end delay increase rapidly. Compared with the situation when EI>10s, the tendency increase obviously. The immediate cause is that the brief back-off algorithm and adaptive mechanism of AS-MAC can't satisfy over-load and T_{as} period is not long enough for the transmission of redundant SCHs, as shown in Fig.1(b), T_w is unavailable.

AS-MAC has some problems that lower delivery rate under a low degree can lead network to collapse, higher energy consumption can deplete out of the energy of the nodes, and when a message doesn't arrive at the destination on time, the message may become invalid.

In addition, performances of most MAC protocols are plotted by varying the EI or the sensing range. However, the situation of net can not be quantified accurately in this way, spatial and temporal correlation is a better choice, so does AS-MAC.

Considering the defects of AS-MAC, STCAS-MAC is proposed in this paper.

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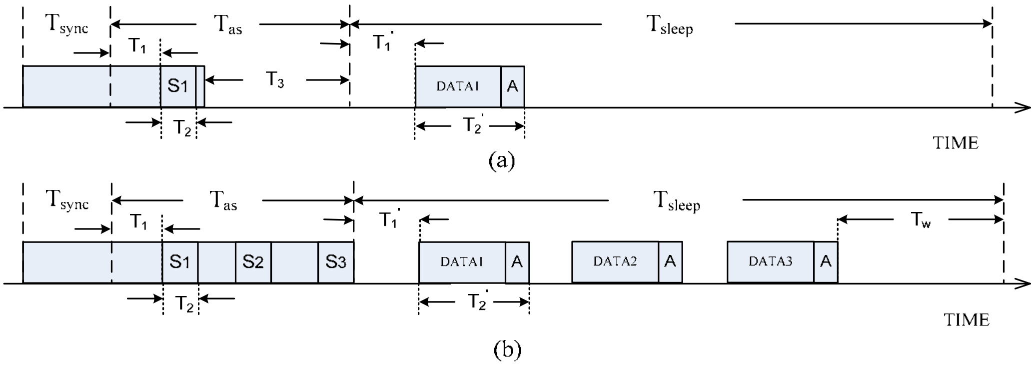

Figure 1. Frame structure in AS-MAC

IV. THE DESIGN OF MAC PROTOCOL

In this section, two parameters are presented to quantize the correlation between neighboring nodes, and the influence of them is discussed in part *A*. On this basis, STCAS-MAC is described in detail in part *B*.

A. Preparatory Work

This part presents DOSC and DOTC as parameters of spatial and temporal correlation respectively, which can reflect the real situation of network load.

Firstly, before we give the definition of spatial and temporal, we give our explanation of network load. We divide network load into local network load and global network load. We define local network load as the intensity of the local area network load which is related to spatial correlation, and define global network load as the average of the network load which is related to the temporal correlation.

Some attributes[6][7][13] consider spatial correlation in terms that they inhibit some nodes which are not necessary to transmit their data. But in this paper, we only consider the impact of spatial correlation on network load. So we give the definition of spatial and temporal correlation in our work, although it has been given in [5]. Literatures[5][13] indicated that the degree of spatial correlation increases with the decreasing internode separation. In our consideration, the spatial correlation is in connection with the density of network nodes, the Sensing and transmitting range of the nodes and the probability that a node can sensor an event happened in its sensor area. Here assume the sensors are ideal, that means it can detect all the events that in its sensing area. In this way, this paper sets DOSC to be the average number of messages which are triggered by one event. The same as spatial correlation, literatures[12][13] consider temporal correlation as the temporal variation characteristics of the phenomenon. But in this paper, we consider temporal correlation as the correlate level of messages which are triggered by adjacent events, and set DOTC as a parameter to reflect it. From the definition of spatial and temporal correlation, we can see that DOSC and DOTC are more direct and accurate as parameters to reflect network load comparing with EI and sensing range.

As equation(1) shown, DOSC is in direct proportion to the square of Sensing range. ρ is the density, R is the sensing or transmitting range.

$$DOSC = \Pi \rho R^2 \tag{1}$$

To simplify design, time correlation is divided into two parts, as equation(2), DOTC is set as a Boolean variable. *F* is frequency, ω is a fixed value, in this paper: ω=1/10.

$$DOTC = \begin{cases} 0, F < \omega \\ 1, F > \omega \end{cases} \tag{2}$$

B. The Detail of STCAS-MAC

STCAS-MAC is an adaptive MAC protocol. It is evolved from AS-MAC. The cycle consists of three duration periods, called T_{sync}, T_{as} and T_{sleep} periods respectively. STCAS-MAC is similar to AS-MAC in the way that it exchanges SCH packets in T_{as} period, and transmits the practical data in T_{sleep} by a demand wakeup method. In T_{as} period, the nodes contend channel, using a revised virtual carrier sensing method from AS-MAC. A mapping function exists between the transmitting-times of SCH in T_{as} and practical data in T_{sleep}. This method can avoid collision.

The goal of our work is that using the lowest energy and the least time to accomplish more data-transmitting.

The major design in our protocol is as follows:

1) Adaptive Algorithm

The provided adaptive algorithm includes Two-level Back-off Algorithm and Adaptive Mapping Algorithm. The former is to satisfy intensive or precarious situation of channel contention and the latter adapts T_{sleep} to DOSC and DOTC to satisfy the variance of network flow.

a) Two-level Back-off Algorith: the first level back-off algorithm is that sink node determines the size of back-off window for first delivering(SCWsize) and resending (CWsize), considering the network load which is reflected by DOSC and DOTC. The initial value is the primitive value of the second-level back-off algorithm. The size of back-off window has a relationship with DOSC and DOTC as shown in Fig. 2. The size of SCWsize is not influenced by DOTC, because there are up to 5 nodes participating the first delivering. When the temporal correlation is existing, CWsize increases more obviously. After SCWsize and CWsize are determined, the second-level back-off algorithm will be executed as Fig.3

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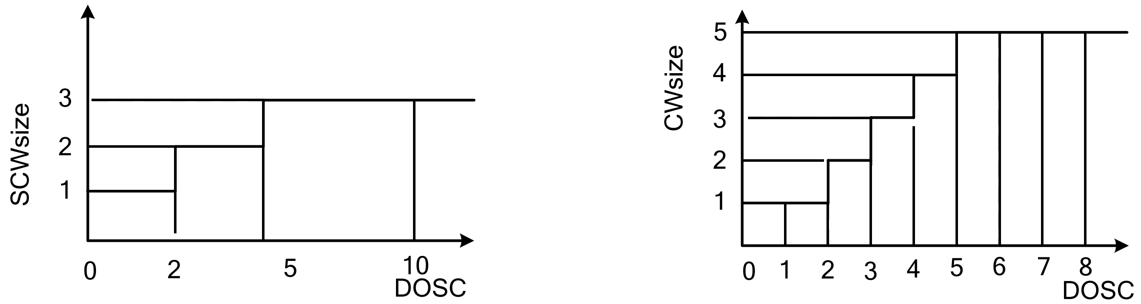
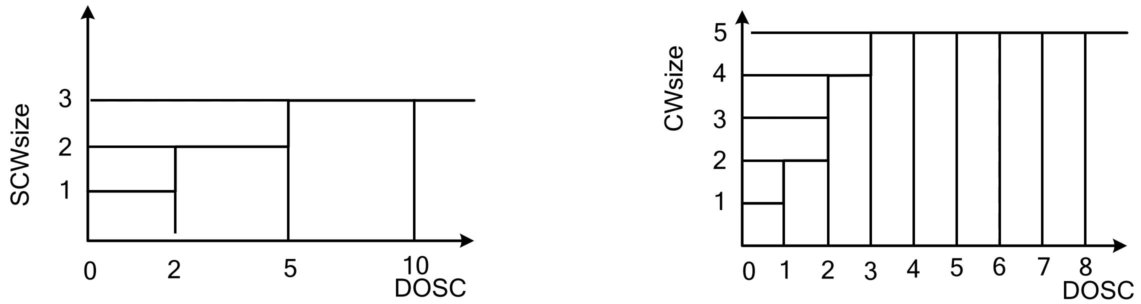
shown. The second-level back-off algorithm is a simple back-off method that it can adapt the size of back-off window to the local network load well without increasing of complexity.



a. DOTC=0



b. DOTC=1

Figure 2. The first level back-off algorithm

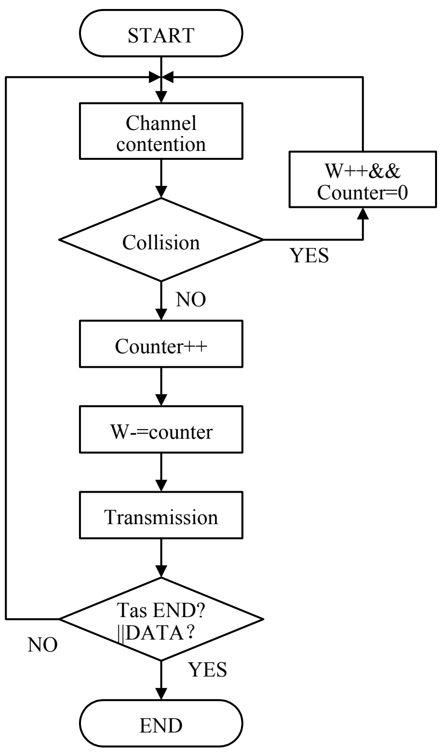


Figure 3. The second level back-off mechanism

b) Adaptive Mapping Algorithm: STCAS-MAC improves AS-MAC in the terms of assigning a value to Tsleep period in *an* adapting way: As shown in Fig.1, there are great potentials for further performance enhancement in AS-MAC. When the traffic is heavy, as Fig.1(a) shown, with Tw period the node has nothing to do in AS-MAC. Adaptive Mapping Algorithm of STAS-MAC can amplify the length of T_{as}, as Fig.4(a) shown, in one cycle, STCAS-MAC can transmit more data comparing to AS-MAC. When the traffic is light, as shown in Fig.1(b), the node in T_3 period of AS-MAC is in the state of sleeping, saving energy but have to wait T_{sleep} period to come for transmission. However, in STAS-MAC, the Adaptive Mapping Algorithm can adapt the length of T_{as} to the traffic, as Fig.4(b) shown. Comparing with AS-MAC, STCAS-MAC can achieve a shorter end-to-end delay without energy increasing.

To predigest design, STCAS-MAC chooses a sub-function to describe the relation between DOSC-DOTC and ratio of T_{sleep}, as shown in Fig.5.

It should be noted that, when the traffic load turns heavy, STCAS-MAC update ratio immediately, however, when it turns light, some residual messages are still in the net. So we wait for a period and then update the ratio.

2) Effective Determination

As shown in Fig.6, a send-buffer is added to each node in the network. The schedule mechanism is First-In-First-Out. The buffers added can drop some messages that may are out of date, so it decreases the rate of valueless messages waiting for delivering. In addition, a determination is added before each message to be transmitted. In these ways, STCAS-MAC can avoid wasting on some needless transitions.

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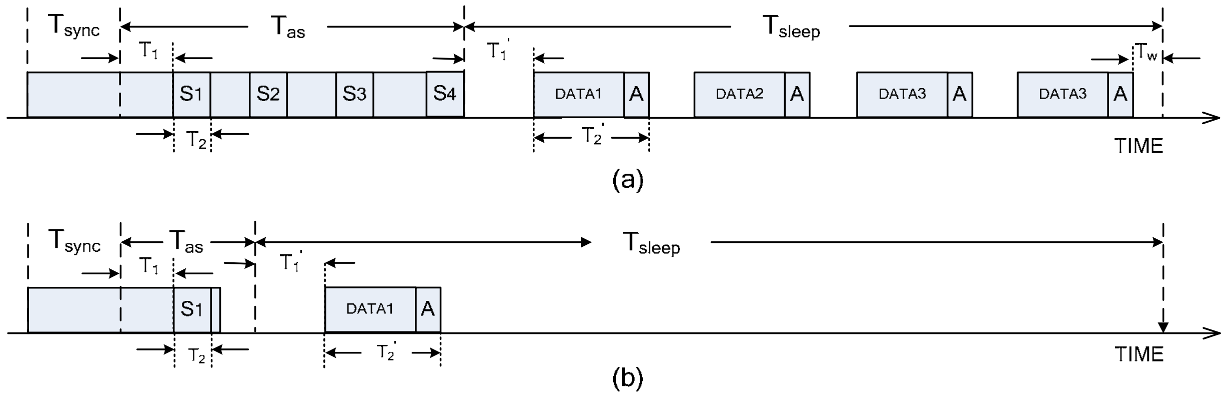

TABLE I. Adaptive mapping algorithm

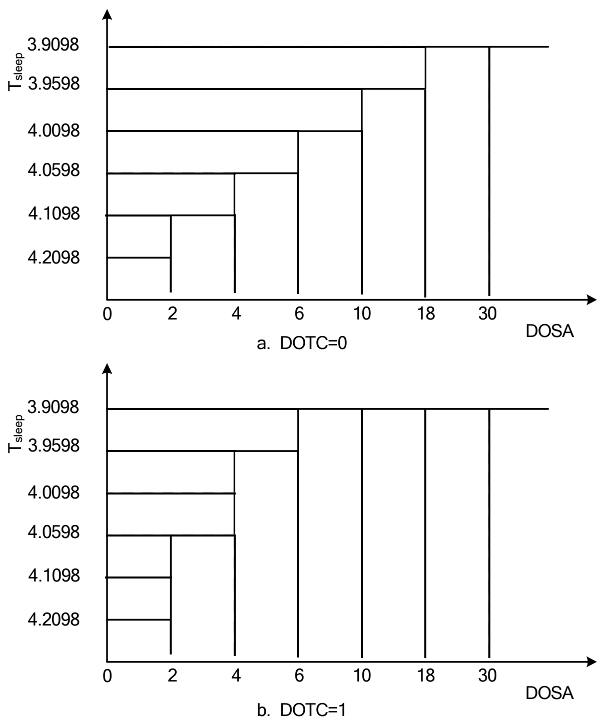

Figure 4. Sub-Function of adaptive mapping algorithm

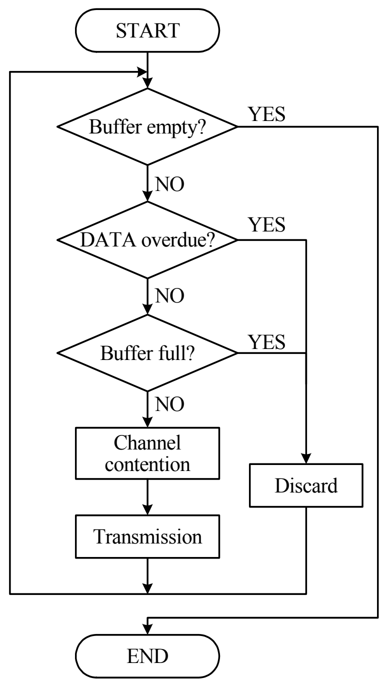

Figure 5. Effective determination

V. PROTOCOL EXPERIMENTATION

In this section, simulation will be taken to verify whether STCAS-MAC does a great advancement in several performances. Especially when the traffic load is heavy or variation, the new protocol can improve the effective delivery ratio or adaptation obviously.

A. Simulation Design

In order to prove the protocol is efficiency, we used the same network parameters in[8] for STCAS-MAC, except that the contention Window(CW), as shown in TABLE I.

As AS-MAC, the duration of T_{sleep} period of STCAS-MAC must satisfy the condition (3). However, T_{sleep} is adaptive in STCAS-MAC as TABLE II.

The size of data packet is 100 bytes. We use the shortest path routing function available in OMNET++ library.

TABLE I.
NETWORKING PARAMETERS

Bandwidth	20Kbps	Channel Encoding Ratio	2
Tx Power	31.2mW	Tx Range	250m
Rx Power	22.2mW	Carrier Sensing Range	550m
Idle Power	22.2mW	Size of RTS/CTS/ACK	10B
Sleep Power	3μW	Size of SCH	15B
SIFS	5ms	Size of Data	100B
DIFS	10ms	Retry Limit	5
Duty Cycle	5%	State Transition Time	2.47ms
State Transition Power	31.2mW	ω	1/10

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$$\frac{T_{SCH}}{T_{Data}+T_{ACK}} \leq \frac{T_{AS}}{T_{Sleep}} \tag{3}$$

TABLE II.
DUTY CYCLE CONFIGURATION

	T_{Sync}(ms)	T_{Data}(ms)	T_{Sleep}(ms)	T_{cycle}(ms)
AS-MAC STCAS-MAC	55.2 55.2	400 adaptive	4009.8 adaptive	4465.0 4465.0

The simulation is performed on OMNET++, with a network of 49(7*7) nodes grid. The distance between neighbors is 200 meters. The nodes can communicate with neighbors each other. All the data generated which are sent to the sink node are transmitted by multi-hop. Comparing with AS-MAC, to verify STCAS-MAC is outstanding in QoS， we assume the maximum delay the net can tolerate is 120s.

In our problem description, our test shown that when EI>10s, all the performances line are smooth, that means DOTC has no influence on MAC protocol. However, when EI□10s, all the performances line increase or decrease rapidly. So this paper will simulate STCAS-MAC in two conditions. The first condition is EI=200s, and the second condition is EI=random(2,10).

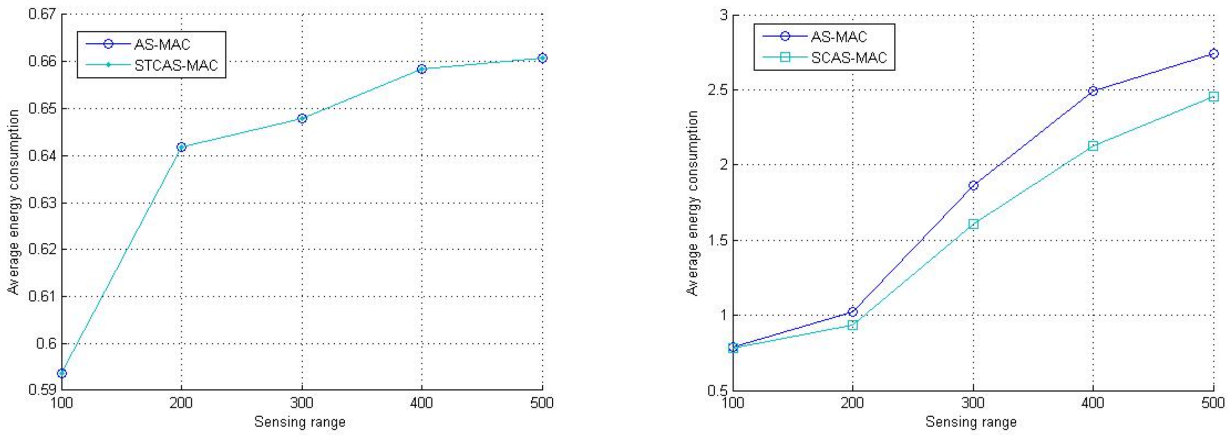
B. Result and Discussion

As Fig.7(a) shown, when DOTC=0(i.e. the global network load is light), the energy consumption lines of STCAS-MAC and AS-MAC are close, because both STCAS-MAC and AS-MAC don't waste extra energy except for transmitting necessary data, and time-out mechanism minimize the idle listening energy consumption. As Fig.7(b) shown, STCAS-MAC outperforms AS-MAC in energy consuming especially when DOTC=1(i.e. the local traffic is heavy). Comparing with AS-MAC, the Two-level Back-off Algorithm can decrease the collision and the Adaptive Mapping Algorithm of STCAS-MAC can relieve retransmission that caused by heavy traffic load. It decreases energy consumption accordingly.

AS Fig.8 and Fig.9 shown, STCAS-MAC achieves a lower average and maximum end-to-end delay. When DOTC=0(i.e. the global traffic load is light), T_{sleep} period can achieve earlier than AS-MAC. That means, for a single node, the right of it to deliver messages arrivals earlier. As Fig.8(b) and Fig.9(b) shown, when DOTC=0(i.e. the global traffic is heavy), because STCAS-MAC can adjust the ratio of T_{as} and T_{sleep}, in one period STCAS-MAC can transmit more messages. That means STCAS-MAC can achieve a higher throughout. So STCAS-MAC reduced the average transmit delay.

Fig.10(a) shows that both STCAS-MAC and AS-MAC can achieve 100% delivery ratio and effective delivery ratio when DOTC=0(i.e. the global traffic load is light). The reason is similar to energy consumption shown by Fig.8(a). Fig.10(b) shows that although STCAS-MAC discard message when it finds that the message is out of time or not available, the delivery ratio of STCAS-MAC is still higher than the delivery ratio of AS-MAC, Meanwhile, the Effective Determination Mechanism of STCAS-MAC makes sure that all of the messages sink node received are effective, so the delivery ratio and effective delivery ratio is equal.

To sum up, comparing to AS-MAC, STCAS-MAC has the advantage of performances. When network load is light, STCAS-MAC can achieve a lower end-to-end delay; when network load is heavy, STCAS-MAC can achieve a higher throughput, thus it can achieve lower end-to-end delay and energy consumption, higher delivery and effective delivery ratio. On the other hand, the simulation result shows that spatial and temporal correlation-based mechanism is feasible and predominant.



(a) (b)

Figure 6. Average energy consumption

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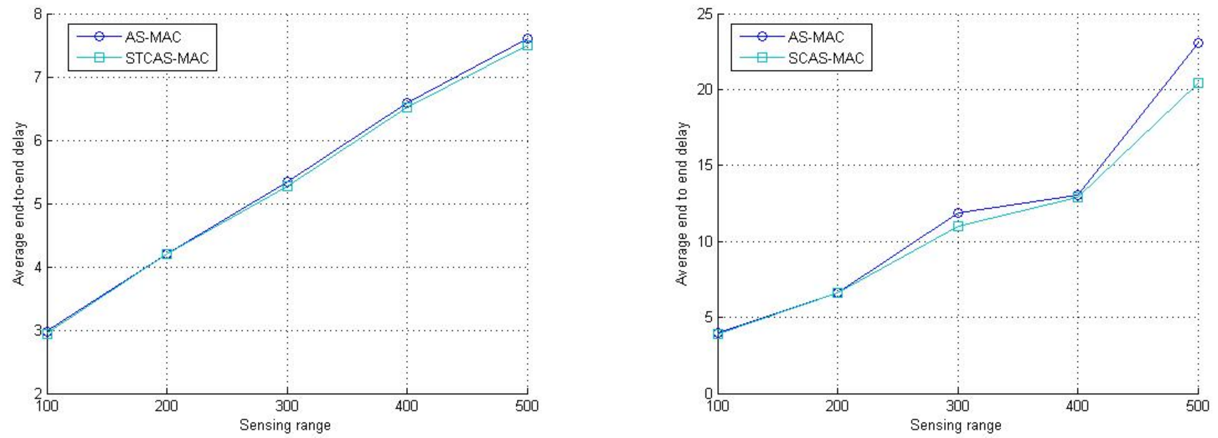
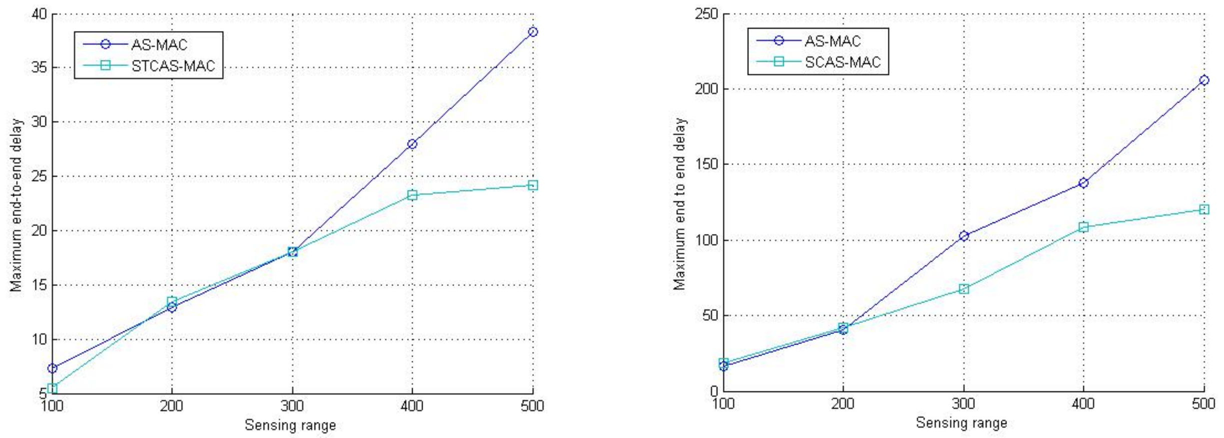


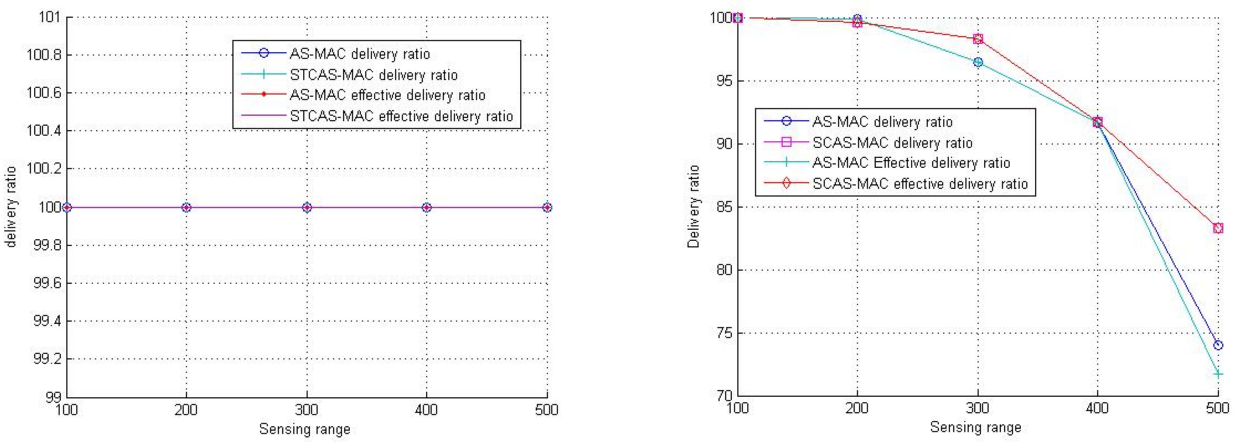
(a) (b)

Figure 7. Average end to end delay



(a) (b)

Figure 8. Maximum end to end delay



(a) (b)

Figure 9. Delivery and effective delivery ratio

VI. CONCLUSIONS

Based on spatial and temporal correlation, this paper defines the traffic as two types, local traffic and global traffic. Then it presented DOSA and DOTA as parameters to quantify local and global traffic respectively. We analyzed performances which are given by spatial and time correlation on AS-MAC. Considering local and global traffic we provided an adaptive mechanism, a

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determination mechanism and a new node state. Simulation results showed that STCAS-MAC outperform AS-MAC in energy consuming, end-to-end delay and adaptation.

However, the defect is that the parameters we given between global traffic and adaptive is not accurately. Meanwhile, the mapping of local traffic and parameters is not accurate. More simulation work will be conducted to text global traffic's affect on net performance. More results will be Wireless sensor network is high correlative about application. So the versatile MAC protocols must be adjusted to different applications. Adaptive mechanism plays a great role in popularizing of MAC protocols.

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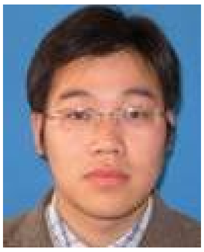

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