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Performance analysis of S-MAC protocol

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SUMMARY

Wireless sensor networks have been developed in the way of higher speed, more stability, and more energy efficiency in recent years. Because most wireless sensors are powered by energy-constrained batteries, efficient energy consumption plays the most important role in the design of wireless sensor networks. For energy efficiency, aside from economizing the use of power in the sensor hardware, extensive research efforts have been dedicated towards designing energy-efficient protocols in the MAC layer. Among them, the S-MAC (sensor medium access control) protocol proposed a combined scheduling and contention scheme to decide when to put sensors into the sleep state for saving energy. In this paper, we further conduct the performance analysis of S-MAC protocol, in which the mathematical equations for the saturation throughput analysis of S-MAC protocol are derived, and then simulation data are substituted into those equations and the S-MAC protocol, respectively. The simulated throughput results have shown that our derived equations can capture the characteristics of the S-MAC protocol. In addition, as compared with the conventional carrier sense multiple access/collision avoidance protocol, the simulation results show that the S-MAC protocol performs better in terms of power consumption, delay, and collision rate. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS: S-MAC; sensor network; adaptive listening

1. INTRODUCTION

In recent years, rapid advance of embedded systems and memory techniques has fostered vigorous development of wireless sensor networks (WSNs) [1–3]. The main characteristic of WSNs is to deploy a large number of small-sized sensors in a large-scale geographical area to monitor physical and environmental conditions. In general, the most challenge in the use of WSNs is that sensor nodes are operated with limited power [4], and hence, a lot of previous works focused on designing energy-efficient MAC protocols in WSNs (e.g., X-MAC [5], PMAC [6], UW-MAC [7], OMAC [8], and cooperative MAC [9]) to provide the efficiency in sharing the common radio channel while satisfying the fairness requirements for sensor nodes. Among those notable works, we are concerned with the sensor medium access control (S-MAC) protocol [10, 11] (a MAC protocol designed for WSNs) based on the IEEE 802.11 protocol [12, 13], which considers periodic listen and sleep to achieve a significant reduction in power consumption.

The S-MAC protocol [10, 11] was motivated from the conventional limitation of WSNs in which wireless sensors may spend much time on detecting whether they need to transmit or not, but in fact, essential time used for transmission is usually very short so that the time of idle listening wastes a lot of energy. Therefore, the S-MAC protocol proposed a scheme of periodic listen and sleep to solve this problem. The S-MAC protocol employs periodically relative synchronization, that is, broadcasting SYNC packets to establish listen/sleep schedules of sensor nodes periodically, and adaptively

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choosing large slot time to provide robustness when topology changes or clock drifts. The main designs behind the S-MAC protocol's differences from the others are given as follows:

- The S-MAC protocol is based on a *periodic listen and sleep* scheme implemented in multihop networks, in which sensor nodes go to sleep periodically to avoid idle listening, so that energy consumption can be reduced significantly.
- Although periodic sleep reduces energy consumption, it increases latency, because senders always have to wait for their receivers to wake up before sending out data. Hence, the S-MAC protocol applies a technique of *adaptive listening* to reduce the latency, behind which the basic idea is to let the sensor node overhear its neighbor's transmissions and wake up for a short period of time at the end of the transmission, so that if the node is the next-hop node of its neighbor's transmission, it can immediately receive the data from its neighbor rather than wait for its next periodic listening.
- To avoid energy waste on overhearing, the S-MAC protocol extends the work of PAMAS [14] to propose *overhearing avoidance*, behind which the basic idea is to let interfering nodes go to sleep after hearing a request to send (RTS) or clear to send (CTS) packet.
- To decrease application-perceived control overhead and latency due to transmission of a long message, the S-MAC protocol applies *message passing*, in which the long message are fragmented into many small fragments, and then they are transmitted in a burst.

As the S-MAC protocol [10, 11] was proposed without any mathematical analysis for performance, the main contribution of this paper is to conduct the saturation throughput analysis of the S-MAC protocol, in which a comprehensive derivation of the mathematical equations for the saturation throughput analysis is given in detail, and then a thorough simulation is conducted for the evaluation of the experimental performance of those equations and the S-MAC protocol. First, we substitute the simulation data into those mathematical equations of the saturation throughput analysis and the simulation of S-MAC protocol, respectively. The simulation results show that the throughputs between them are very similar, meaning that the saturation throughput analysis can capture the characteristics of the S-MAC protocol. Next, the simulation of the S-MAC protocol is compared with the conventional CSMA/CA protocol, and the simulation results show that the S-MAC protocol performs better in terms of power consumption, delay, and collision rate. Note that in the previous literature, analytical analysis for other networks existed, for example, bidirectional multi-channel IEEE 802.11 MAC protocols [15], multi-channel MAC protocol for ad hoc networks [16], and so on.

The rest of this paper is organized as follows. Section 3 gives the main components of the S-MAC protocol. Section 2 gives the related works of the S-MAC protocol. A mathematical analysis for S-MAC protocol is given in Section 4, and a simulation comparison is given in Section 5. A conclusion is given in Section 6.

2. RELATED WORK

Since the S-MAC protocol [11] was proposed, it has become one of the most well-known MAC protocols for WSNs and had a huge number of variants and extensions in previous literature. Recent surveys for WMNs can be found in [17] and [18]. Some of the most notable works related to this paper are introduced in the following.

One line of the extensions to the S-MAC protocol is to design its dynamic versions. The timeout MAC (T-MAC) protocol [19] is a contention-based MAC protocol that introduces an adaptive duty cycle in the S-MAC protocol by dynamically ending its active time. By the protocol, the amount of energy wasted on idle listening can be reduced, while a reasonable throughput can still be maintained. Because the tradeoff between power consumption and latency was not studied in the S-MAC protocol, the dynamic sensor MAC (DSMAC) protocol [20] added to the S-MAC protocol a dynamic duty cycle feature with changing traffic conditions without assuming any requirement for prior application knowledge, so that a good tradeoff between power consumption and latency can be achieved without much overhead.

The traffic-load adaptive MAC (TA-MAC) protocol [21] modified the static contention window mechanism of S-MAC protocol and adjusted the initial contention window according to the current traffic load so that the collision probability can be reduced. It also designed a fast backoff scheme to reduce the idle listening time during backoff. The work in [22] found that the asymmetrical deployment of the sensor nodes in WSNs brings more energy consumption and unnecessary collisions, and hence, it proposed the polling service-based MAC (PSMAC) protocol [22] that joins the MAC layer and physical layer of the sensor nodes to propose a transmission power control MAC protocol based on the S-MAC protocol.

Another line for the variants of S-MAC protocol is to modify the S-MAC protocol for mobile WSNs. One notable work along this line is the MS-MAC protocol [23], in which each sensor node detects the mobility of its neighborhood according to the analysis of the received periodical SYNC messages from neighbor nodes. Any change in the strength of the received message implies the mobility of its neighbor node or itself, and then the sensor node adjusts its working listen/sleep schedule adaptively according to the mobility patterns in the neighborhood. The work in [24] proposed a novel mobility-aware TDMA-based MAC protocol for mobile sensor networks that splits a given round into a control part and a data part, in which the control part is used to manage mobility, where the other part is used to transmit messages. The collision-freedom in the data part of a schedule can be guaranteed in the protocol.

In recent studies, it was found that energy consumption can be reduced significantly without incurring overhead for clock synchronization by asynchronous sleep-wake scheduling protocols. Among them, in order to exploit the inherent broadcast nature of the wireless medium to reduce the delay due to synchronization, the work in [25] proposed an optimal ‘anycast’ technique under periodic sleep-wake patterns, in which the so-called ‘anycasting’ allows each sensor node to forward packets to the first node that wakes up among a set of candidate next-hop nodes. Another recent work in [26] presented an improved energy-efficient MAC protocol for WSNs that avoids overhearing and reduces contention and delay by asynchronously scheduling the wake-up time of neighboring nodes.

For theoretical analysis, a recent article in [27] proposed a comprehensive analysis of the MAC unreliability problem in WSNs. From application aspect, a recent article in [28] applies the MAC protocols for WSNs to sap flow, soil moisture, and soil water potential sensors.

3. MAIN COMPONENTS OF THE S-MAC PROTOCOL

In this section, we introduce the main components of the S-MAC protocol: periodic listen and sleep, collision avoidance, adaptive listening, and overhearing avoidance.

3.1. Periodic listen and sleep

Some basic terms and concepts for periodic listen and sleep are given as follows:

Working schedule. Figure 1 illustrates a working schedule of S-MAC protocol, which consists of listen intervals and sleep intervals. A complete cycle of listen and sleep is called a *time frame*. Each sensor node can freely choose its own working listen/sleep schedule, and can also follow its neighboring nodes’ schedules. Note that the time frame is distinct from the MAC frame, and the MAC frame is simply called a frame throughout the rest of this paper.

SYNC packet. As shown in Figure 2, sensor nodes establish their own working schedules during the initial period, and then exchange their working schedules by periodically broadcasting a SYNC packet to their immediate neighbors during

Figure 1. Working schedule.

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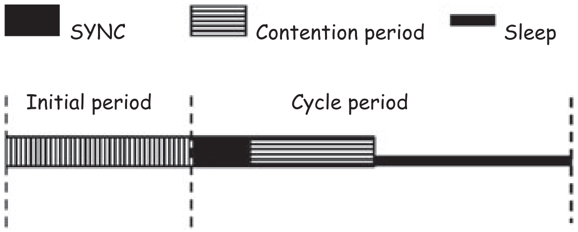
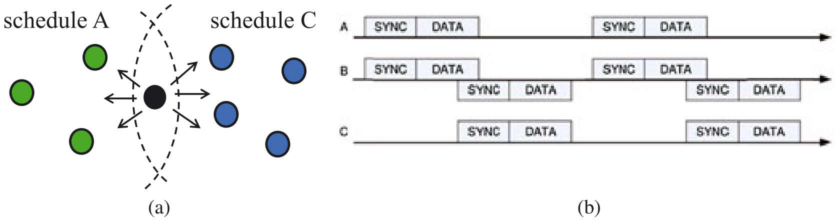


Figure 2. SYNC period in a time frame of the working schedule.



(a) (b)

Figure 3. (a) A border node located between two schedules, say A and C. (b) The border node follows schedule B, which adapts both the two schedules A and C.

the SYNC period. During the contention period, if a sensor node does not receive any SYNC packet, it will apply its own working schedule; otherwise (it receives some SYNC packet sent by other nodes), it follows the working schedule of that node.

Neighbor lists. Each sensor node in the S-MAC protocol must create a table called *neighbor list* to record the locations of previously-known neighbor nodes and the information of their corresponding working schedules.

Border node. In some situations, a sensor node may receive two different working schedules from its neighbors via SYNC packets. Therefore, it can be regarded as a border node between two schedules, say A and C, as illustrated in Figure 3(a), and it follows schedule B, which adapts both the two schedules A and C as shown in Figure 3(b). Because the border nodes work with many different schedules, their energy consumption is higher than other normal nodes.

3.2. Collision avoidance

Consider the diagram of transmitting data using S-MAC protocol in Figure 4. The sender node first sends a RTS packet to request transmission after getting contention window. Note that contention window optimization [29] is a challenging research topic, but is not concerned in this paper, that is, we assume the contention window to be fixed. After the receiver node receives the RTS packet, it returns a CTS packet in order to announce that the sender node can begin to transmit data. Except

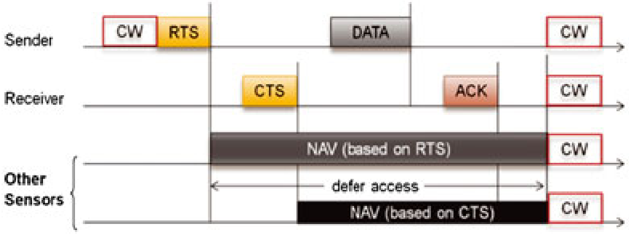


Figure 4. The diagram of transmitting data with sensor medium access control protocol.

for the sender node and the receiver node, all the other nodes have to sleep after the sender node sends the RTS packet to the receiver node. That is the reason why the collision avoidance scheme can assure that the sender node and the receiver node can transmit packets to each other without any interferences.

3.3. Adaptive listening

Although periodic listen and sleep can decrease power consumption effectively, transmission delay due to the sleep schedule is still a challenging problem. Therefore, the S-MAC protocol provides a mechanism called *adaptive listening* to decrease transmission delay.

Consider a three-hop network topology as shown in Figure 5. Assuming that each node has the same working schedule in this network, Figure 6 shows that the process of transmitting data packets from node A to node D without adaptive listening, in which each of the nodes that are not evolved with the current transmission go to sleep before finishing the transmission, according to the working listen/sleep schedule. For example, as shown in Figure 6, nodes C and D sleep in time frame n; nodes A and D sleep in time frame $n + 1$; nodes A and B sleep in time frame $n + 2$.

Now, we consider the case where adaptive listening is applied. The basic idea behind adaptive listening is that at the end of one transmission, the S-MAC protocol gives another probability of transmitting data packets to those nodes involved in this transmission, including sender, receiver, and their neighbors that overhear this transmission. By doing so, a node may have two DATA periods for sending or receiving data packets in a time frame. Take Figure 7 as an example to illustrate how the adaptive listening function in S-MAC works. Normally, node C needs to sleep in time frame n in this example, but with adaptive listening, node C does not sleep because it needs to wait to receive the RTS packet from node B to transmit packets. At the same time, node A goes to sleep in order not to hear the RTS packet sent by node B. If nodes have not heard any packets such as RTS and CTS during the adaptive listen period (ALP), they go to sleep automatically.

It is worth noticing that the scheme of adaptive listening has a problem: the time of transmitting the data packet may be too long so that the data packet collides with the SYNC packet of the next time frame, as illustrated in Figure 8. Although the S-MAC protocol builds an ALP in the sleep interval to avoid the collision with next SYNC packet, it cannot be guaranteed whether the time of transmitting packets after adaptive listening is long enough. Hence, this action would lead to the collision of the data packets that are being transmitted with the SYNC packet, which is about to be received.

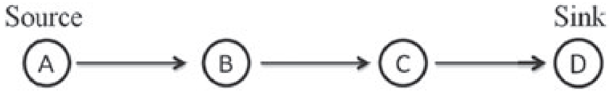


Figure 5. Three-hop network.

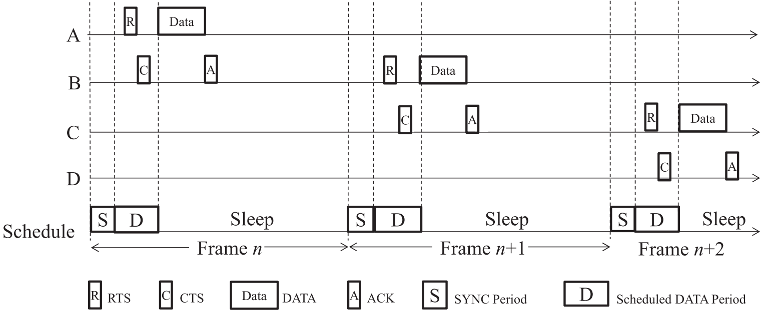


Figure 6. Transmit data packets through a three-hop network without adaptive listening.

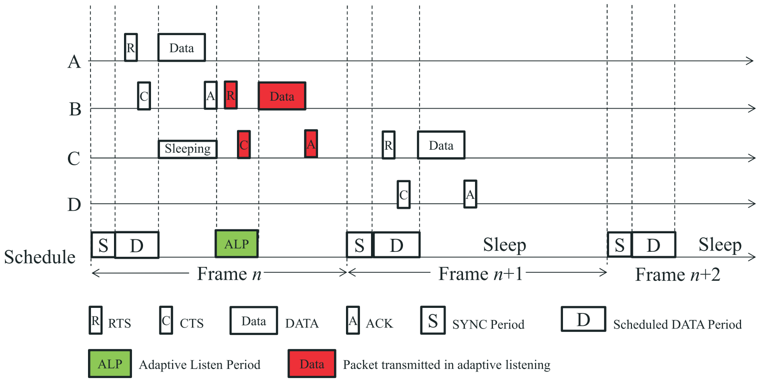


Figure 7. Transmit data packets through a three-hop network with adaptive listening.

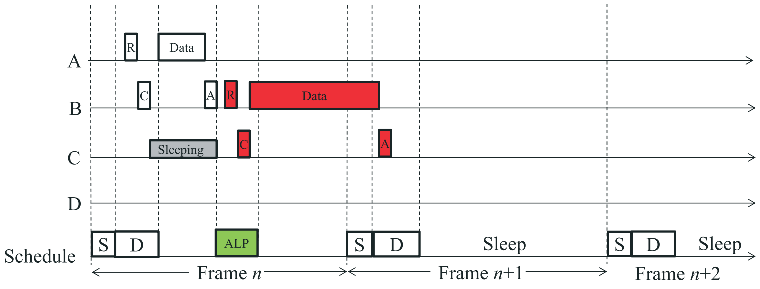


Figure 8. Time of data transmission is too long in adaptive listen period.

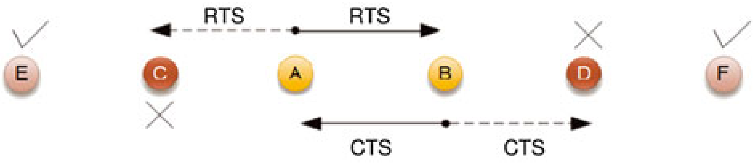


Figure 9. The diagram of overhearing avoidance.

3.4. *Overhearing avoidance*

Consider the diagram in Figure 9, in which node A sends a RTS and B returns a CTS. The other nodes that are not in the transmission range of nodes A and B can adapt their own working schedules. But if nodes (nodes C and D in Figure 9) are located in the transmission range, they need to go to sleep in order not to interfere with this transmission.

4. MATHEMATICAL ANALYSIS

Before showing the simulation of S-MAC protocol, we conduct a mathematical analysis on the throughput of the S-MAC protocol. We assume all the nodes to be of uniform configuration and be transmitted in the way of multi-hop network. According to the properties of the S-MAC protocol, all the nodes have fixed sleep schedules. The default settings of S-MAC protocol are applied for contention window size. The variables used in our mathematical analysis is given in Table I.

Because we assigned the contention window size W to a fixed average contention window size $\overline{W}$, we have

$$W = \overline{W} \tag{1}$$

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Table I. Variables used in our mathematical analysis.

Variables	Meaning and explanation
$\overline{W}$	Average contention window size
P_f	Probability of transmission failure
P	Transmission probability
L_{data}	Data frame size
L_{ack}	ACK frame size
P_s	Probability of a successful transmission
P_I	Probability of idle channel
P_c	Probability of a collided transmission
P_{err}	Probability of a transmission errors
η	Extended retransmission limit
n	Number of sensor nodes
T_s	Duration of a successful transmission
T_I	Duration of idle channel
T_c	Duration of a collided transmission
T_{err}	Duration of a transmission error
T_{frame}	Length of a time frame
BER	Channel bit error rate
σ	Duration of a time slot

Let P_f denote the probability of transmission failure. In the beginning of an active time frame of the working schedule, a sensor node starts to transmit a frame with probability p, and defers the transmission with probability $1-p$. Let X be a random variable that models $(X-1)$ transmission failures before the first successful transmission. According to Bernoulli's theorem in probability, the probability of the random variable can be presented as follows:

$$P(X=x)=(1-p)^{x-1}p, \forall x \in \mathbb{N} \tag{2}$$

The average contention window size is determined by the expected value of x, and thus we have

$$\frac{\overline{W}+1}{2}=\frac{1}{p} \tag{3}$$

By rearranging the previously mentioned equation, we obtain

$$p=\frac{2}{\overline{W}+1} \tag{4}$$

Now we consider the probability of transmission failure (P_f). Because P_f is defined as the probability that a transmitted frame collides or is received with error, we have

$$P_f=1-(1-p)^{n-1}(1-P_e) \tag{5}$$

where n is the number of sensor nodes; P_e is the probability that a data frame error or an ACK frame error occurs consecutively when transmitting a data frame. Because both the errors of data and ACK frames cause ACK timeout and force the sender to immediately resend the data frame until it exceeds the extended retransmission limit or receives an ACK frame successfully, we can express P_e as the summation of the probability that a data or ACK frame error happens consecutively. Then, it follows that

$$P_e=\sum_{i=0}^{\eta}\begin{pmatrix}\eta\\ i\end{pmatrix}(P_e^{\text{data}})^i((1-P_e^{\text{data}})\cdot P_e^{\text{ack}})^{\eta-i} \tag{6}$$

where η, P_e^{data}, and P_e^{ack} stand for the extended retransmission limit, the probability for receiving a data frame with error, and the probability for receiving an ACK frame with error, respectively.

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Thus, we have

$$p_e^{\text{data}} = 1 - (1 - BER)^{L_{\text{data}}} \tag{7}$$

$$p_e^{\text{ack}} = 1 - (1 - BER)^{L_{\text{ack}}} \tag{8}$$

where L_{data} and L_{ack} are the sizes of a data frame and an ACK frame, respectively.

In what follows, we conduct a mathematical analysis of saturation throughput on the S-MAC protocol. Note that a notable work for saturation throughput analysis can be found in [30]. Because the saturation throughput is defined as a relation of the successfully transmitted payload size over a randomly chosen time slot in the active stage [31], the system saturation throughput S can be defined as follows:

$$S = \frac{P_s L_{\text{data}}}{P_I T_I + P_s T_s + P_c T_c + P_{\text{err}} T_{\text{err}}} \tag{9}$$

The probabilities in Equation (9) are explained as follows. The probability P_s of a successful transmission measures the case where the system transmits a data packet without any collision or bit error. Hence, P_s can be expressed as follows:

$$P_s = np(1-p)^{n-1}(1-P_e) \tag{10}$$

P_I is the probability of sensor nodes that are idle, and can be calculated as follows:

$$P_I = (1-p)^n \tag{11}$$

P_c is the probability that a collision occurs in a time frame, and can be calculated as follows:

$$P_c = 1 - (1-p)^n - np(1-p)^{n-1} \tag{12}$$

Let P_{err} denote the probability that a transmission error occurs on a data frame or ACK frame and then the sender gives up its transmission. Thus, we have

$$P_{\text{err}} = np(1-p)^{n-1} P_e \tag{13}$$

Now we discuss the durations of transmissions in Equation (9). Remember that sensor nodes change to the sleep mode in a time frame (consisting of a listen interval and a sleep interval) in the S-MAC protocol. Let T_{frame} denote the sum of the lengths of a listen interval and a sleep interval. Let ST denote the time of transmitting data successfully. Then, we have

$$ST = T_{\text{DIFS}} + T_{\text{CW}} + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + T_{\text{SIFS}} + T_{\text{data}} + T_{\text{SIFS}} + T_{\text{ack}} \tag{14}$$

$$= T_{\text{DIFS}} + T_{\text{CW}} + T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{data}} + 3T_{\text{SIFS}} + T_{\text{ack}} \tag{15}$$

where T_{DIFS}, T_{CW}, T_{RTS}, T_{CTS}, T_{SIFS}, T_{data}, and T_{ack} denote the DIFS time, average contention window, time of transmitting a RTS packet, time of transmitting a CTS packet, time of an SIFS, time of transmitting a data frame, and time of returning an ACK, respectively. T_I is the duration of idle channel with

$$T_I = \sigma \tag{16}$$

Assuming that RT is the remaining time after successful transmission, that is, the time from the sender's receiving an ACK to the nodes's awaking next time, we have

$$T_s = ST + RT \tag{17}$$

Because collisions only occur when RTS packets are being transmitted, sensor nodes enter the sleep interval after transmitting data with errors. So, we have

$$T_c = T_{\text{DIFS}} + T_{\text{CW}} + T_{\text{RTS}} + RT \tag{18}$$

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According to the S-MAC protocol, when there is a data error or an ACK error, the sender has to transmit the data again. Therefore, we have

$$T_{\mathrm{err}} = T_{\mathrm{frame}} \tag{19}$$

As a result, we find that T_{frame} is the sum of T_s, T_c, and T_{err}. Also, because the summation of P_{err}, P_s, P_c, and P_I is one, we obtain the following equation by substituting T_{frame} to Equation (9):

$$S = \frac{P_s L_{\mathrm{data}}}{T_{\mathrm{frame}} - P_I (T_{\mathrm{frame}} - T_I)} \tag{20}$$

5. SIMULATION ANALYSIS

In this section, we conduct a simulation analysis, and compare it with the results of mathematical analysis detailed in the previous section. Our simulation model is built using the Network Simulator version 2 (NS-2), and each simulation runs for at least 1000 simulation seconds. The default values used in the simulation are listed in Table II. Figure 10 illustrates the 50-node network topology of our simulation.

We substitute the parameters in Table II into mathematical equations in the previous section and the simulation of S-MAC protocol, respectively. The throughput results of mathematical analysis and simulation are shown in Figure 11, in which we can observe that as the number of sensor nodes increase, the throughput decreases. Because the increase in number of sensor nodes leads to an increase in the probability of transmitting data at the same time, it easily causes collision of sensor nodes. That is, the reason why throughput decreases as the number of sensor nodes increases.

Table II. Default attribute values used in the simulation.

Attribute	Meaning and explanation	Value
β	Radio bandwidth	20 kbps
L_{ctr}	Length of a control packet	10 bytes
$L_{\mathrm{MAC-header}}$	Length of the MAC header	10 bytes
L_{payload}	MAC layer payload size	50 bytes
W	Initial contention window size	63
W_{SYNC}	Contention window size for SYNC frame	63
η	Extended retransmission limit	5
DC	Duty cycle	10%
T_{DIFS}	DIFS time	5 ms
T_{SIFS}	SIFS time	5 ms
T_{slot}	Slot time	1 ms
δ	Propagation delay	5 μs

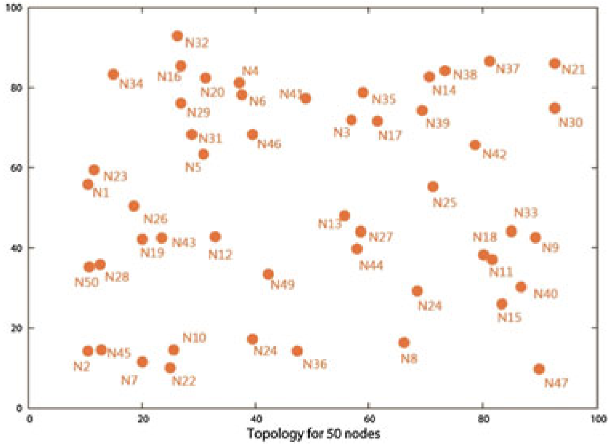

Figure 10. The 50-node network topology used in our simulation.

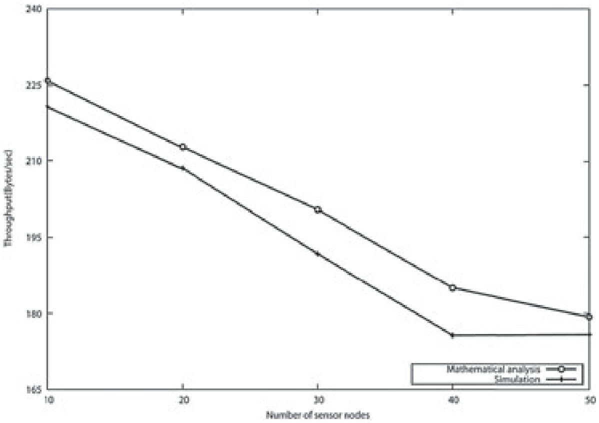

Figure 11. Throughputs of the mathematical analysis and the simulation of sensor medium access control protocol.

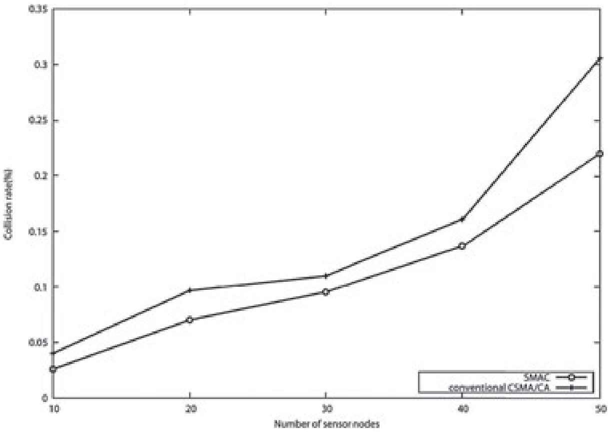

Figure 12. Plot of collision rates versus number of sensor nodes for the sensor medium access control and the conventional CSMA/CA protocols.

Although the throughput of the mathematical analysis is higher than that of the simulation, the gap between them is small over any number of sensor nodes.

The plots of collision rates, accessing delay, and queuing delay versus number of sensor nodes for the S-MAC and the conventional CSMA/CA protocols are given in Figures 12–14, respectively. From Figure 12, we observe that the collision rate increases as the number of sensor nodes increases. As for the comparison between the two protocols, the collision rate of the S-MAC protocol is always lower than that of the conventional CSMA/CA protocol. From Figure 13, the accessing delay increases as the number of sensor nodes increases, because many nodes contend for bandwidth at the same time. In Figure 14, the queuing delay increases as the number of sensor nodes increases, because we fix the contention window. As the number of sensor nodes increases, the size of contention window cannot be adjusted dynamically in the S-MAC protocol, and thus data takes longer time in queuing before being transmitted.

The throughputs of different numbers of sensor nodes for the S-MAC protocol are given in Figure 15, from which we observe that some sensor nodes provide good performance, and the others are not. The reasons are given as follows. In the S-MAC protocol, if a sensor node always chooses a larger contention window, it needs to wait more time before transmitting data, and hence, it has a higher throughput. Oppositely, if a sensor node always chooses a smaller contention window, it can transmit data without waiting long time, and hence, it has a low throughput. As a result, we find that when nodes transmit again, they easily collide and lead to starvation.

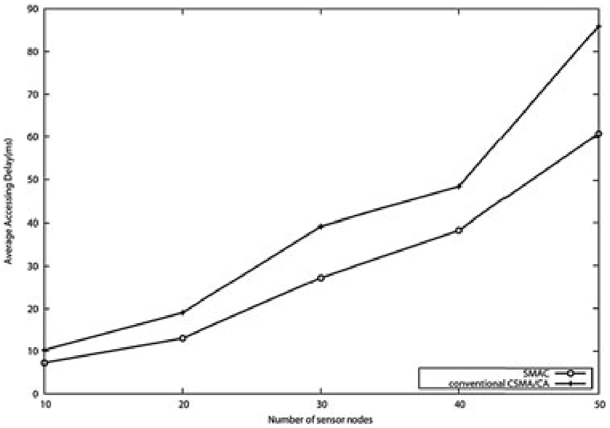

Figure 13. Plot of accessing delay versus number of sensor nodes for the sensor medium access control and the conventional CSMA/CA protocols.

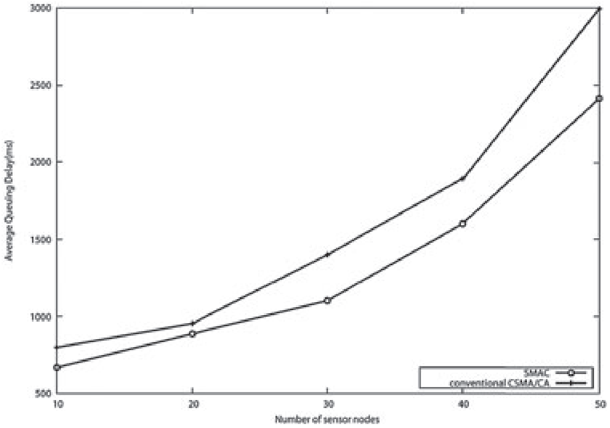

Figure 14. Plot of queuing delay versus number of sensor nodes for the sensor medium access control and the conventional CSMA/CA protocols.

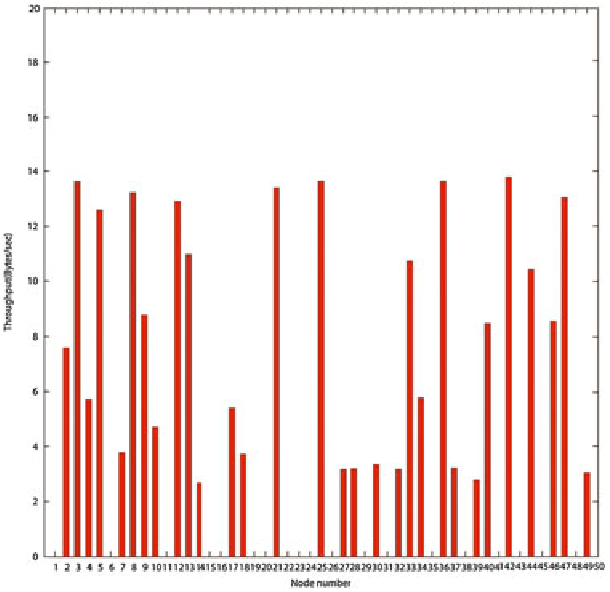

Figure 15. Throughputs versus number of sensor nodes for the sensor medium access control protocol.

6. CONCLUSION

To evaluate the performance of the S-MAC protocol, this paper has conducted not only the saturation throughput analysis of the S-MAC protocol but also its simulation analysis. In the saturation throughput analysis, we have derived a system of mathematical equations, and those equations can capture the characteristics of the S-MAC protocol via simulation. After we implemented the S-MAC protocol in the network simulator, we found some advantages of the S-MAC protocol as compared with conventional CSMA/CA protocol, such as lower power consumption, lower delay, lower collision rate, more easily implemented in WSNs. In addition, the overhearing problem can be lessened. However, the S-MAC protocol still has some flaws, for example, the time frames and the sleep intervals are fixed so that they cannot dynamically adjust the frequency of changing the working listen/sleep schedule to adapt to the change of the Internet environment. Because its contention window is fixed, it also causes some starvation problems. A line of future works is to improve the indicated flaws for S-MAC protocol. In addition, it would be of interest to conduct the performance analysis for other variants for S-MAC protocol, for example, dynamic versions or mobile versions.

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