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An Energy Conservation MAC Protocol in Wireless Sensor Networks

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Abstract Wireless sensor networks use battery-operated computing and sensing devices. Because of the limitation of battery power in the sensor nodes, energy conservation is a crucial issue in wireless sensor networks. Consequently, there is much literature presenting energy-efficient MAC protocols based on active/sleep duty cycle mechanisms to conserve energy. Convergecast is a common communication pattern across many sensor network applications featuring data gathering from many different source nodes to a single sink node. This leads to high data collision rates, high energy consumption, and low throughput near the sink node. This paper proposes an efficient slot reservation MAC protocol to reduce energy consumption and to make transmission more efficient in data gathering wireless sensor networks. The simulation results show that our protocol provides high throughput, low delivery latency and low energy consumption compared to other methods.

Keywords Energy conservation · MAC protocol · Wireless sensor networks

1 Introduction

Wireless sensor network (WSN) is an emerging technology that is expected to be used in a wide range of applications such as target tracking, environment monitoring, habitat sensing, and home security [1–3]. Usually it is composed of a large number of battery-operated distributed nodes, making energy conservation one of the most important issues in WSNs. Energy conservation can be addressed at each layer of the network protocol stack, but our focus in this paper is the Medium Access Control (MAC) layer. The role of a network is

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to ensure that data can be delivered as expected. A general rule for achieving a predictable operation is to reduce as much as possible the complexity of the applications and their services. Thus, optimizing the communication performance of the sensor networks becomes very important. A good MAC protocol must always consider the following attributes: energy efficiency, scalability, fairness, latency, and throughput.

The status of a radio transmitter consists of four possible operations with different power levels: transmitting, receiving, listening, and sleeping. Typically, the power consumption of listening is the same as that of receiving. The transmitting power consumption depends on the transmission power level. From the data sheet of the MICAz Mote sensors radio chip [4,5], the power levels are: 17.4 mA for transmission with maximum power level, 8.5 mA for transmission with minimum power level, 18.8 mA for receiving data, 426 μA for idle mode (crystal oscillator and voltage regulator on), 20 μA for power down (only voltage regulator on). In practice, turning the radio into sleep mode is the most power conserving method. If nodes can turn off the radio when there is no data to send or receive and wake up at the right time to transmit or receive, the available energy of a battery can be used in an optimal way.

This paper presents an energy conservation MAC protocol for WSNs. Our protocol combines contention-based, scheduling-based, and reserving-based schemes to achieve energy efficiency, reduce transmission delay, and decrease collision probability of data transmission. Only a rough time synchronization is needed in our protocol. All nodes must record all its neighbors' wake-up schedules. While transmitting, nodes use a reserving-bit to inform the receiver that they still want to transmit data. Thus, the receiver can reserve slots for those senders in order to decrease the number of sensor nodes that want to contend the same transmission slot. The main contribution of this work is to conserve energy by reducing the collision probability of nodes competing for the same time slot. Our protocol improves network throughput and reduces transmission delay while at the same time conserving energy.

This paper is organized as follows. Section 2 reviews relevant works in the literature. Section 3 describes our proposed protocol. Section 4 presents the simulation results. Finally, we draw our conclusions in Sect. 5.

2 Related Work

Over the past few years several MAC protocols have been developed for WSNs. They can be categorized into centralized and decentralized MAC protocols. Most of the centralized protocols operate as a cluster-based scheme. In a cluster-based scheme the base station or cluster header will allocate time slots to each member for creating a collision free operation within the cluster. Therefore, accurate time synchronization protocol is essential in centralized protocols. The other type of protocol is the decentralized-based MAC protocol. These protocols can be divided into scheduled and random access schemes. In the scheduled schemes, all nodes need to periodically broadcast their wake-up schedule and maintain their neighbors' schedule information. The nodes are then allowed to transmit data during the active periods of the receivers and save energy according to their own schedules. Only a rough time synchronization is required in the scheduled schemes, such as S-MAC, T-MAC, P-MAC, and D-MAC.

S-MAC and T-MAC are two well-known MAC protocols in WSNs. In S-MAC [6] the four major sources of energy waste are: collision, overhearing, control packet overhead, and idle listening. Therefore, S-MAC tries to reduce waste by putting sensor nodes into a periodical sleeping mode at a low and fixed duty cycle. T-MAC [7] improves on S-MAC by using an adaptive duty cycle. Sensor nodes go to sleep when there is no activity at time

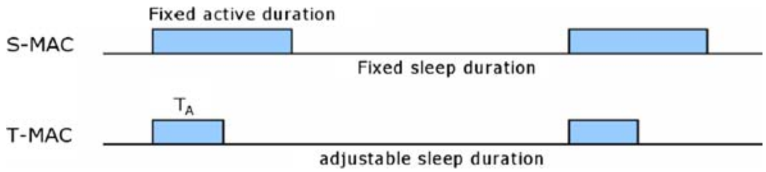


Fig. 1 The schedules of S-MAC and T-MAC protocols

$T_A = (C + R + T) \times 1.5)$, where C is the length of the contention interval, R is the length of an *RTS* packet, and T is a short time between the end of the *RTS* packet and the beginning of the *CTS* packet. Figure 1 shows the difference between S-MAC and T-MAC protocols. T-MAC provides a better throughput than S-MAC under variable traffic. When the traffic load is heavy, the throughput of T-MAC performs more efficiently than S-MAC. However, both the throughputs of S-MAC and T-MAC are influenced by packet collisions. Thus, an efficient collision avoidance method is needed to decrease the waste of battery energy of sensor nodes and to improve the overall network performance.

P-MAC [8] is a time-slotted and pattern-based scheduling protocol. Each sensor node determines its sleep/wake-up schedule based on its own traffic and the traffic patterns of its neighbors. In P-MAC, time is divided into super time frames (STF) which have two sub-frames: PRTF and PETF. PRTF is a data transmission sub-frame. Each sensor node decides to stay awake for transmitting and receiving data or going to sleep for saving energy based upon the patterns of its neighboring nodes. In the PETF sub-frame, nodes exchange their traffic patterns with their neighbors. The purpose of this pattern-exchange is to ensure that the schedules of the sensor nodes are adapted to the current traffic load. Although P-MAC can conserve energy by using the traffic-pattern information, it needs to spend extra energy and bandwidth to maintain the pattern information.

D-MAC [9] presents a continuous packet forwarding scheme along the data gathering tree to solve the data forwarding interruption problem. A node skews its wake-up schedule dt ahead of the schedule of the sink (d is the depth of the tree and t is the period of sending or receiving a packet). D-MAC staggers the active/sleep schedule of nodes in the data gathering tree. By allowing packets to be forwarded on the multi-hop path, D-MAC can decrease the transmission delay. D-MAC is a non-flexibility protocol. If the network topology is changing, all the nodes need to re-construct their active/sleep schedules. Another category of decentralized MAC protocol is the random-access based scheme. In this classification, nodes contend the channel “on-demand” without any schedule or synchronization. Wise-MAC, STEM, and B-MAC are examples of this category.

Wise-MAC [10] is an unslotted MAC protocol. Each node only maintains the sleep/wake-up times of its neighbors. When a sensor node has packets to send, the node will hold the data packets until the receiver is active. The node first sends the duration of the preamble to inform the receiver, then transmits the data and finally receives an ACK from the receiver. In Wise-MAC, each node will periodically wake up for a short interval. If there is no message from other nodes, the node will go to sleep to conserve energy. This is a simple and easy protocol for saving a node’s energy requirements, however, the transmission latency will increase.

STEM [11] is a two-radio architecture. One radio is for transmitting data and the other one is for waking up sensor nodes. Sensor nodes can go to sleep until communication is desired. STEM can conserve energy but it requires a higher hardware cost for the two radio transmitters.

B-MAC [12] uses in-channel signaling to wake up the destination node. It operates by periodically listening to the channel for activity. Nodes will turn on their receivers if a channel is sensed to be busy, and they turn off after a data packet is received or after a certain time out. While transmitting, a sender will send a long preamble time period to inform the destination to receive a data packet. However, a receiver needs to wake up first and listen to the channel until a data packet is received. Thus, the receiver spends time on idle listening which results in the wasting of energy.

In the literature, many MAC protocols use a periodic sleep/wake-up schedule technique to reduce energy waste from idle listening and overhearing. However, collision problems occur if the convergecast [13] routing (many-to-one) or many-to-many communication is not well-solved. If there are many senders who want to all transmit data to a destination simultaneously in its active interval, then these senders must share the same communication channel with each other. Most of these MAC protocols use the CSMA/CA and RTS/CTS scheme to reduce the effect of collision. However, if the traffic load is heavy, the collision rate is high. This situation wastes the energy of the sensor nodes. Therefore, we propose a novel MAC protocol to conserve energy and at the same time improve the network throughput. The details of this protocol are described in the next section.

3 ESR-MAC Protocol Design

As mentioned previously, the goal of our protocol is to reduce the collision problem and to improve throughput without reducing the energy efficiency. Many researches indicated that the most significant source of energy waste is idle listening. In order to decrease energy waste from idle listening, nodes will periodically wake up and listen to the channel. If nodes have packets to send, they have to share the time slot with other competitors. Although some protocols present CSMA/CA-liked schemes to lessen the effect from this congestion, the probability of a collision taking place will still increase during periods of heavy traffic. However, traffic density may vary both in time and location for different applications. When we look at a data gathering tree, the traffic pattern is like a ripple spreading from the sink node. The closer to the sink, the heavier the traffic. Nodes need to report their sensed data and forward their data packet to other nodes. As a result the region near the sink node becomes a traffic bottleneck and results in a significant amount of collisions. Previous sleep/wake up MAC protocols could not solve this contention and collision problem. Therefore, this contention problem will increase the delay and collision problem and at the same time waste a significant amount of energy. In this paper, we propose an Efficient Slot Reservation MAC (ESR-MAC) protocol which can reduce the number of nodes contending this contention slot. We present a slot reservation scheme that will lessen the effect from both contention and collision. ESR-MAC can decrease the transmission delay and improve throughput without reducing the energy efficiency.

3.1 Network and Application Assumptions

Sensor networks are composed of many small nodes which are deployed in an ad hoc manner, using a short range and multi-hop communication mechanisms. Nodes in the network are battery-operated and have no mobility. We implement a rough time synchronization scheme as per [14,15]. Nodes in WSNs do not need a high overhead for global synchronization. Each node only records its neighbors' sleep/wake-up times. The neighbors' time offset can be achieved by collecting the “hello” messages which are periodically broadcast by each node. With the neighbors’ time offset, senders can awaken and transmit data packets to receivers at the right time. Each node must also maintain its own sleep/wake-up schedule. When there is no data to be transmitted, sensor nodes can follow the sleep/wake-up schedule and turn the radio into sleep mode and save energy.

We used the surveillance or environment measurement as an example of applications. For such applications, nodes need to periodically report their collected data to a sink. However, no matter how fast the reporting rate, the application will cause contention and collision problems. This has a strong influence on our protocol design. The main idea of the ESR-MAC protocol is to reduce the waste of energy from collisions and to improve the overall network performance.

3.2 Slots Reservation Scheme

Our proposed protocol, ESR-MAC, is a rough slot-based scheme. We allow each node to transmit only one data packet per slot. A duty cycle consists of one contention slot, one control slot, and at most n reservation slots. For a sensor node, the duty cycle is determined at the initial state and equals to $(1+1+n)$ slots. However, different nodes can have a different number of reservation slots n. In the ESR-MAC protocol, nodes periodically wake up at a contention slot in order to receive data packets. Sensor nodes contend the contention slot with each other. In order to avoid collisions, the CSMA/CA-like protocol is used. If a node misses or fails to access the contention slot, it needs to wait until next duty cycle. If it obtains access to the contention slot, it can then successfully transmit a data packet in the contention slot. In our protocol, we permit the node (winner of accessing the contention slot) to piggyback a reservation bit in the data frame to notify that it still has data to transmit or not in the next duty cycle. Consequently, the receiver can schedule the reservation slot according to the reservation bit in the data frame. The schedule will then be broadcast at the control slot to all the neighbors. This process guarantees that nodes that are listed in the schedule can transmit data at the reservation slot in the next duty cycle. This method reduces the number of nodes at the contention slot and decreases the collision probability. If the reservation slots are not reserved for any senders, then the node turns the radio into sleep mode to save energy and wakes up until the next cycle.

The framework of ESR-MAC is shown in Fig. 2. There may be no reservation slots when the traffic is light or there may be no sleep slots if the traffic is heavy. According to the specification of MICAz [4], we can precisely calculate the length of the contention, control, and

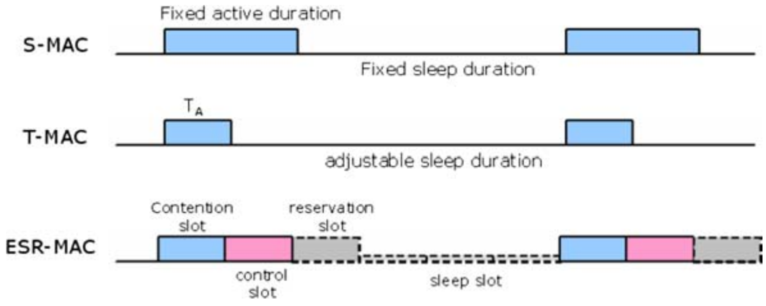
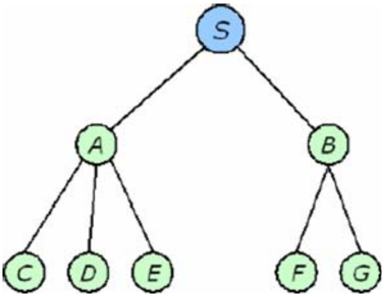


Fig. 2 The framework of S-MAC, T-MAC and ESR-MAC protocols

Fig. 3 An example data gathering tree



reservation slots. For the contention slot, a random back-off process is first operated in order to avoid collision. Then, the winner of contenders can transmit data packets immediately. The length of the contention slot includes a random back-off period and a data transmission period. One unit of CSMA back-off period is equal to 0.32 ms, and the maximum contention window size is set to 2^k where k is an integer. Therefore, the length of a random back-off period is 2.56 ms if $k = 3 (0.32\,\text{ms} \times 2^k)$. Because the data rate of a CC2420 radio chip is 250 kbps, the data transmission period is 1.408 ms if the packet size is 44 bytes (44 bytes × 8/250 ms). Thus, the length of a contention slot is 3.968 ms with a fixed contention window size of 8, and a maximum packet size of 44 bytes, in a MICAz device. For a control slot, the first two bytes are used for synchronization and the next $2n$ bytes are the schedule list which indicates the access right of n reservation slots at the next duty cycle (size of node ID is 2 bytes). So, the length of a control slot is $2(1 + n) \times 8/250$ ms. If $n = 10$, the length of a control slot is 0.704 ms. For the reservation slots, the sensor nodes that were listed in the broadcast schedule can transmit data packets in sequence. Because the reservation scheme is a collision free method, senders can transmit data packets directly without a random back-off mechanism. The length of a reservation slot is 1.408 ms. Thus, a duty cycle of a node is equal to 3.968 ms + 0.704 ms + 14.08 ms = 18.752 ms, where $CW = 8$, the packet size = 44 bytes, and $n = 10$.

In our slot reservation scheme, if there is no traffic in the network, then nodes must wake up at the contention slot for receiving a data packet and at the control slot for broadcasting the schedule of the reservation slots. Contrary to S-MAC and T-MAC, our protocol is a slotted MAC protocol. Nodes can handle their traffic more efficiently based on the slotted architecture. With the time slotted architecture, receiver can reserve slots to the senders and perform a collision free transmission. Therefore, our protocol can improve the network throughput and reduce transmission delays without impacting on the conservation of energy.

In the following, we will present an example of our proposed slots reservation scheme. As shown in Fig. 3, a data gathering tree is already constructed and all the nodes will periodically report their sensing data to sink node S.

First, each node determines its active/sleep schedule and exchanges its schedule information with its neighbors. After collecting its neighbors' active/sleep schedules, each node begins its scheduled duty cycle. If the contention slot period of a node overlaps with the contention slot period of its parent, it may decrease the performance of our ESR-MAC. For example, assume the contention slot period of node A overlaps with its parent node S in Fig. 3. Node A cannot receive data packets from node C, D, or E at its own contention slot if it tries to transmit data packets to node S during its contention slot. To reduce this conflict, a node cannot determine its active/sleep schedule until it receives the active/sleep schedule from its parent. Thus, each node can choose a proper active/sleep schedule such that its control slot period does not overlap with that of its parent. Since a node has only one transceiver, we

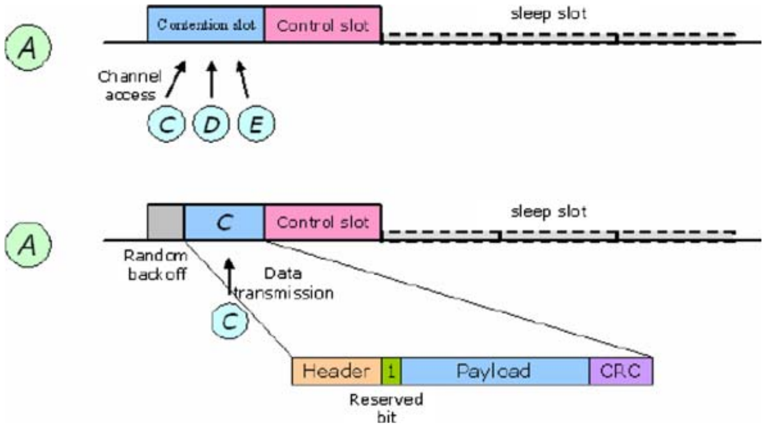


Fig. 4 An example of ESR-MAC protocols

assume that packet sending has a higher priority than packet receiving. This assumption is considered about the validity of a packet.

In this example, node A must handle its own traffic pattern and forward three data packets from its children to sink node S. First, we discuss the receiving part of node A. Node A wakes up at its contention slot and its three children, C, D, and E, will contend with each other at this slot. A random back-off scheme is used to avoid collision. Assuming that node C wins the access to the contention slot, then it will transmit data to node A. We assume that nodes always have packets to send in the next duty cycle, so the reserved bit in the data frame is set to 1 as shown in Fig. 4.

While receiving a packet, node A will preserve a reservation slot to node C for the next transmission. In the first run, there are no reservation slots in node A's schedule, instead there are sleep slots to save more energy, as shown in Fig. 5a. Nodes D and E fail to contend the slot, so they need to contend for being able to transmit in the next run. After the sleeping slots, node A wakes up at its contention slot again. This time only nodes D and E participate in the contention process. We assume that node E wins this contention. Node E transmits a data packet at the contention slot and its reserved bit in the data frame is set to 1. In the control slot, node A will broadcast a message to notify the scheduled list of the reservation slots. The information in this message contains a reservation slot for node C. In this duty cycle, node C will transmit at the reservation slot which was preserved in the last cycle, and the reserved bit in the data frame is still set to 1 to reserve for the next transmission, as shown in Fig. 5b. In the third run, only node D will contend the contention slot. After the contention slot, node A broadcasts its reservation schedule to its neighbors. Nodes C and E are included in the schedule. Then, nodes C and E will transmit at the reservation slots as shown in Fig. 5c.

Next, we describe the transmission scenario of node A. Node A needs to forward the packets of its children and its own data to sink node S. Node A will wake up while node S's contention slot is coming up and it contends the slot with node B. During the time at the contention slot, node A operates a random back-off scheme to access the contention channel. If it wins the channel, it can immediately transmit a data packet, otherwise it contends the channel in the next duty cycle. The proposed protocol is summarized as follows.

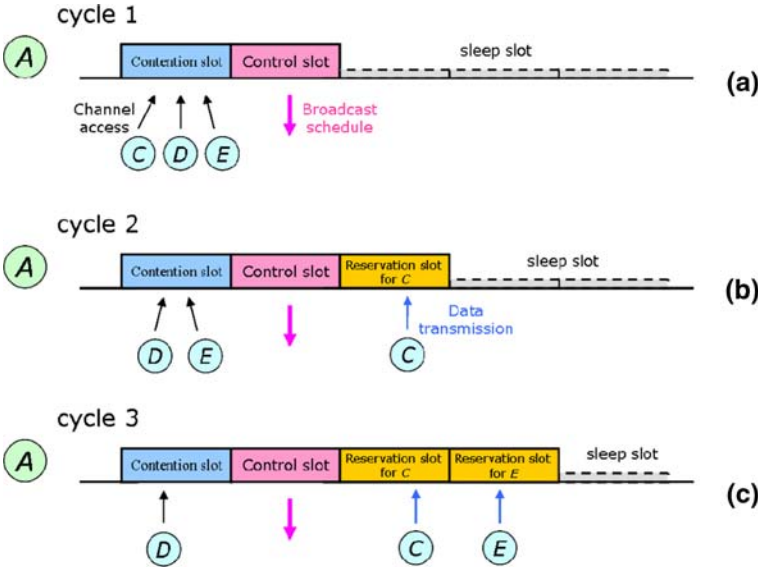


Fig. 5 The sleep/wake up schedule of node A

ESR-MAC Protocol:

Initial:

Each node determines its own duty cycle and broadcasts it to its neighbors if it receives the active/sleep schedule from its parent.

Begin:

(1) When a node has packets to send it waits until the receiver's contention slot has arrived. Then, the node contends the slot with other senders. If a node has more than one packet to transmit to the receiver, it will set the reservation bit in the data frame to preserve a reservation slot in the next duty cycle of the receiver. If a node is listed in the schedule list of a receiver, then that node will transmit its data packet in the indicated reservation slot.

(2) When a node has no data to send, it will execute its own active/sleep schedule as follows.

In the contention slot: Listen to the channel and receive data packets.

In the control slot: The node broadcasts its time for time synchronization. According to the reservation bit, a node preserves the reservation slots to the senders and broadcasts the scheduled list to inform the senders.

In the reservation slot: If the reservation slot is reserved by the senders, the node wakes up to receive data packets, otherwise it goes into sleep mode in order to save energy.

In the sleeping slot: The node turns off the radio in order to save energy.

4 Simulation Results

In our simulations, we compare the performance of our proposed protocol with two schedule-based MAC protocols S-MAC and T-MAC. We use GloMoSim [16], a network simulator, to simulate the nodes' behavior for each MAC protocol. We present two network topologies for investigating the performance among the three protocols. The first scenario is a single-hop

Table 1 The energy consumption defined by the CC2420 radio chip

Term	Description	Unit	Value
Packet (Data)	Size of a data packet	byte	44
Packet (RTSorCTS)	Size of RTS or CTS control packets	byte	17
Packet (ACK)	Size of an acknowledge packet	byte	11
Power (Rx)	Power required for receiving a packet	mW	62.1
Power (Tx)	Power required for transmitting a packet	mW	28.1 (−25 dbm) 57.4 (0 dbm)
Power (idle)	Power required for idle listening	mW	62.1
Power (sleep)	Power required for sleep mode	mW	1.41
Tx_{rate}	Transmit bit rate	bps	250

network environment in which s senders report their sensed data to the sink periodically. This case displays the affect of the traffic bottleneck. In the second scenario we place 100 nodes in a 100 m × 100 m 2-dimensional area in a random distribution with a transmission range set to 20 m. In this network, there is a sink node, and all the sensor nodes will report data to the sink node. Since the nodes have no mobility, we chose the *Bellman-ford* algorithm [17] as the routing protocol and a CSMA-like scheme is used to avoid collision in the simulation. Each simulation lasts 1000 s and each result is obtained from the average of 100 simulation results. The type of traffic loads are CBR and set to 1, 10, 20, 30, 40 and 50 packets per second. As a result, the energy consumption of a sensor node includes receiving, transmitting, idle listening and sleeping states. Table 1 lists the constants and variables, respectively, for the calculation of the energy consumption in the radio chip of the CC2420 data sheet [4] and the documents of Mica Mote [5].

4.1 Single-hop Network Environment

In this subsection, three performance metrics are investigated. The successful rate is defined as the total received packets over the total transmitted packets. The energy consumption means the average energy consumption among sensor nodes. The throughput is defined as the total number of bits received per second at the sink node. First, we increase the number of senders and the traffic load to demonstrate the impact on the collision rates and the success rates. In our ESR-MAC protocol, we set a fixed contention window size, $CW = 8$, and the maximum number of reservation slots, $n = 10$. Then the maximum duty cycle of a node is 18.752 ms. For a fair comparison, we set the same length of duty cycles for both S-MAC and T-MAC protocols. In addition, we take S-MAC with 50% active period as the competition and the value of T_A in T-MAC is set to 4.658 ms [7].

Figures 6 and 7 show the simulation results of the success rate of S-MAC, T-MAC, and ESR-MAC protocols in different density environments. The results show that while the number of senders, s, increases from 5 to 20, the collision probability increases for both protocols. For the traffic load, the success rate decreases as the traffic load increases. Both the S-MAC and T-MAC protocols were operated with a CSMA-like scheme. The only difference between these two protocols is that T-MAC uses a short duration T_A to reduce the effect of idle listening. This process can save more energy but cannot reduce the collision probability if the number of senders is increased or if the traffic load becomes heavy. Consequently, T-MAC provides a higher success rate than S-MAC because T-MAC can adjust its nodes' active period dynamically to receive more packets when the traffic is heavy. In our simulations,

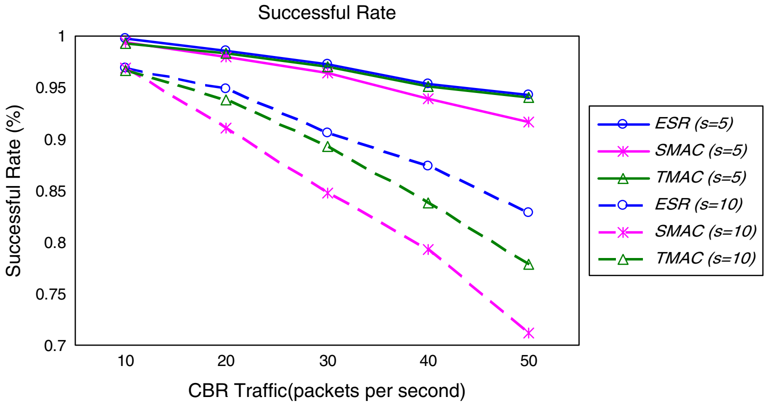


Fig. 6 The success rate of the S-MAC, T-MAC, and ESR-MAC protocols with $s = 5$ and $s = 10$

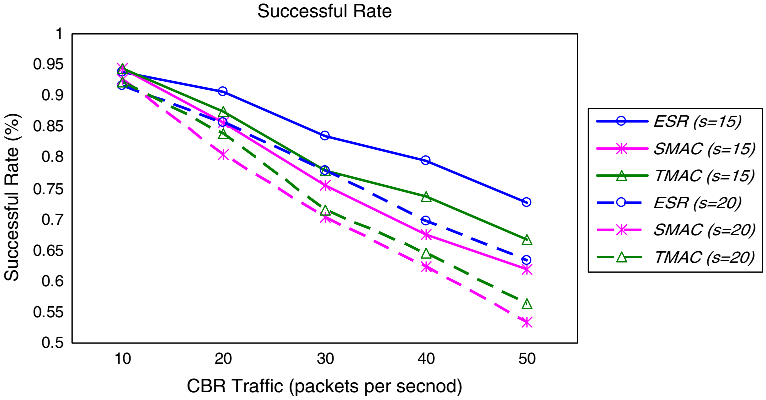


Fig. 7 The success rate of the S-MAC, T-MAC and ESR-MAC protocols with $s = 15$ and $s = 20$

the worst success rates of S-MAC and T-MAC are 53.34% and 62.69% when the number of senders is 20 and the traffic load is 50 packets per second.

As the number of senders is equal to 5, both the ESR-MAC and T-MAC have the same successful rate. When the traffic load is heavy or when the number of senders is increased, the ESR-MAC protocol has a better successful rate than the S-MAC and T-MAC protocols. Our reservation scheme can reduce the quantity of the contenders and consequently decrease the collision rate. Although the reservation slots are used to avoid collision during free transmission, collisions still happen at the contention slots. Therefore, the successful rate of our protocol decreases when the traffic load becomes heavy or when the number of senders increases. The worst case scenario for the successful rate of our protocol is 70.59% when the number of senders is equal to 20 and the traffic load is 50 packets per second. This result is better than the S-MAC and T-MAC protocols.

In the following, we compare the energy consumption of the three protocols. The energy consumption of each node is the summation of energy consumptions of a node in transmission, receiving, idle, and sleeping modes. In our simulations, the result of S-MAC is affected by the ratio of the active/sleep periods. The longer the sleep period is, the larger the energy saving. In Figs. 8 and 9, the energy consumption of the S-MAC protocol is not

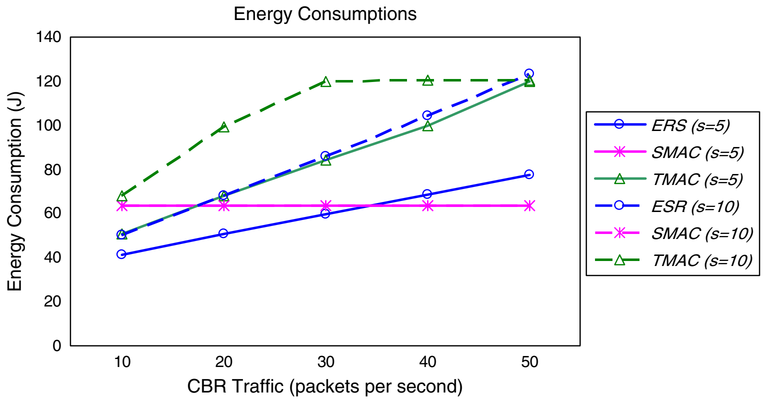


Fig. 8 The energy consumption of the S-MAC, T-MAC, and ESR-MAC protocols with $s = 5$ and $s = 10$

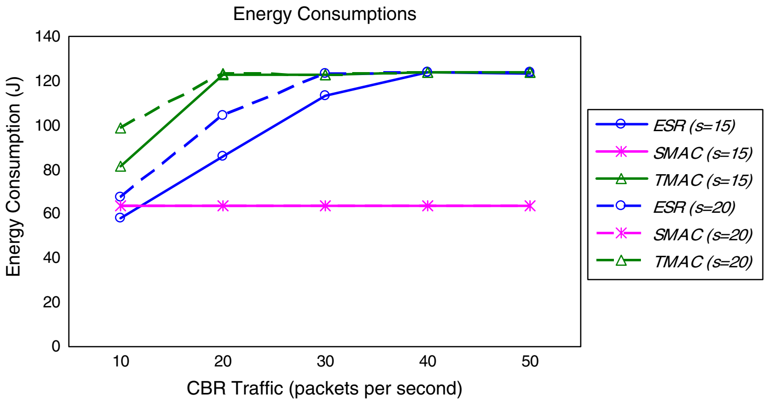


Fig. 9 The energy consumption of the S-MAC, T-MAC, and ESR-MAC protocols with $s = 15$ and $s = 20$

affected by the traffic or by the number of senders. The results remain stable because of the fixed active/sleep periods. Nodes wake up to receive during their active period and go into sleep during their sleep period. Although no traffic might have arrived, nodes still wake up to listen to the channel. This idle listening wastes energy and does not improve the network throughput.

T-MAC can dynamically adjust the active/sleep periods. As a result, the throughput of T-MAC is better than that of S-MAC. But, the energy consumption of T-MAC increases when the traffic becomes heavy or the number of senders increases. The energy consumption of our ESR-MAC protocol also increases in the same scenario. In Figs. 8 and 9, the energy consumptions increase if the traffic load becomes heavy. However, ESR-MAC has better energy consumption than T-MAC. ESR-MAC uses the reservation scheme to cope with the heavy traffic or the increase in senders. The reservation slots of the ESR-MAC protocol can efficiently reduce the number of contenders, thereby decreasing the collision probability. In addition, the reservation scheme provides collision free slots, guaranteeing data transmission and improving throughput. An investigation of the T-MAC protocol shows that the energy consumption of T-MAC rapidly achieves saturation when the number of senders equals to 20. The increase in contenders leads to a high collision rate, with the result that nodes cannot

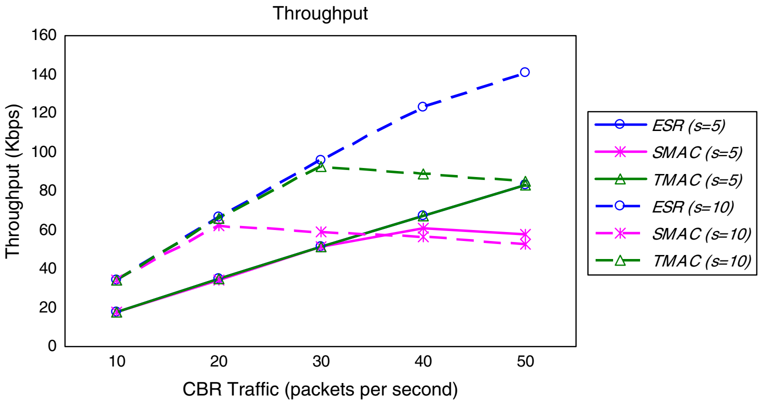


Fig. 10 The throughput of the S-MAC, T-MAC, and ESR-MAC protocols with $s = 5$ and $s = 10$

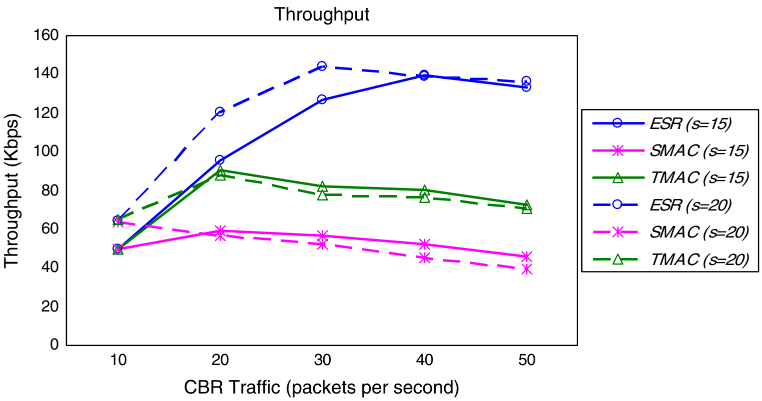


Fig. 11 The throughput of the S-MAC, T-MAC and ESR-MAC protocols with $s = 15$ and $s = 20$

correctly and reliably receive data packets and waste energy when they receive error packets. Moreover, a heavy-traffic load and a large number of senders makes that T-MAC cannot enter the sleeping mode to save energy. Therefore, T-MAC cannot improve the collision problem when the traffic is heavy or when the number of senders is large.

In the following simulations, we show the throughput of S-MAC, T-MAC, and ESR-MAC in Figs. 10 and 11, respectively. Because of the similar successful rates of ESR-MAC and T-MAC protocols, ESR-MAC also shows the similar throughput as T-MAC protocol if the number of senders is equal to 5. When the traffic load is heavy or when the number of senders is increased, ESR-MAC has a higher throughput than S-MAC and T-MAC. Because of the reservation scheme, ESR-MAC can handle the traffic-bottleneck problem and can support a high network throughput. The throughput of ESR-MAC depends on the length of the reservation slots. In the light-traffic scenario, the reservation slots will become sleep slots. However, the sensor nodes that lose at the contention slot must spend more time to access the channel at the next contention slot. In the heavy-traffic pattern, we will reserve more reservation slots than under a light-traffic load and can thereby improve the network throughput.

4.2 The Multi-hop Network Environment

In a multi-hop network environment, all the nodes periodically report data to the designated sink node. One hundred sensor nodes with 20 meters of transmission range and a sink node are randomly deployed in an area 100 meters square. We consider two performance metrics: the transmission delay which means the average transmission delay per hop and the energy utilization which is defined as the average energy cost per byte.

The simulation of the transmission delay is shown in Fig. 12. The transmission delay is defined as the duration of the attempts by a node to transmit a packet until the packet successfully reaches to the receiver. The average transmission delay increases with the increase of the traffic load of the three MAC protocols. Since S-MAC has a longer active period than T-MAC and ESR-MAC, the senders have a higher probability to transmit packets immediately. As a result, S-MAC has the best performance in a light-traffic environment. With T-MAC, light traffic results in receivers quickly entering the sleep mode after a duration T_A. This results in the transmission delay of T-MAC being longer than that of S-MAC under a light-traffic load. In ESR-MAC, if the traffic load is light, we have small reservation slots with a sleeping period that is longer than the active period. So, the waiting time of the ESR-MAC protocol is longer than that of the S-MAC protocol. However, our ESR-MAC protocol provides a reservation scheme to reduce the collision probability and to improve the transmission delay of continuous data packets. Therefore, the transmission delay of ESR-MAC increases only slightly as the traffic load increases. In S-MAC, the fixed active/sleep periods have a poor performance in heavy traffic. The transmission delay of S-MAC increases when the traffic load increases. Although T-MAC proposed a dynamic active/sleep periods that adapts to the traffic variation, serious collisions remain and still lead to longer transmission delays. The average transmission delays of S-MAC, T-MAC and ESR-MAC are 4.6, 9.2 and 9.1 ms, respectively at light-traffic load (10 packets per second). However, the average transmission delays of S-MAC, T-MAC and ESR-MAC are 35.9 ms, 32 ms and 18.6 ms, respectively, in heavy-traffic load (40 packets per second).

Figure 13 shows the results of the transmission delay by hop count. We simulate both light-traffic and heavy-traffic scenarios denoted as ESR-10 and ESR-40, respectively. The delay time increases with the increase in the hop count. S-MAC has the lowest transmission delay in a light-traffic environment. A longer active period makes the S-MAC transmission

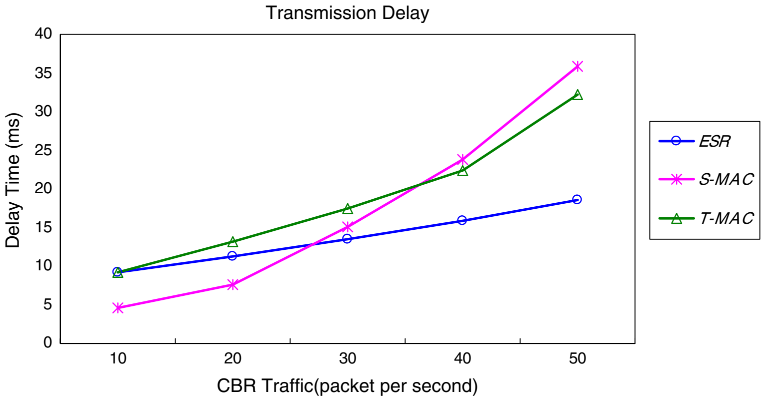


Fig. 12 Te average transmission delay per hop

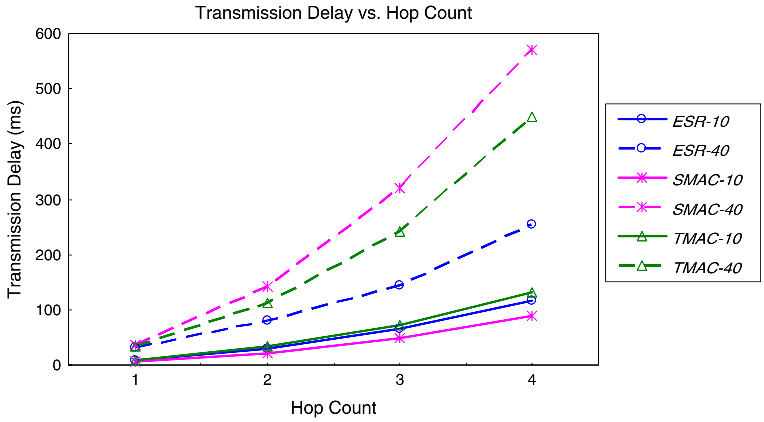


Fig. 13 The relationship between transmission delay and hop count

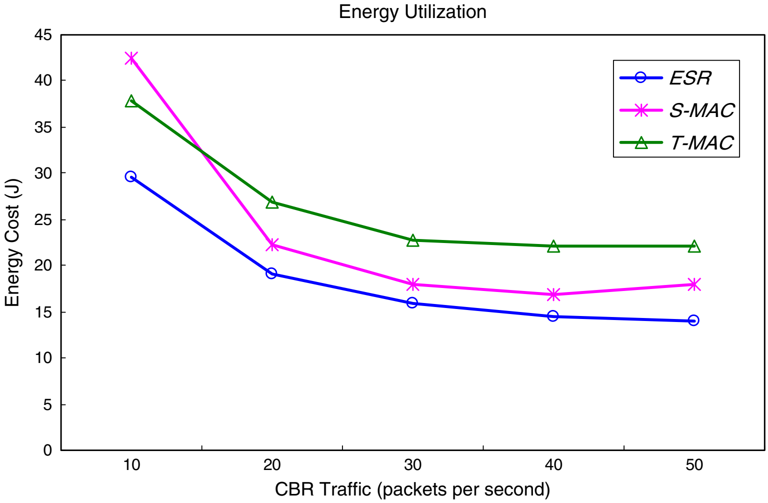


Fig. 14 The average energy consumptions

faster, but it costs more energy for each packet transmission. Under heavy-traffic load, the ESR-MAC protocol can reserve slots for continuous transmissions. As a result, the delay time of ESR-MAC increases only slowly with the increase in traffic load. The transmission delays under light-traffic load with four hops are 88 ms for S-MAC, 132 ms for T-MAC, and 117 ms for ESR-MAC, respectively. Under heavy-traffic load with the same hop count, the delay times of S-MAC, T-MAC, and ESR-MAC are 571 ms, 449 ms and 255 ms, respectively.

Here, we show the total energy utilization of the S-MAC, T-MAC, and ESR-MAC protocols. In our simulation, each node periodically reports its sensing data to the sink node. While sink node successfully receives 50,000 packets, we terminate the simulation and calculate the total energy consumption of the network. In Fig. 14, all protocols have the worst energy utilization under light-traffic loads because most of the energy is wasted in idle listening. Since ESR-MAC and T-MAC can save energy by turning off the radio if there is no traffic, their energy costs are better than that of S-MAC. When the traffic load is greater than 30 packets per second, both the S-MAC and T-MAC protocols reduce their energy utilization since high collision rates reduce their throughputs. However, our ESR-MAC is not affected by the increasing in traffic load because our protocol allows senders to transmit continuous packets at the reservation slots. Therefore, our ESR-MAC protocol has the lowest energy consumption since the reservation scheme allows for a more efficient packets transmission than the S-MAC and T-MAC protocols.

5 Conclusion

This paper presents a novel MAC protocol for WSNs. Our protocol combines contention-based, scheduling-based, and reserving-based schemes to achieve energy efficiency, improve network throughput, and decrease collision probability. Based on the reservation bit in the data packet, sensor nodes can preserve collision free slots for continuous transmissions. Therefore, the ESR-MAC protocol is an efficient method for managing the battery energy for sensor nodes. When traffic is light, ESR-MAC can save additional energy by switching the radio to sleeping mode. In a heavy-traffic scenario, our proposed protocol can reserve collision free slots for continuous transmissions. Thus, collision probability is decreased and network throughput is improved.

In the single-hop simulation, ESR-MAC has a higher success rate and a higher throughput than either S-MAC or T-MAC. In the multi-hop environment, S-MAC has a shorter transmission delay than T-MAC and ESR-MAC under a light-traffic load scenario. When the traffic load is higher than 30 packets per second, ESR-MAC has the smaller transmission delay compared to S-MAC and T-MAC. The transmission delay increases as the hop count increases. S-MAC has the lowest transmission delay at light-traffic load and ESR-MAC has the lowest delay under a heavy-traffic load. The simulation results also show that the proposed ESR-MAC protocol has lower energy consumption than the S-MAC and T-MAC protocols. To conclude the simulation results, the ESR-MAC protocol provides a higher throughput and has lower energy consumption compared to the S-MAC and T-MAC protocols.

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