A Random Backoff Algorithm for Wireless Sensor Networks

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Abstract. Medium Access Control (MAC) protocols employ a backoff algorithm to resolve contention among nodes to acquire channel access. It is desirable to design the backoff algorithm so that the node with lots of remaining energy has a high probability to win in channel contention since the network lifetime can be prolonged by balancing energy consumption over the wireless sensor network. However, most MAC protocols designed for wireless sensor networks have fixed contention period regardless of residual energy, which gives every node the same opportunity to win in the competition. In this paper, we propose a backoff algorithm for wireless MAC which uses dynamic contention period based on the amount of residual energy at each node. Simulation results show that our scheme achieves more power saving and a longer lifetime comparing with the conventional backoff algorithms.

1 Introduction

Wireless sensor networking is one of the most essential technologies for implementation of ubiquitous computing. Sensor networks will be applied in variant environments, i.e. health care, military, warehousing, and transportation management. The sensor nodes are usually scatted in a sensor field and data are routed back to the sink by multi-hop. These sensor networks usually share the same communication channel. Sensor nodes have limited in power, computational capacities, memory and short-range radio communication ability. The limited battery life of sensor nodes raises the efficient energy consumption as a key issue in wireless sensor networks. There are four major sources of energy waste; collision, overhearing, control packet overhead and idle listening. Collision of transmitted packets increases energy consumption due to the follow-on retransmissions. Overhearing also spends unnecessary power since a node picks up packets that are destined to other nodes. Sending and receiving control packets consumes energy too. Idle listening meaninglessly consumes battery power by listening to receive possible traffic that is not sent [1].

MAC protocols support nodes to access the communication channels in the networks. Traditional MAC protocols focus on improving fairness, latency, bandwidth utilization

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and throughput. But, MAC design for wireless sensor networks additional requires energy efficiency as one of its primary concerns due to the specific energy constrained environment. MAC protocols for wireless sensor networks should try to reduce the energy wastage while allocating shared medium among sensor nodes and prevent nodes from transmitting at the same time [2][3]. We focus on the energy efficient MAC protocols for wireless sensor networks.

MAC protocols employ a backoff algorithm to resolve contention among nodes to acquire channel access. The backoff algorithm uniformly chooses a random value from the range [0, CW], where CW is the contention window size. Every node has the same contention window for the backoff algorithm regardless of node status such as node's remaining power. So, the nodes with the low energy level can win in channel contention with the same probability as the nodes with much power. This may lead to the formation of hole in the network since the node with the low energy level can die quickly, which reduces network lifetime substantially [2].

In this paper, we propose a new backoff algorithm for MAC in wireless sensor networks that adaptively determines the contention period of sensor nodes based on their residual energy. The rest of the paper is organized as follows. In Section 2, we review some MAC protocols and backoff algorithm used in wireless sensor networks. In Section 3, our backoff algorithm is introduced in details. Section 4 contains the performance evaluation via simulations. Finally, Section 5 contains the conclusion.

2 Related Works

There have been several MAC protocols designed for wireless sensor networks. There are two categories of existing MAC protocol. The first category is a contention-based MAC protocols such as IEEE 802.11 [4]. The main problem of contention-based MAC is that they consume much energy by idle listening. The second category is a contention free MAC protocols such as TDMA. TDMA for wireless sensor networks has two problems that it does not support scalability and it needs centralized control of all nodes [5].

In this section, we briefly review some contention-based MAC protocols. Sensor-MAC (S-MAC) is probably most well known sensor MAC protocol for energy efficiency. It has the following characteristics. S-MAC frame consists of the sleep and the listen periods. S-MAC solves an idle listening problem by putting nodes into periodic sleep state. Each node sleeps for some time, and then wakes up and listens to detect if any other node wants to communicate to it. During sleeping, the nodes turn off radio, and set the wake up time according to the schedule. Before each sensor node starts its periodic listen and sleep, it needs to select a schedule and exchange it with its neighbor nodes. Each sensor node maintains a schedule table, which is composed of neighbor schedules. The schedule is updated periodically to maintain synchronization among the neighboring nodes by SYNK packets. The listen period is divided to receive SYNK packets and data packets [1][6]. The frame structure used in S-MAC is shown in Fig. 1.

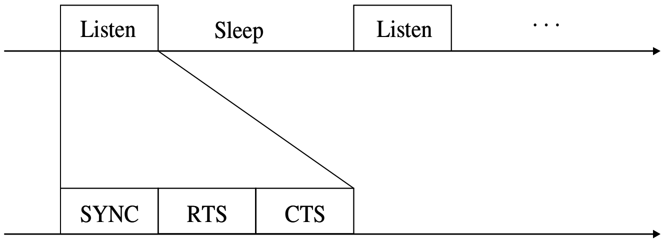

Fig. 1. Periodic listen and sleep of S-MAC

S-MAC can reduce the idle listening time, but it is not an optimal solution since it uses a fixed duty cycle. So, S-MAC still has the idle listening problem because sensor nodes waste their energy in active time while there is no traffic.

Several MAC protocols have been developed to resolve the problem of S-MAC. To maintain an optimal active time under variable traffic, Timeout-MAC (T-MAC) dynamically ends the active part when nodes are idle state for a time threshold TA. But T-MAC has a synchronization problem among nodes [7]. DMAC is proposed to achieve very low latency and energy efficiency. DMAC is designed to solve the interruption problem and allow continuous packet forwarding. DMAC adjusts the duty cycle adaptively based on their traffic load in the network [8]. Dynamic Sensor MAC (DSMAC) has been proposed to decrease the latency for delay-sensitive applications. DSMAC is able to dynamically determine the sleeping interval with fixed listen interval and one-hop latency values. Therefore, the duty cycle of sensor nodes is adjusted to adapt to the current traffic condition [3]. Pattern-MAC (PMAC) is proposed to save more power saving than the existing MAC protocols without compromising on the throughput. PMAC adaptively determines the sleep-wake up schedules for a node based on its own traffic, and the traffic patterns of its neighbors. In PMAC, a sensor node gets information about the activity in its neighborhood before exchange through patterns. Based on these patterns, sensor nodes can put itself into a long sleep for several time frames when there is no traffic in the network [9].

In all these contention-based MAC mentioned so far, every node randomly selects a time slot in the fixed contention window to finish its carrier sensing operation. If it has not detected any transmission by the end of that time, it wins the channel contention and acquires transmission opportunity. The channel access mechanism is shown in Fig. 2. The backoff counter is decreased by a slot time as long as the channel is sensed idle, while it is frozen when the channel is sensed busy. When the backoff counter reaches zero, the station starts its data frame transmission. Since every node has the same contention window for the backoff algorithm, it has the same opportunity to win in channel contention regardless of node status. For example, the nodes with the lower energy level can win in channel contention with the same probability as the nodes with much power. So, the node with the low energy level can die quickly. This may lead to the formation of hole in the network, thereby reducing network lifetime substantially [2][10].

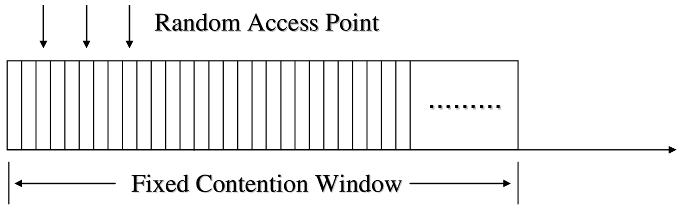

Fig. 2. Channel access scheme of a contention-based MAC protocol

3 Proposed Backoff Algorithm

In this paper, we propose a backoff algorithm where the contention window is dynamically adjusted based on the amount of remaining energy at each node. In our scheme, the nodes with lots of remaining energy have the higher probability to win in channel contention while the nodes with a little remaining energy have the lower probability to access the channel.

In other words, as the node consumes more energy, it is less likely to win in channel contention. Nodes are initially given the same contention window size (which determines the minimum backoff duration) to have the same opportunity to win in the channel competition. But, when a node consumes more and more energy as times goes on, its contention window becomes longer to have less probability of channel access. Fig. 3 shows the basic concept of our backoff algorithm that uses the contention window size to be determined depending on the remaining energy of each node.

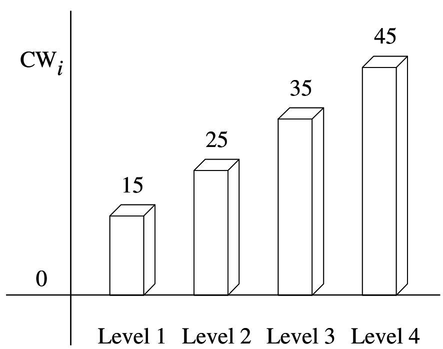

Fig. 3. Dynamic contention window in our backoff algorithm

In our algorithm, each node is categorized into 4 levels depending on its residual energy. Each node initially starts from level 1 where its contention window CW_1 size is given 15 as shown in Fig. 3. When the node consumes more than 25% of its initial energy, its category is changed to level 2 and its contention window size CW_2 is increased to 25. Similarly, if the node consumes more than 50% of its initial energy, its category is changed to level 3 and its contention window size CW_2 is again increased to 35. In this way, the contention window size becomes longer as the node consumes more power. The backoff time used by the node in the category i is given by

$$Backoff\ Time = Random\ (0, CW_i) \times aSlotTime \tag{1}$$

where aSlotTime means the time duration of a slot.

Table 1. Contention window size depending on the residual energy

Category	Percentage of residual energy relative to initial power	Contention window size (CW_i)
Level 1	$75\% < Residual\ energy \leq 100\%$	15
Level 2	$50\% < Residual\ energy \leq 75\%$	25
Level 3	$25\% < Residual\ energy \leq 50\%$	35
Level 4	$0\% < Residual\ energy \leq 25\%$	45

Our backoff algorithm makes all sensor nodes in the network consume their energies uniformly. Balancing the energy consumption among the nodes in the sensor networks avoids the early energy depletion of certain nodes. As a result, the network lifetime can be prolonged by preventing early network disconnection [11]. Note that the contention period should be determined properly considering that too long contention period may cause the idle listening problem. The pseudo-code of proposed algorithm is as follows:

[Channel Access Mechanism]

$CW_{\min} = 15$

Determine CW size based on the amount of residual energy at each node:

$CW_i = CW_{\min} + \Delta CW(E_{level} - 1)$; ΔCW : *Increment of CW size*

; E_{level} : *Energy level* (1, 2, 3, 4)

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Choose a random value in [0, CW] at each node

// To acquire transmission opportunity

If (Channel is idle)

    Decrease the timer

    If (Timer is zero)

        Send data

Else

    Freeze the timer
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Fig. 4. The pseudo-code of proposed algorithm

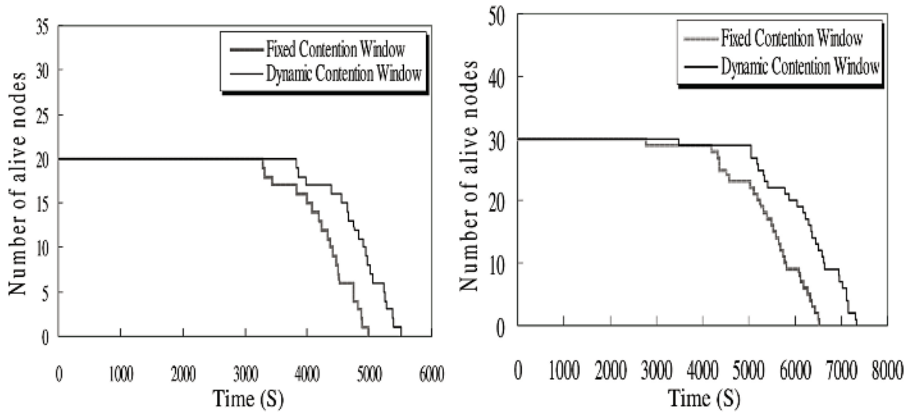
4 Simulations

We evaluate our backoff algorithm via simulation. We used the Digital wireless LAN module as the energy model where Idle:Rx:Tx ratio is 1:2:2.5 [12]. The sleeping energy consumption is set to 0 (it is usually ignored). Simulation parameters for performance evaluation are shown in Table 2.

Table 2. Parameters used in the simulations

Parameter	Value
Channel bandwidth	20 Kbps
Control packet length	10 bytes
Data packet length	200 bytes
Slot size	2 ms
Frame size	1000 ms
Transmit energy consumption	15 mW
Receive energy consumption	12 mW
Idle energy consumption	6 mW

In the simulation, we use constant bit rate (CBR) model with different time intervals. If the message inter-arrival period is 1 second, each node generates a message every 1 second. We measure the energy consumption at each source node working in different modes: transmitting, receiving and idle modes.



(a) Lifetime of network with 20 nodes (b) Lifetime of network with 30 nodes

Fig. 5. Number of alive nodes

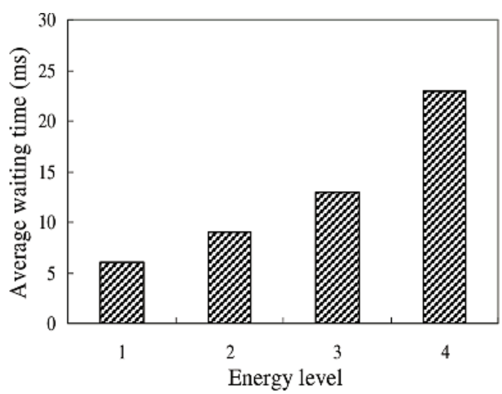
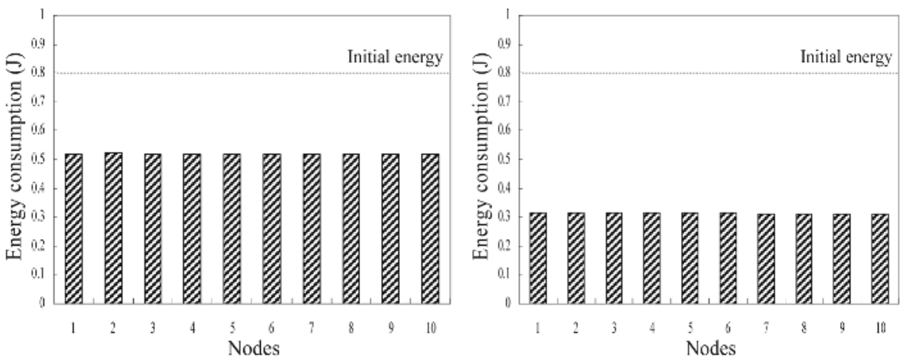


Fig. 6. The average waiting time to acquire channel access

The advantage of our backoff algorithm with dynamic contention window can be clearly seen in Fig. 5. Fig. 5 shows the number of alive nodes as time goes on. We observe the elapsed time until the first node (or the last node) fails due to dead batteries. In particular, time for first node to die is very important factor because it gives the time instant when the first node runs out of energy, which reflects the time for network partitioning [13][14]. From this figure, we can see that our backoff algorithm with dynamic contention windows extends the network lifetime comparing with the conventional one using a fixed contention window. This indicates that our scheme is more energy efficient than the conventional scheme. Energy efficiency of our scheme can be more apparently seen when the sensor network becomes large and it has more sensor nodes in the network.

Fig. 6 shows the average waiting time experienced by data packet until it acquires channel access from the time that it is generated. In this test, the 20 source nodes periodically generate data packets. We run simulation for a period of 3000 seconds. In this figure, it can be seen that the node which has more remaining energy has a shorter average waiting time which successfully satisfies the intention of our algorithm.



(a) Energy consumption after 1000 seconds (b) Energy consumption after 2000 seconds

Fig. 7. Energy consumption at each node

Fig. 7 shows how uniformly each node consumes its energy over the network. For test, all nodes are given the same initial power, and the consumed energy at each node is measured after some time (e.g. 1000 seconds or 2000 seconds). We can see that our backoff algorithm balances the energy consumption among the nodes in the sensor network. This indicates that our algorithm is more energy efficient than the conventional one since the early energy depletion of certain nodes is prevented, and thus the network lifetime can be extended by our algorithm.

Fig. 8 shows the average residual energy among nodes in the network. In this test, the 10 source nodes periodically generate data packets. For test, all nodes are given the same initial power by 1J, and the average of residual energy at all nodes is measured after 1000, 2000 and 3000 seconds. This result is also coincident with the assurance that our algorithm is more energy efficient than the conventional one.

Finally, we evaluate the data throughput of our backoff algorithm with different message inter-arrival times. In the test, the 10 source nodes periodically generate data packets. Simulations are carried out in single hop environments. We run our simulation for a period of 1000 seconds. Each node generates packets with some

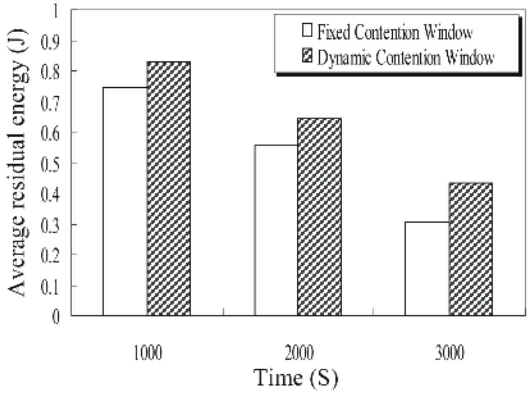


Fig. 8. Average residual energy

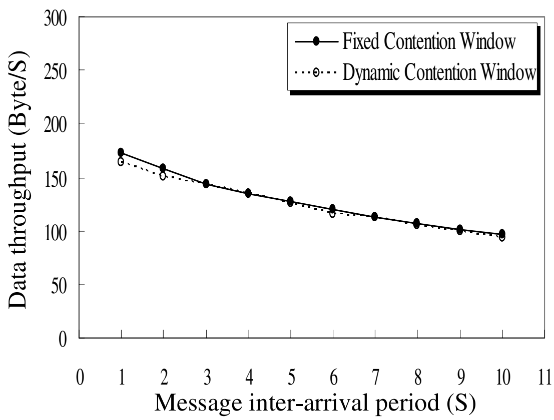


Fig. 9. Throughput under different traffic loads

payload (200 bytes) to be sent to their neighbor nodes via contention. Fig. 9 shows that our backoff algorithm with dynamic contention windows offers a similar data throughput to the conventional backoff which uses a fixed contention window. We cannot observe any significant difference in data throughput between them.

5 Conclusion

We have proposed a backoff algorithm in which each node adaptively determines its contention window size based on the amount of its residual energy. In the proposed backoff algorithm, as each node consumes more energy, it increases its contention window size to be less likely to win in channel contention. This can balance energy consumption among nodes to prolong network lifetime. Simulation results show that our scheme achieves a more power saving and a longer lifetime when compared with the conventional backoff algorithm.

Acknowledgement

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