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Abstract

Aiming at large-scale Wireless Sensor Network (WSN) whose main communication mode is broadcast, the main factors restricting access performance of contention-based Media Access Control (MAC) protocols were analyzed in this paper. Accordingly, a kind of adaptive probability Access mechanism was put forward, through which contention-based MAC protocols can transmit acknowledgement packet according to acknowledgement probability in the broadcast communication mode and adaptively adjust the acknowledgement probability on the basis of network status in the transmission window. Plentiful simulation results show that the MAC protocol based on the proposed adaptive probability acknowledgement mechanism has better access control performance and energy consumption performance.

1. Introduction

Wireless Sensor Network (WSN) is a kind of measuring and controlling network system consisting of a mass of ubiquitous tiny sensor nodes that have communication and computing capabilities, and a typical autonomous and intelligent system which can independently accomplish specific duties depending on the changing environment[1,2]. Compared with traditional network systems, WSN is featured with large-scale, random-deployment, multi-hop communication, self-organization, collaborative working, etc. These features ensure that WSN find a wild range of applications in sectors of military, industry, health care, home life, environment protection, etc.. WSN is involved with many research fields such as micro-electro-mechanical systems (MEMS), communication, automation, artificial intelligence and so on. However, the benefits that WSN will bring to our society are immeasurable. To be sure, WSN gives us a new set of challenges, including limited resources, complicated dynamic topology, and scalability, etc., all of which need to be addressed before we can get real benefits from it. Currently, WSN has won more and more attentions from researchers and governments of various countries, becoming a new R&D focus.

Medium access control (MAC) protocols have been developed to support nodes to access the communication channels in the network. MAC protocols are considered as the sub-layer on link layer which control how and when a node can access medium to communicate with the other nodes in the network. The MAC protocol is an important and difficult problem in WSN studies.

MAC protocols of WSN mainly include scheduling-based protocols (e.g., TDMA) and contention-based protocols (e.g., CSMA/CA). First, we look at the advantages of contention-based MAC protocols compared with scheduling-based protocols[3]. It is obvious that, with contention-based MAC protocols we do not need to schedule in advance, it is more dynamical and flexible to change. Contention-based MAC protocols allocate resource on-demand, if some nodes in the network have more traffic load than other nodes or so some regions have higher density than the others do, contention-based MAC protocols are easier to redistribute the network resource. On the other hand, we can say that contention-based MAC protocols are more scalable than scheduling-based protocols, especially when the network topologies change. There is no requirement to form communication clusters and peer-to-peer communication is supported directly. Contention-based MAC protocols do not need the time synchronization as in scheduling-based protocol.

All in all, the contention-based MAC protocols match the features of WSN, such as, large-scale, random-deployment, stochastic emergent communication and difficult global time synchronization. Consequently, the contention-based
MAC protocols have been used and studied widely and extendedly in WSN field. S-MAC [4], one of the famous energy efficient protocols in sensor network, is a contention-based random access protocol with a fixed listen/sleep cycle. It uses a coordinated sleeping mechanism, similar to the power saving mechanism of IEEE 802.11. Sift [5] is a contention-based MAC protocol proposed for event-driven sensor network environments. Sift is a contention slot assignment algorithm based on probability and can decrease latency considerably. WiseMAC protocol uses non-persistent CSMA (np-CSMA) with preamble sampling as in [6] to decrease idle listening. The two S-MAC variants, namely, T-MAC and DSMAC, have the same features as S-MAC. Timeout-MAC (T-MAC) [7] is proposed to enhance the poor results of the S-MAC protocol under variable traffic loads. Dynamic Sensor-MAC (DSMAC) [8] adds a dynamic duty-cycle feature to S-MAC. These MAC protocols make some contributions to energy efficiency, collision avoidance, throughput, latency, scalability and adaptation. Broadcast is the main communication mode of WSN. However, Broadcast data packets do not use any strategies in these MAC, which increases collision probability [9].

Therefore, the main factors restricting access performance of competition based MAC protocols were analyzed in this paper. And an adaptive probability access mechanism was proposed, through which competition based MAC protocols can transmit acknowledgement packet according to acknowledgement probability in the broadcast communication mode and adaptively adjust the acknowledgement probability on the basis of network status in the transmission window. Great deals of simulation experiments show that the proposed adaptive probability access mechanism can improve the protocol performance.

The remainder of the paper is organized as follows: Section II motivates the need for access mechanism for broadcast communication. Section III describes the proposed protocol in detail. Section IV presents our simulation experiments and analysis. We conclude the paper in Section V.

2. The motivation for probability access mechanism

Most contention-based MAC protocols is based on CSMA/CA (Carrier Sense Multiple Access/Confliction Avoidance). With CSMA/CA protocol, one node must listen to the medium before transmitting data packets. On one hand, if the medium is idle and idle time is greater than certain value, this node can transmit the data packet. Before transmitting data packets, the node can use RTS/CTS (Request to Send/Clear to Send) messages to negotiate medium. RTS/CTS have been taken the advantages to solve the hidden terminal and exposed terminal problems and reduce the collision probability of data packets. On the other hand, if the medium becomes busy before the idle time of the medium reached certain value, the transmission will be deferred. And if the medium is still busy after deference the node execute the backoff process selecting random backoff time. The node can access wireless channel again after backoff process. Packet transmission process will probably fail because of multipath effect, wireless disturbance and etc. Destination node will transmit ACK packet to source node when it receives the data packet successfully. Otherwise, source node think last transmission failed and will retransmit the packet after backoff process. To reduce the collision probability, content window of backoff time will be multiplied by 2 each transmission fail. After around of successful and failed transmission, the node will perform the new access process if there are packets waiting in message queue.

Communication of WSN is event-triggered. Collective sensing of nodes in the event-happened area will cause the emergent collective broadcast. Therefore, communication collision is serious, accessing the media for nodes is very difficult, and a mass of data are lost. Analyses show that aiming at the typical communication mode of WSN, the contention-based MAC protocols have the following problems.

- RTS/CTS Mechanism: RTS/CTS mechanism is only adopted to solve hidden terminal and exposed terminal problems under unicast communication mode in most contention-based MAC protocols. Because RTS/CTS have increased the communication expenses, protocols usually use RTS/CTS mechanism only while transmitting long data packets. However, measuring and control data packets of WSN are very short. Therefore, the cost adopting RTS/CTS is high. In addition, RTS/CTS mechanism is not used in the broadcasting communication mode in most contention-based MAC protocols. And the main communication mode of WSN is broadcast. If there are nodes to transmit packets at the same time in the nodal sense range or disturbance range. Moreover, the greater collision time is, the less the chance of accessing channel for node is, resulting in serious data loss. This kind of situation often happens because of WSN special features, such as, large scale, high density, and emergent communication. Therefore, packet collision in the broadcast mode is the main problem for WSN protocols.
Receiving confirmation mechanism: Most contention-based MAC protocols adopt confirming mechanism of receiving packets to guarantee successful receiving of packets. However, it does not support transmitting ACK packet in broadcast communication mode.

Because of above problem, there are difficulties in implementing the basic access function in WSN. We tried to add RTS/CTS into the broadcasting mode. Simulation results indicated that conflicts of RTS/CTS packets had seriously increased extra burden of the network so that very little improved network performance resulted or, even worse. In addition, using Receiving confirmation mechanism of unicast mode in the broadcast mode, all destination nodes receiving data packet transmit ACK packet to the source node. This kind of corresponding MAC protocol is named BA MAC, which may cause explosion of ACK packets to influence system performance. The new mechanism guaranteeing reliable broadcast communication is necessary.

3. Adaptive probability access mechanism

This section puts forward an adaptive probability access mechanism for the contention-based MAC protocols based on above analyses in last section. In the broadcast communication mode, nodes receiving broadcast data packet determine whether to transmit acknowledgement packet and dynamically optimize the acknowledgement probability using adaptive adjustment mechanism. The MAC protocol based on this probability access mechanism is called p-BA MAC. The probability access mechanism can divided two steps, i.e., initialization of acknowledgement probability and adaptive adjustment of acknowledgement probability, and will in detail described in the following subsection.

3.1. Acknowledgement probability initialization

For description convenience, the following variants are defined.

- \( m \): \( m \) is the size of data packet transmission window, including the retransmission packet.
- \( A_i \): \( A_i \) is the count of received acknowledgement packet for the \( i \)th packet in one transmission window, \( i = 1, \ldots, m \).
- \( C_i \): \( C_i \) denotes whether the \( i \)th packet is a retransmission packet. If the packet is retransmission packet, \( C_i = 1 \), otherwise, \( C_i = 0 \).
- \( E_r \): the power dissipation that nodes transmit packet.

\[ E_r \] the power dissipation that nodes receive packet.

\[ P_i \] the probability of transmitting acknowledgement packet for node \( i \), its initial value is \( P_i^0 \).

\[ \beta \] the adjustment factor of acknowledgement probability, its initial value is 1.

Figure 1. Communication Model Between nodes

During the network initialization, each node computes the probability by which that neighbor nodes transmit ACK packet after receiving its broadcast packet. The detail process of computing acknowledgement probability is as follows.

As Figure 1 shows, suppose covering area of the wireless sensor network is a rectangle whose length and width is respectively \( l \) and \( w \), then we have \( n+1 \) nodes in the rectangle. The nodes are distributed uniformly. Radius of communication among the nodes is \( r \). Apparently, solution to node count within the communication radius for Node \( i(x, y) \) is a typical binomial distribution problem. According to the nature of binomial distribution, the neighbor count \( N_{ap} \) of Node \( i \) is depicted in (1).

\[
N_{ap} = n \times \frac{S_i}{l \times w} 
\]  

(1)

where \( S_i \) is the effective regional areas covered by Node \( i \).

Obviously, the ideal probability of transmitting ACK packet guarantees that only one neighbor transmit ACK packet. Accordingly, protocol not only guarantees the reliable transmission of broadcast packet, but also minimizes the increased network load. Then the initial probability transmitting ACK packet for neighbor nodes receiving the broadcast packet is defined as \( P_i^0 \).

\[
P_i^0 = \frac{1}{N_{ap}} 
\]  

(2)

During the period of network operation, transmitting nodes execute probability access mechanism according to the following steps.

- Each node calculates the probability of replying ACK packet of its neighbor nodes, i.e., \( P_i^p \), during
network initialization period. Set acknowledgement probability \( P_i = P_i^0 \).

- Node carries the \( P_i \) in data packet and requests its neighbor node receiving its packet to reply ACK packet when transmitting data packet in the broadcasting mode.

During the period of network operation, receiving nodes execute probability access mechanism according to the following steps.

- Node receiving the broadcast packet firstly generates a random number \( rnd \) in the interval \([0,1]\) with uniform distribution. Then, it compares the random number \( rnd \) and the acknowledgement probability \( P_i \). If \( rnd < P_i \), it will transmit ACK packet, otherwise, it won’t transmit ACK packet.

3.2. Acknowledgement probability adjustment based on window

Because the initial acknowledgement probability is a statistic value, it possibly dose not match the actual situation. Furthermore, with the network operation, some nodes will sleep, some nodes will failure, and some nodes will dissipate the energy. Therefore, the network topology will frequently change and the neighbor count of nodes will change. These factors will influence the performance of access mechanism. Obviously, protocols should support the adaptive adjustment of acknowledgement probability. A window-based adaptive adjustment mechanism of acknowledgement probability is put forward.

The adjustment of acknowledgement probability should obey the following rules. If there are too many data packets receiving multiple acknowledgement packets in a window, the acknowledgement probability should be decreased. If there are too many data packets not receiving acknowledgement packets in a window, the acknowledgement probability should be increased. So, the adjustment factor \( \beta \) is defined as followed.

- \( \beta \) is a random number in the interval \((1.0, 2.0]\) if \( \sum_{i=1}^{m} A_i - 1 > \sum_{i=1}^{m} C_i - 1 \times (e_i + e_i) \).
- \( \sum_{i=1}^{m} C_i - 1 \times e_i < \sum_{i=1}^{m} A_i - 1 \times (e_i + e_i) \) otherwise.
- \( \beta = 1.0 \) otherwise.

During the period of network operation, transmitting nodes execute the adaptive adjustment mechanism of acknowledgement probability according to the following steps.

- Set the acknowledgement probability as \( P_i = P_i \times \beta \) at the beginning of a transmission window.
- Memorize the transmission and acknowledgement situation into collection \( A_i \) and collection \( C_i \) in the transmission window.
- Recalculate the adjustment factor \( \beta \) according to above adjustment strategy at the end of the transmission window, and repeat above process.

4. Case study

4.1 Simulation setting and performance criteria

Simulation examples were studied in this section to show the performance and characteristics of the \( p \)-BA MAC protocol. In our simulation, FLOODING, SPIN and DD route algorithm were selected. And \( p \)-BA MAC protocol was compared with CSMA/CA and BA MAC.

![Figure 2. Performance criteria](image)

In each of our experiments, we study five different sensor fields, ranging from 50 to 250 nodes in increment of 50 nodes. Our node field generated by randomly placing the nodes is in a 100m by 100m square, which is divided into 5 by 5 regions. The radius of radio communication of 50-node network is 30m, 100-node is 20m, 150-node is 20m, 200-node is 15m and 250-node is 15m. Other simulation environment was set up as follows: propagation delay of radio being \( 3\times10^8 \)m/s, speed of radio communication, 1Mbps, this test network assumes no losses and no queuing delay, having data packet size of 64 byte, meta-data packet size of 16 byte, and interest packet size of 32, data generation cycle of 10s, initial energy of 20Jules, the transmission window size of 10 packets, 50mW of idle power dissipation, 395mW of receive power dissipation and 660mW of transmit power dissipation. The wireless sensor network is data-centered, or, in other words, not interested to single node, but to the data of a certain region or a certain geographical position. Therefore, the rectangle area that wireless
sensor network covers has to be divided into $n \times m$ regions as shown in Figure 2. Assume that one of nodes is Sink node, which is responsible for collecting the data of the specific region (i.e., source) in network. The following function and performance criteria were used to evaluate of algorithm performance:

- **Capability of performing tasks:** This criterion stands for whether the network can collect the expected data. Obviously, it reflects the execution quality of network functions and is foremost;
- **Convergence time:** Convergence time of network is defined as the time that Sink node spends collecting the data of the specific region, which reflects the average communication delay time of network;
- **Energy consumption:** This criterion is selected because saving energy is the key goal of WSN. It is represented by energy value that network convergence needs.

### 4.2. Simulation results

![Figure 3. Convergence Criteria](image)

Simulation results are shown in Figure 3 where convergence time and power dissipation comes from experiments performed 50 times. And “□” stands for performance of $p$-BA MAC protocol, “○” shows BA MAC performance, and “*” stands for CSMA/CA performance.

Figure 3(a), (b) and (c) respectively adopts FLOODING, SPIN and DD as route algorithm, where results of DD come from results before reinforcement. In terms of simulation results, CSMA/CA entirely can not work for FLOODING and SPIN. Although CSMA/CA has better convergence time and power dissipation than $p$-BA MAC protocol, these are about 60 percent of data and approximate 40 percent experiments can not collect data. In other words, CSMA/CA has great difficulties in perform tasks of WSN. On the side, $p$-BA MAC protocol is better than BA MAC protocol in all the experiments.
Simulation results show the p-BA MAC protocol is better than CSMA/CA and BA MAC not only in function but also in performance.

We test the average value $\overline{P}$ of acknowledgement probability. Figure 4 shows that $\overline{P}$ changes over time with SPIN route protocol. We can see $\overline{P}$ starts with the initial value. However, initial value is not optimal. After first transmission window, $\overline{P}$ changes evidently. As more working nodes die and neighbor node number decreases over time, $\overline{P}$ increases gradually.

![Figure 4. Average Acknowledgement Probability](image)

5. Conclusions

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In this paper, defects of contention-based MAC protocols used in WSN were summarized and a probability access mechanism was proposed. Simulation results show that the improved MAC protocol fits WSN and has better performance. At present, the research on WSN channel access technology is not mature and still is a research focus of WSN R&D work. Some WSN MAC algorithms/protocols based on contention add sleep mechanism, but don’t fundamentally solve these problems described in this paper. Therefore, our work focus is research of new MAC algorithms and protocols that will be more suitable for WSN in future.

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7. References