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Distance Adaptive Contention Window Mechanism for Wireless Sensor Networks

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Abstract: Recently, Wireless Sensor Network (WSN) is a fast growing technology, which collects various data for user and provides user with requested information in timely. A sensor network has a Many-to-One communication architecture which each sensor node transmits its sensed data to the sink node. However, most existing sensor network protocols do not consider Many-to-One paradigm and all sensor nodes access the channel with same probability. In this paper, we propose Distance Adaptive Contention Window (DACW) modified IEEE 802.15.4 standard. The key mechanism of DCAW is a dynamical channel access MAC protocol, which is to adjust Contention Window (CW) according to the hop count distance to sink and traffic condition. With DACW, each sensor node can achieve self-routing capability with low overhead and performance enhancement. Furthermore, DACW can be easily applied to existing routing protocols without additional overhead and shows that its performance is better than the existing MAC protocol by the simulation result.

1. Introduction

Recently, there are many network protocols for users with portable devices to access network resources easily, any time, anywhere, in a timely way. A Wireless Sensor Network (WSN) is the one of growing technologies. In sensor networks, sensor nodes are usually scattered and the position of sensor nodes needs not be predetermined. It means that WSN is a self-configuring network of tiny nodes connected by wireless links and communicates with a sink node. In addition, due to the use of wireless channel, WSN has limited bandwidth and limited battery power.

Devising an efficient protocol for sensor networks is a challenging issue and many protocols have been proposed. For example, in MAC layer, SMAC (Sensor MAC) [1], IEEE 802.15.4 [2] are such protocols to access wireless link. And AODV (Adhoc On demand Distance Vector Routing) [3], Directed Diffusion [4], ZigBee Alliance [5] are most representative protocols to support the network layer. Although these protocols suggest energy efficient and reliable packet delivery mechanisms, all sensor nodes try to access the channel with same probability. This means that channel access protocols do not consider Many-to-One communication architecture. If WSN has heavy data traffic, there is severe bottleneck in the sink node and its neighboring nodes, which leads frequent packet collision, long end-to-end delivery latency, poor delivery ratio and much control packet overhead related to reinitiating the route discovery procedure. In addition, the congested node consumes more energy to retransmit lots of packets, resulting in network partitions. Figure 1 shows an example network topology which represents the Many-to-One communication architecture. On the other hand, when WSN has low data traffic, additional backoff scheme to channel access is unnecessary, which results in energy waste in idle channel listening.

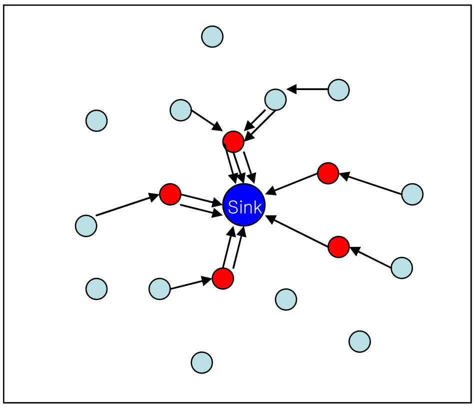

Figure 1. Many-to-One communication in WSNs

In this paper, we propose a new scheme, Distance Adaptive Contention Window (DACW), to enhance the throughput by dynamically tuning the contention window (CW) in the MAC layer. When there is heavy traffic in the network, DACW alleviates the congestion. And if there is low traffic, it reduces the contention time to transmit the packet promptly.

The rest of this paper is organized as follows. In Section 2, we review several MAC protocols and related works for WSNs. In Section 3, we illustrate the detail operation of our proposed scheme. And performance evaluation by simulations is presented in Section 4. Finally, concluding remarks are given in Section 5.

2. Related Works

2. 1 MAC layer protocols for WSNs

There have been several research efforts to exploit the MAC-level performance enhancement of MAC layer in WSNs. Existing MAC protocols for WSNs are classified to TDMA (Time Division Multiple Access) and contention driven protocols. In TDMA, the sink node assigns time slots to sensor nodes to be scheduled. When all nodes are synchronized, nodes can transmit their own packets by a

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round robin method, which achieves an efficient and fair channel access. However, this scheme has big overhead to synchronize with neighbors and has a problem of scalability such as a topology change.

The most representative example of contention based protocols is SMAC. The basic operation of SMAC is to divide the duty cycle into sleep and active period, which achieves low energy consumption, and reduces idle listening. In order to synchronize among neighboring nodes, SMAC use SYNC packet which includes sleep/active schedule information. When a node receives the SYNC packet, it adjusts its scheduling and turns off the radio for energy saving. After the end of the sleep period, it returns to active state and can transmit packets. In the active state, SMAC use RTS-CTS (Request to Send/Clear To Send) control packets for channel reservation. Then, by using CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance), it can transmit frames into the channel. The overall duty cycle of SMAC is shown in Figure 2.

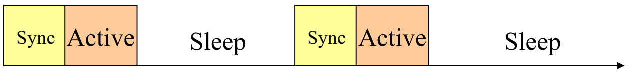

Figure 2. Periodic sleep and active in SMAC

Another example of MAC for WSNs is IEEE 802.15.4 which is a standard protocol for wireless personal area networks. It allows the use of a superframe structure which is defined by the coordinator. The superframe is bounded by beacon frames and is divided into 16 equally sized slots. The superframe is also consisted of active and inactive state. During the inactive state, the coordinator may enter a sleep mode. And the active state consists of Contention Access Period (CAP) and Contention Free Period (CFP). Any node wishing to transmit frames during the CAP should compete with neighbor nodes using the slotted CSMA/CA mechanism. On the other hand, the CFP assigns guaranteed time slots (GTSs). The GTSs locates in the end of the active superframe beginning at a slot boundary immediately following the CAP. By using GTSs, nodes can access the guaranteed channel without any contention. The superframe structure of the IEEE 802.15.4 is shown in Figure 3.

Both SMAC and IEEE 802.15.4 protocols are based on the contention access mechanism using CSMA/CA. Thus they use a random backoff scheme to acquire the channel, which can be easily implemented and guarantees long term fairness. However, both protocols do not offer dynamic backoff count according to the traffic condition or network environments. Moreover, in Many-to-One networks, they do not offer any solutions for traffic concentration on sink and neighbor nodes of sink.

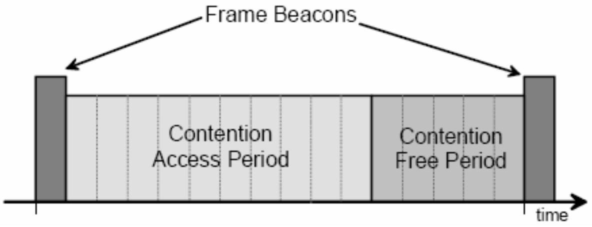

Figure 3. The superframe structure of IEEE 802.15.4

2. 2 Protocols with dynamic tuning of contention window

There are several related works for dynamic tuning of CW to enhance the performance in MAC layer. When the network traffic is dynamically changed, they have tried to propose dynamic CW adjustment algorithms or find optimal CW values. Natkaniec et al. [6] showed the relationship between MAC performance and CW values according to the number of contending nodes. They also showed that the performance enhancement can be achieved by the selection of the optimal CW_{min} value, which depends on the number of contending nodes. Bianchi et al. [7] showed that the CSMA/CA suffers from several performance degradations and the throughput is strongly dependent on both the number of active nodes and the total traffic load offered to the network. These works showed that the performance can be substantially enhanced if the exponential backoff mechanism is substituted by an adaptive CW adjustment mechanism, depending on the number of contending nodes. However, these researches considered only infrastructure WLAN environments and are not directly applicable to multi-hop wireless sensor networks.

For the performance enhancement in wireless sensor networks, there is Task Aware MAC (TA-MAC) protocol [8]. TA-MAC illustrated the relationship between traffic load and channel access opportunity and intended to improve throughput performance by adjusting channel access probability. In Traffic Adaptive MAC protocol [9], the network traffic load is defined as the number of lost packets due to collision and proposed adaptive CW tuning algorithm according to the load. However, TA-MAC [8] suffers significant overhead for neighbor nodes to monitor on another. Traffic Adaptive MAC [9] also imposes a certain overhead on the monitoring the number of channel collisions and it does not suggest the differentiated CW adjustment scheme between equally loaded nodes, which is not suitable for Many-To-One communication architecture.

3. Proposed Protocol

DACW assumes that the network architecture is a Many-To-One communication structure and a multi-hop topology between sensor nodes and the sink node. In this situation, various routing protocols such as Directed Diffusion or AODV can be adapted to our network. By using these protocols, every node wishing to transmit packets can maintain the routing table and can find out the number of hop count to the sink node. For example, in Directed Diffusion, the sink node broadcast interest packets to receive intended data packets from target sensor nodes. The interest packet includes a specified data type, a location rage, a time stamp, a time interval and the number of hops which is the distance from the sink. In AODV, a source node wishing to transmit data packets broadcast Route Request (RREQ) packets and receive Route Reply (RREP) packets from the destination node, which enable the node to update its routing table entries. Thus, these protocols can calculate the number of hops between nodes and the sink.

After determining the route to the destination using the routing algorithm, each node calculates the optimal contention window by using two metrics. The first metric is traffic load information and the other is the number of hops known as the routing table. For traffic load, DACW use packet delivery ratio as LQI (Link Quality Indicator) value, which is a characterization of the quality of the wireless channel. In order to determine exactly whether the link is bottleneck or not, DACW defines T_{LQI} and M_{LQI}, which are a predefined threshold value of LQI and the measured LQI, respectively.

At first, DACW randomly selects an initial CW value by using a Backoff Exponent (BE) as (1), which is the basic method of IEEE 802.15.4 protocol. If it is believed that there is a bottleneck in the network, DACW dynamically increases the congestion window according to LQI and the number of hop count as (2). On the other hand, if it is considered to be low traffic, DACW shrinks the congestion window as (3). The detailed algorithm is as follows.

$$CW = Rand\,(0,\, 2^{BE} - 1) \tag{1}$$

$$Adaptive\_CW = CW + \frac{P_{RNG}}{N_{HOPS}}, T_{LQI} > M_{LQI} \tag{2}$$

$$Adaptive\_CW = CW - \frac{P_{RNG}}{N_{HOPS}}, T_{LQI} < M_{LQI} \tag{3}$$

$$1 < P_{RNG} < CW, \tag{4}$$

where N_{HOPS} and P_{RNG} are the number of hops to the sink node and a parameter of CW range, respectively. When a node has small N_{HOPS}, it will have more relaying traffic due to Many-to-One communication architecture. In this situation, DACW should assign more Adaptive_CW variation range to give higher priority as well as more reliable transmission. To do this, by changing the P_{RNG}, we can change the variation range of CW. This means that if P_{RNG} is set to be large, it will be suitable for the network with high traffic variations. On the contrary, when P_{RNG} is very small, it operates like the CSMA/CA mechanism. In order to adjust P_{RNG} more dynamically in frame retransmission period, we use BE value, which is shown in expression (5) and (6). When the channel condition seems to be poor and there are several retransmissions, BE increases. Thus, by using BE, DACW can adjust CW value more adaptively in frame retransmission situation.

$$Adaptive\_CW = CW + \frac{P_{RNG} + BE}{N_{HOPS}}, T_{LQI} > M_{LQI} \tag{5}$$

$$Adaptive\_CW = CW - \frac{P_{RNG} + BE}{N_{HOPS}}, T_{LQI} < M_{LQI} \tag{6}$$

The other feature of DACW is that the Adaptive_CW changes linearly rather than exponentially because most sensor networks have small CW values to adapt themselves to poor conditions such as low bandwidth and limited battery power. Finally, these features can be said that DACW is a cross layer scheme because it uses routing table information for MAC layer operations. Moreover, we can say that it is a self-routing scheme, which is less overhead to route the packets and can deliver packets more correctly.

4. Performance Evaluation

4. 1 Simulation environment

In order to evaluate the performance of the proposed protocol, we used the ns-2 simulator [10] with AODV routing protocol and run the simulation for 300 seconds. It is assumed that 50 sensor nodes are randomly placed in an 80m x 80m rectangle network area. All sensor nodes have routing capacity and the radio propagation range for a node is set to 15m. The number of data connections is 20 and all source nodes generate constant bit rate (CBR) traffic. Each pair of source and destination nodes of a connection is randomly selected without duplicate sources. In order to represent different network traffic load, we used eight different packet arrival intervals of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 second with packet size of 80 bytes. The maximum buffer size of each node's interface is set to 50. For the threshold value and the parameter, T_{LQI} is set to 0.5 and P_{RNG} is set to 6, respectively.

We have evaluated the performance of the proposed protocol and compare it to that of the IEEE 802.15.4 standard using the following metrics; Packet delivery ratio – average number of data packets actually received by receivers over the number of data packets originated by sources. End-to-end delay - average time elapsed between when a data packet is originated by a source and when it is successfully received by the sink node. Normalized control overhead - total number of data and control packets transmitted by sensor node in the network, divided by the total number of data packets received by the sink node.

4. 2 Simulation result

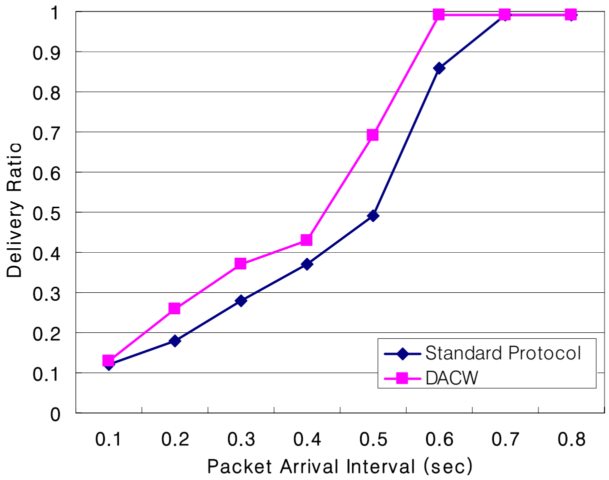

Figure 4. Packet delivery ratio

The packet delivery ratio as a function of different packet arrival intervals is shown in Figure 4. As shown in the figure, we can see that the delivery ratio of DACW is better than IEEE 802.15.4 protocol in the interval between 0.2 and 0.6. This is because DACW prevents severe channel contention by increasing the CW when the bottleneck occurs, and it reduces unnecessary packet collisions by decreasing the CW when the traffic is low. However, when the packet arrival interval is over 0.7 or under 0.2, delivery ratio of all protocols are saturated because there is so little traffic or the entire network is congested, respectively.

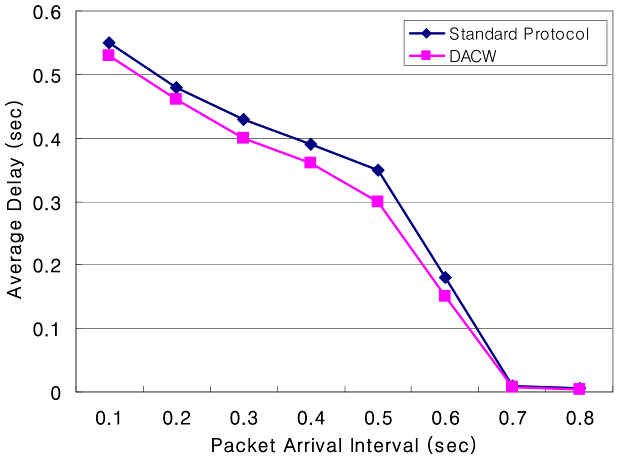

Figure 5. Packet end-to-end delay

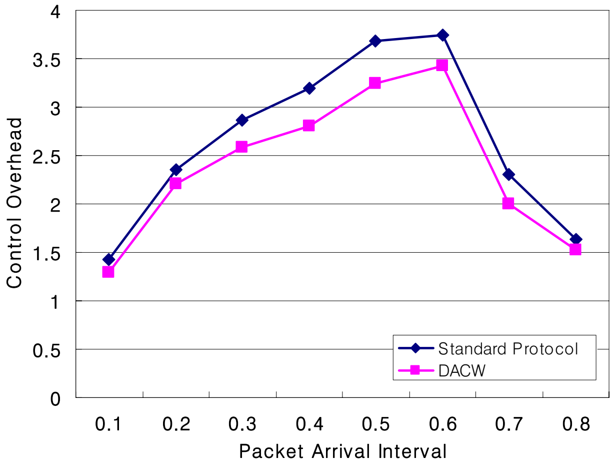

Figure 6. Normalized control overhead

Figure 5 illustrates the end-to-end delay as a function of the packet arrival interval. For the same packet interval range of Figure 4, DACW shows lower end-to-end delay than IEEE 802.15.4 because IEEE 802.15.4 suffers from frequent packet retransmission by packet collisions. When the traffic load is heavy, DACW can avoid retransmission delay due to increasing the CW, while in the low traffic environment, it can reduce the unnecessary channel idle time by shrinking CW. However, if the network is significantly congested or little traffic is generated, the end-to-end delay performance is also saturated as shown in the delivery ratio result.

Finally, figure 6 shows the normalized control overhead as a function of packet arrival interval. In the figure, the overhead of IEEE 802.15.4 is higher than DACW because 802.15.4 has more packet collisions. This means that it results in more retransmissions of control packets such as RREQ, RREP and RERR. In addition, we can see that as the traffic load increases, there are more buffer overflows by congestions, which leads the control packet overhead to decrease by dropping control packets. On the contrary, at a point of the time when the packet arrival interval reaches 0.6, which means traffic load decreases, the control overhead decreases again due to good channel quality. Consequently, by using DACW, the number of control packet flooding is decreased, which leads the energy consumption of each node to be saved.

5. Conclusion

In wireless sensor networks, the performance of the MAC protocol is strongly dependent on the contention window size. However, most exist protocols do not consider Many-to-One communication paradigm between several nodes and a sink. In this paper, we have proposed DACW (Distance Adaptive Contention Window) which can dynamically adjust contention window according to Many-to-One communication features such as the number of hops and traffic load information. In the proposed mechanism, a smaller CW value is selected when there is less traffic load, while a larger CW value is selected when there is heavy traffic load. However, the variation range increases as the node is closer to the sink. The proposed scheme is evaluated by a simulation, and the results show that DACW has a good performance in terms of packet delivery ratio, end-to-end delay, and normalized control overhead when the traffic load of the network is dynamically changed.

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