

Performance Enhancement in IEEE 802.15.4 Wireless Sensor Networks by Link-Quality Based Node Grouping

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Abstract—IEEE 802.15.4 is the most successful low-rate wireless personal area network (LR-WPAN) standard enabling the deployment of wireless sensor networks (WSNs). However, in WSNs, each node has a limited communication range and battery lifetime. Moreover, sensor nodes may be scattered over a wide area. Hence, a hidden node collision is a crucial factor affecting the overall performance of WSNs. In this letter, we propose an advanced mechanism of mitigating the hidden node collision by grouping sensor nodes according to the link-quality indicator (LQI) information.

Keywords—Wireless sensor networks, hidden node problem, IEEE 802.15.4, node grouping, link-quality indicator.

I. INTRODUCTION

Currently, IEEE 802.15.4 [1] is the most widespread communication specification for WSNs. The medium access control (MAC) layer of IEEE 802.15.4 adopts the carrier sense multiple access with collision avoidance (CSMA-CA) scheme, which is a modification of the distributed coordinator function (DCF) defined in [2]. The protocols of the CSMA family adopt a randomized medium access scheme in an exponential backoff manner. However, as the number of nodes increases, these MAC protocols suffer from an increased number of frame collisions. In particular, when two nodes are not visible to each other and transmit to another node that is visible to both of them, a so-called hidden node collision occurs. A hidden node collision drastically worsens the performance, i.e., degrades the throughput. Moreover, the nodes in WSNs have a limited communication range and the nodes may be randomly deployed over a wide area. Hence, the nodes in WSNs are inherently vulnerable to a hidden node collision. Consequently, a hidden node collision increases the retransmission rate resulting in a decay of the battery lifetime. Moreover, a hidden node collision deteriorates the short-term fairness, as shown in [3], which causes an

unbalanced transmission rate among the nodes. In IEEE 802.11 networks, even though a similar CSMA-CA scheme is applied, the number of hidden node collisions can be reduced by introducing request-to-send (RTS) and clear-to-send (CTS) handshake mechanisms. However, the RTS and CTS mechanisms were not introduced in IEEE 802.15.4 WSNs because of the protocol overhead. Hence, mitigating a hidden node collision is a very critical issue in IEEE 802.15.4 based WSNs, and many research works [4]-[6] have addressed the method of resolving the hidden node problem. In the carrier sense tuning mechanism [4], the receiver sensitivity of the transceiver in a sensor node is tuned to extend the radio coverage. However, additional power is required to increase the receiver sensitivity, and it is not easy to implement this scheme in energy-constrained sensor nodes. In [5], a node grouping mechanism is proposed. All nodes are separated into several groups. Nodes in the same group are not in a hidden node relationship. To prevent a hidden node collision, non-overlapping medium-access time periods are assigned to the groups. However, this grouping method does not reflect the channel condition of each node. In [6], a cross-layer scheme for detecting nodes in a hidden node relationship is proposed. This scheme picks up nodes triggering a hidden node collision, and these nodes are scheduled in a preserved time slot for transmission. However, the scheme is not effective when many sensor nodes have hidden-node relationships with each other. In this paper, we propose an advanced node-grouping method to mitigate the hidden-node effect in WSNs. In the proposed scheme, nodes are sorted according to the received signal strength level and an efficient node-grouping algorithm is proposed.

II. OVERVIEW OF IEEE 802.15.4

Two different device types can participate in IEEE

802.15.4 networks: a full-function device (FFD) and a reduced-function device (RFD). An FFD can operate as a personal area network (PAN) coordinator, and is the principal controller of a PAN. An IEEE 802.15.4 network can operate in either of two topologies: a star topology or a peer-to-peer topology. In a star topology, communication is established between the central PAN coordinator and the neighbor nodes. An IEEE 802.15.4 network can operate in beacon-enabled mode or non-beacon enabled mode. In this letter, we consider a star topology for IEEE 802.15.4 WSNs operating in beacon-enabled mode. In beacon-enabled mode, the PAN coordinator transmits a beacon frame periodically. The superframe is bounded by the beacon frames and is divided into 16 equally sized slots. The beacon frame is transmitted in the first slot of the superframe. The superframe can be divided into an active period and an inactive period. An active period is divided into a contention access period (CAP) and a contention free period (CFP). The structure of this superframe is described by the values of `macBeaconOrder` and `macSuperframeOrder`. The beacon interval BI is obtained from `macBeaconOrderBO` as follows: $0 \leq BO \leq 14, BI = aBaseSuperframeDuration \times 2^{BO}$ symbols. The length of the active portion of superframe duration SD is described using `macSuperframeOrderSO` as follows: $0 \leq SO \leq BO \leq 14, SD = aBaseSuperframeDuration \times 2^{SO}$ symbols. The CAP immediately follows the beacon frame, and the CFP immediately follows the CAP. For low-latency applications, the PAN coordinator may allocate the guaranteed time slots (GTSs). These GTSs constitute the CFP, and a maximum of seven GTSs can be allocated in a CFP. A superframe structure is shown in Fig. 1. All nodes wanting to communicate during CAP need to use a slotted CSMA-CA scheme. In a slotted CSMA-CA scheme, the MAC sublayer will delay for a random number of backoff periods ranging from 0 to $2^{BE} - 1$, where BE is the backoff exponent, and then requests the physical layer to perform a clear channel assessment (CCA). If the channel is assessed as idle for two backoff periods, a frame is transmitted. Two successive frames transmitted from a node should be separated by at least an interframe spacing (IFS) period.

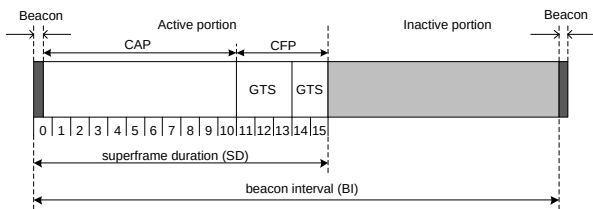


Figure 1. Superframe structure of IEEE 802.15.4

III. PROPOSED GROUPING ALGORITHM

We propose an advanced grouping method that mitigates the hidden node effect. Initially, all nodes share the same

CAP and are vulnerable to a hidden-node collision. After the grouping algorithm is performed, the CAP is partitioned into several sub-CAPs, and all nodes are required to access the medium only during the designated sub-CAP. In our first phase of the proposed algorithm, we determine the epoch during which the grouping algorithm should be started. When the detrimental effect of the hidden node collision is severe, we should run the grouping algorithm. Moreover, when the topology of the WSN is changed, we may run the grouping algorithm again. In IEEE 802.15.4 CSMA-CA, a frame contention collision occurs when more than two nodes select the same backoff period. In this kind of collision, frames interfere with each other from the beginning of the frame transmission. However, when a hidden-node collision occurs, the PAN coordinator may have some chance of recognizing the part of the frame that arrived at the PAN coordinator earlier than the other frames [7]. Consequently, when the PAN coordinator receives a partially corrupted frame, the PAN coordinator assumes that a hidden node collision has occurred. Therefore, we can use the ratio between the number of collisions and the number of assumed hidden node collisions in the WSN as the metric representing the severity of the hidden node collision as follows:

$$Z = \frac{C_h}{C_c}, \quad (1)$$

where C_h and C_c are the number of assumed hidden-node collisions, and the number of collisions for the most recent n frame collisions, respectively. Additionally, the link-quality indicator (LQI) is measured by the PAN coordinator for each received frame. The PAN coordinator updates the average LQI for each node W_i according to the moving average as follows:

$$W_i[t] = \left(1 - \frac{1}{T_c}\right) W_i[t-1] + \frac{1}{T_c} L_i[t], i = 1, \dots, K, (2)$$

where t , T_c , L_i , and K are the index of the received frames, the moving average window size, the LQI for node i , and the total number of neighbor nodes in the WSN, respectively. When $Z > \delta$, where δ is the threshold representing the tolerable severity of a hidden node collision, the PAN coordinator starts the grouping algorithm. When the algorithm starts, the PAN coordinator sorts W_i in descending order and sends a Grouping Initiation Message with the beacon frame. The frame control field of the beacon frame MAC header is 2 octets in length and contains the frame type, addressing fields, and other flags. There is also a reserved subfield (7 to 9 bits) in the frame control field. We send a Grouping Initiation Message in this subfield. Moreover, we populate the beacon payload field with the addresses of the neighbor nodes which are sorted according to W_i in descending order. After receiving the beacon frame with the Grouping Initiation Message, neighbor nodes change their transceiver state to an RX_ON state and operate in promiscuous mode. When they succeed in receiving a neighbor's frame, they record the address of the sending node. We call this record a

listening list of the node. According to the address list transmitted by the PAN coordinator, each neighbor node sends a responding frame, which acknowledges it has received the Grouping Initiation Message, to the PAN coordinator. Moreover, the payload field of the responding frame is populated with its listening list.

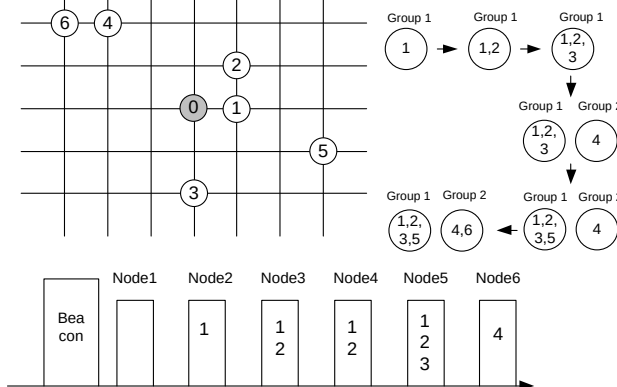


Figure 2. Proposed algorithm with 6 neighbor nodes

An example topology with 6 neighbor nodes is depicted in Fig. 2, where node 0 is the central PAN coordinator. Let the distance between the adjacent lines be 5 m, and the carrier sensing range be 18 m. After the PAN coordinator sends the beacon frame with a Grouping Initiation Message, each neighbor node sends a responding frame with its listening list. This sequence is depicted in Fig. 2. Node 1 transmits the responding frame, and node 2 listens for the transmission of node 1. Node 3 listens for the transmission of both nodes 1 and 2. Node 4 also listens for the transmission of nodes 1 and 2, however, it cannot listen for the transmission of node 3. Node 5 listens for the transmission of nodes 1, 2, and 3. Node 6 listens only for the transmission of node 4. All of this information is transmitted to the PAN coordinator sequentially. Every time the frame is received from the neighbor nodes, the PAN coordinator dynamically assigns a group for the node transmitting the responding frame. A group assignment is quite simple and efficient since all neighbor nodes are sorted according to the average LQIs. The basic philosophy of the grouping algorithm is to assign as many nodes as possible in a group and to assign the nodes that have good LQIs in the same group. This grouping policy reduces the total number of groups and enhances the overall WSN throughput by prioritizing the grouping order according to the average LQIs. When the PAN coordinator receives the responding frame along with the listening list, the PAN coordinator searches for a subset group of the list. When the PAN coordinator finds the group, the node joins that group. When the PAN coordinator fails to find a subset group of the listening list, and the number of current groups is smaller than the maximum number of groups allowed, a new group is created and the node becomes the first member of the new group. However, when a new group

cannot be created because a number of groups have reached the maximum allowable size, the node joins the last group. In Fig. 2, this grouping algorithm is applied to the given topology.

Finishing the grouping algorithm for all the neighbor nodes, the PAN coordinator divides the CAP into several sub-CAPs. We assume that the PAN coordinator knows the traffic load of each neighbor node. The time duration of each sub-CAP is assigned to be proportional to the traffic load of each group.

IV. SIMULATION RESULTS

We performed a simulation using the ns-2 network simulator [8]. We extensively modified the ns-2 IEEE 802.15.4 MAC simulator to incorporate the proposed grouping message protocol and the LQI-based dynamic grouping algorithm. We placed 15 nodes around the central PAN coordinator. The detailed node distribution used for the simulation is shown in Fig. 3, where the distance between an adjacent line is 5 m and the carrier sensing range is approximately 24 m. The current consumptions are 19.7 mA, 17.4 mA, and 20 μ A for Rx, Tx, and an idle state, respectively.

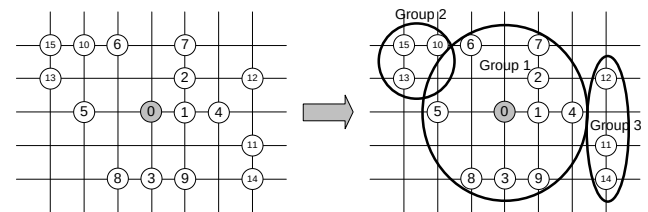


Figure 3. Node distribution

The offered traffic load from each node to the PAN coordinator is changed from 1 to 14 kbps. Moreover, we changed the packet size from 70 to 100 bytes. According to the proposed grouping algorithm, 15 nodes are grouped into 3 groups, as shown in Fig. 3. There are 16 time slots in each superframe duration. We allocated time slots 0-9 to group 1, time slots 10-12 to group 2, and time slots 13-15 to group 3. We ran the simulation for 200 s, the results of which are shown in Figs. 4 and 5. As we increase the offered traffic load in each node, the average throughput increases linearly. However, when the grouping algorithm is not applied, the average throughput becomes bell-shaped. The maximum throughput is attained when the offered traffic load in each node is 5 kbps. As the packet size increases, the average throughput increases gradually, as shown in Fig. 4. The hidden node collisions mainly occur between the nodes in group 2 and those in group 3. The nodes with a small packet size have a greater chance of accessing a wireless medium than nodes with a large packet size. Hence, when the packet size is small, the number of hidden-node collisions between groups 2 and 3 increases resulting in a decrease in the average throughput. The

average power consumption increases as the traffic load increases. However, when the grouping algorithm is applied, the average power consumption is much lower than for the non-grouping mode. The grouping algorithm shows a good performance in both throughput and power consumption.

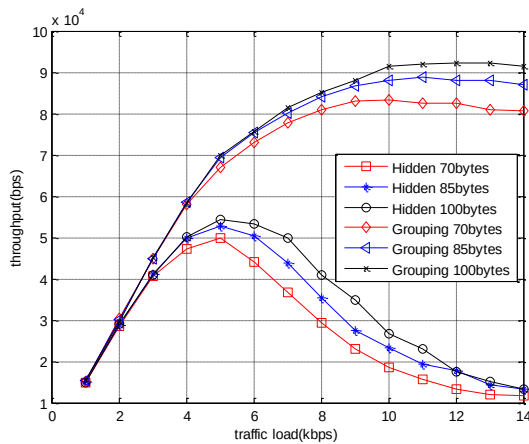


Figure 4. Average throughput with varying packet size

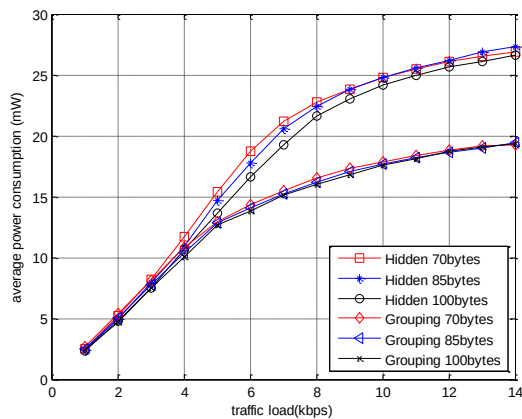


Figure 5. Average power consumption with varying packet size

V. CONCLUSION

In this paper, an advanced grouping method was proposed. The main characteristics of the proposed method are the usage of the average LQI and the piggyback of hidden-node information. The grouping order is determined according to the average LQI. Hence, the nodes close to the PAN coordinator are grouped earlier than the other nodes. This results in efficient grouping. Moreover, the hidden-node information exchanges are simplified by the piggybacking of the hidden node information. The simulation results show that the proposed scheme achieves good performance in both throughput and power consumption.

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