Dynamic Backoff for Wireless Personal Networks

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Abstract—Based on IEEE 802.15.4 low-rate wireless personal area networks (LR-WPANs), this paper proposes a *memorized backoff scheme (MBS)* with the *exponential weighted moving average (EWMA)* approach to dynamically adjust the size of the contention window. The proposed scheme can be implemented in standard IEEE 802.15.4 medium access control (MAC) protocol without adding any new message type and without modifying the communicating procedure. An analytic model and a simulation model are developed to evaluate the performance of IEEE 802.15.4, MBS and MBS+EWMA. The numerical results indicate that in terms of goodput, completion rate, average MAC delay, average queuing delay and average number of collisions for each data frame, our proposed scheme significantly outperforms standard IEEE 802.15.4 backoff scheme.

I. INTRODUCTION

IEEE 802.15.4 is a newly protocol defined for low-rate wireless personal networks (LR-WPANs). In IEEE 802.15.4 standard, the physical and medium access control (MAC) layers are specified [2][3][5]. The characteristics of IEEE 802.15.4 LR-WPAN include

- The system operates in one of the following frequencies.
 1. In 2.4GHz ISM (Industry, Science and Medicine) band, 16 channels are supported and the transmission rate is 250 kbps.
 2. In 915 MHz ISM band, 10 channels are supported and the transmission rate is 40 kbps.
 3. The European 868 MHz band provides 1 channel with 20 Kbps transmission rate.
- Both the star and peer-to-peer network topologies are supported. The clustered tree architecture will be provided in the near future.
- The contention mechanism is similar to IEEE 802.11 CSMA(Carrier Sense Multiple Access)/CA(Collision Avoidance).
- Both the extended addressing and short addressing for mobile stations are supported.
- The power consumption of the mobile station is low, and the executing cycle for each mobile station is short.

Based on the capability of data processing, two types of mobile station are defined in IEEE 802.15.4: reduced function device (RFD) and full function device (FFD). These mobile stations constitute the network called personal operating space (POS). In the POS, a coordinator equipped with the FFD capability

Fig. 1. The Network Topologies

Fig. 2. The Superframe Structure

is responsible for managing the WPAN (e.g., for issuing the Beacon frame). Two network topologies are supported in IEEE 802.15.4. In the star topology shown in Figure 1 (a), each mobile station communicates with others via the coordinator. The coordinator is usually located at a fixed location, and directly connected to the socket for power supply. On the other hand, in the peer-to-peer topology shown in Figure 1 (b), direct communications between mobile stations can be provided. The peer-to-peer topology is used for non-infrastructure wireless networks. The multi-hop routing is allowed in the peer-to-peer topology, and the routing path can be dynamically updated. In IEEE 802.15.4, both the beacon-enabled network and the non beacon-enabled network are defined. This paper considers the beacon-enabled network with the star topology¹.

Figure 2 shows the superframe structure for the beacon-enabled network. A superframe consists of 16 slots. In the 16-slot superframe, the first slot is used for the Beacon frame sent from the coordinator to mobile stations. The beacon

¹The proposed scheme in this paper can easily be extended to accommodate other network configurations.

Fig. 3. The Data Transmission Procedure for IEEE 802.15.4 Standard

includes the information for timing synchronization, system configuration, a list of the mobile stations that have to receive the data frames from the coordinator and so on. The remaining 15 slots are divided into two parts. The first part is contention access period (CAP), and the second part is contention free period (CFP). In CAP, mobile stations equally access the medium by using contention. On the other hand, the slots in CFP are reserved for specific mobile stations assigned by the coordinator. The coordinator is also in charge of the adjustment for the lengths of CAP and CFP.

II. A MEMORIZED BACKOFF SCHEME

In IEEE 802.15.4, every mobile station under the supervision of a coordinator listens to the beacon issued by the coordinator. If more than one mobile stations intend to send/receive the data frame, the CSMA/CA mechanism is used to solve the collision for the medium access. Based on the superframe structure described in the previous section, Figure 3 illustrates the data transmission procedure for IEEE 802.15.4 standard. After listening to the beacon issued by the coordinator, the mobile station is informed that a data frame at the coordinator is destined for the mobile station. Then the mobile station executes the following steps (see the first shadow area of Figure 3).

- S1 The mobile station randomly selects a backoff time according to the pre-defined contention window (i.e., the minimum size of the contention window - CW_{min})², and performs the countdown based on the selected backoff time.
- S2 When executing the countdown to zero, the mobile station detects if the channel is idle.
- S3.a If yes, the **Data Request** frame is transmitted to the coordinator. The mobile station waits for the period of the gap (T_{ack}) and receives the **ACK** frame from coordinator. The T_{ack} is defined gap of data and ACK. Once the waiting time expires, the **Data Request** frame is re-sent from the mobile station to the coordinator. When the mobile station is received the **ACK** frame, it informs the mobile station to receive the data frame from coordinator. Then mobile station

will awake duration of maximum frame response time³.

- S3.b If the channel is busy, the size of the contention window CW for the mobile station is doubled, and the above medium contention process (i.e., Steps 1 and 2) is reiterated. The contention process will be repeatedly executed until the frame is successfully transmitted or until the maximal retry count is reached (then the frame is dropped). Note that in IEEE 802.15.4, a maximum CW value (CW_{max}) is defined⁴. Once the maximum value is reached, the value is retained for the following contentions.

In Figure 3, we assume that Step 3.a is executed. That is, the mobile station occupies the medium access for frame transmission.

- S4 When mobile station is transmitted **Data Request** frame to coordinator, the coordinator randomly also selects a backoff time from contention window. The process is similar to the steps 1. If the coordinator does not transmit data frame to mobile station in duration of maximum frame response time. The mobile station will repeat transmission the **Data Request** frame until the maximal retry count is reached.
- S5 Upon receipt of the data frame from the coordinator, the mobile station delays the T_{ack} duration, and then issues the **ACK** frame to respond to the coordinator.

When a new data frame arrives at the mobile station, the mobile station and the coordinator perform the similar procedure as described above, except that the **Data Request** frame transmission is absent (see the second shadow area of Figure 3).

Figures 4 (a) and (b) illustrate the transmission flows for standard IEEE 802.15.4 backoff scheme and our memorized backoff scheme, respectively. In Figure 4 (a), when Frame A1 and Frame B1 respectively arrive at Mobile Stations A and B in the i th superframe, the two mobile stations randomly select the backoff time based on CW_{min} . If the collision occurs (e.g., due to the same backoff time selected by both Mobile Stations A and B), then the size of the contention window is doubled, and the contention process is repeated. At this contention, Mobile Station A occupies the channel and successfully transmits the frame. In IEEE 802.15.4, the window size will be reset to CW_{min} when the next superframe starts as shown in Figure 4 (a). Suppose that Mobile Stations A and C intend to send the frames in the $(i+1)$ th superframe. The two mobile stations probably select the same backoff period due to the small CW , and the collision may occur again. When the network load is heavy, the serious contention can not be resolved within a narrow backoff window, which results in the increase of the number of collisions. The increase of the number of collisions implies the decrease of the system performance and the increase of the power consumption of the mobile station. If a broad contention window is initially

²In IEEE 802.15.4, $CW_{min} = 2^3$.

³In IEEE 802.15.4, $aMaxFrameResponseTime = 1220$ Symbols

⁴In IEEE 802.15.4, $CW_{max} = 2^5$.

Fig. 4. The Backoff Flows for IEEE 802.15.4 and MBS

used in the $(i+1)$ th superframe, the collisions can be reduced, and mobile stations have higher opportunities to successfully transmit/receive the data frames. On the other hand, when the network load is light, the large contention window incurs the reduction of the network utilization. Therefore, we propose a *memorized backoff scheme* (MBS) to dynamically adjust the contention window based on the traffic load. In this scheme, the CW value for the successful data delivery in the previous superframe is recorded to predict the initial value of the contention window for the current superframe. Then the coordinator announces the initial CW value for the current superframe to mobile stations via the **Beacon** frame. As shown in Figure 4 (b), the initial CW value in the $(i+1)$ th superframe is set to 2^4 if the data frame in the i th superframe is successfully transmitted by using the 2^4 -slot contention window. Furthermore, if three consecutive successful transmissions occur with the 2^4 -slot contention window (which implies that the contention window may be too large), the initial window value for the next superframe is decreased to 2^3 .

Our proposed scheme can be implemented in the standard IEEE 802.15.4 MAC protocol without adding any new message type and without modifying the communicating procedure. Since the **Frame Control** field can be found in all types of IEEE 802.15.4 messages, the reserved bits in the **Frame**

Bits: 0-2	3	4	5	6	7-9	10-11	12-13	14-15
Frame Type	Security Enabled	Frame Pending	Ack. Request	Intra PAN	Backoff window	Dest. Addressing Mode	Reserved	Source Addressing Mode

Fig. 5. The Frame Control Field in IEEE 802.15.4

Control field are utilized to deliver the CW value between the coordinator and mobile stations. As shown in Figure 5, the bits 7-9 are used in the data, **ACK** and **Beacon** frames to record the exponent of the CW value for the successful transmission. Furthermore, in order to accurately estimate the initial value of the contention window, the EWMA [4] approach is incorporated into our proposed MBS. The equation for EWMA is shown in (1) where E_i denotes the exponent of the contention window size for the successful transmission in the i th superframe, and E_A represents the average value of E_{i-1} , E_{i-2} and E_{i-3} . Then the predicted initial value EP_{i+1} of the contention window for the $(i+1)$ th superframe is a weighted combination of E_A and E_i where X calculated from (2) is the weight of E_A . In (2), the X value depends on the difference of E_i and E_A , and the K value is set to the difference between the exponents of CW_{max} and CW_{min} (i.e., $K = 2$ in this paper).

$$EP_{i+1} = XE_A + (1 - X)E_i \quad (1)$$

where

$$X = 1 - \left[\frac{|E_i - E_A|}{K} \right] \quad (2)$$

III. SIMULATION MODEL AND NUMERICAL EXAMPLES

Our developed simulation model follows the specification of IEEE 802.15.4 MAC layer. The input parameters are referred to the IEEE 802.15.4 standard and listed in Table I. The length of data frames is exponentially distributed with a mean of $1/\mu$ UnitBackoffPeriods (slots). Without loss of generality, several assumptions are made to reduce the complexity of the simulation model and described as follows.

- All mobile stations support 250 Kbps transmission rate.
- The coordinator is static and located at the center of simulated area. Note that our simulation model can be easily extended to accommodate the peer-to-peer WPAN.

In our simulation model, the transmission range of a coordinator is assumed to be 10 meters for the transmission rate of 250 Kbps. To observe the mobility impacts, the random way point model [1] in a rectangular field is considered. In the simulation experiments, we simulate a scenario of 10 mobile stations, and their initial locations are randomly assigned within the area as shown in Figure 6. Then each mobile station randomly chooses a direction and keeps moving towards the direction until the boundary of the rectangular field is reached. When the boundary is reached, the mobile station re-selects a direction, and moves toward the direction as described above. The moving speed of the mobile station is randomly selected from 0 to 1 meter/minute.

TABLE I
SYSTEM PARAMETERS USED IN THE SIMULATION MODEL

Parameters	Values
Transmission Rate of Data Frames	250Kbps
Beacon frame size	0.96 ms (240 bits)
UnitBackoffPeriod (slot)	0.32 ms (20 symbols)
T_{ack} Period	0.512 ms (128 bits)
Data Request (Length)	1.7928 ms (144bits)
ACK FramePeriod (Length)	0.498 ms (40 bits)
Waiting Duration For ACK or Data Frame (Length)	2.6892 ms (216 bits)
CW_{min}	8 UnitBackoffPeriods (slots)
CW_{max}	32 UnitBackoffPeriods (slots)
Number of Mobile Stations	10
Average Data Frame Size	12 UnitBackoffPeriods (slots)

Fig. 6. The Scenario for the Simulation Model

Each simulation run lasts 960 seconds, and each simulation result is obtained from averaging the results of 1000 independent simulations. Each mobile station maintains a FIFO waiting buffer of 64 frames, and the mean frame length (i.e., $1/\mu$) is assumed to be 120 bytes (e.g., 12 UnitBackoffPeriods at the 250-Kbps transmission rate, excluding PHY and MAC headers). The network load consists of uplink (from mobile stations to the coordinator) and downlink (from the coordinator to mobile stations) traffic. When the network load (i.e., $N\lambda/\mu$) is less than 0.3, we define the situation is the “light” traffic load. On the other hand, when the network load is greater than 0.7, the situation is defined as the “heavy” traffic load.

Figure 7 shows the effects of the traffic load on Goodput S for MBS, MBS+EWMA and IEEE 802.15.4 schemes. This figure indicates an intuitive result that Goodput S for all schemes increases and then decreases as the traffic load increases. Furthermore, we find that MBS and MBS+EWMA schemes achieve higher goodput than IEEE 802.15.4, and the peak values of the goodput for MBS and MBS+EWMA schemes are much larger than that for IEEE 802.15.4. The high goodput for MBS and MBS+EWMA mainly results from the decrease of the number of contentions/collisions. In other words, by using MBS and MBS+EWMA, the backoff overhead is significantly reduced and therefore the goodput improves. We also observe

Fig. 7. Effects of Traffic Load on Goodput

Fig. 8. Effects of Traffic Load on Completion Rate

that the performance of MBS+EWMA is better than that of MBS, which implies that the proposed EWMA approach effectively predicts the network condition and further reduces the occurrence of collisions.

Figure 8 shows the effects of the traffic load on the completion rate R_c for MBS, MBS+EWMA and IEEE 802.15.4 schemes, where R_c is defined as the number of successful transmitted frames over the total number of transmitted frames. From this figure, we observe that for all schemes, R_c decreases as the traffic load increases. The decreasing rate is sharper for IEEE 802.15.4 than for MBS and MBS+EWMA especially when the traffic load is heavy. The reason is that for IEEE 802.15.4, the collisions for medium contention under the heavy traffic load become severe, which significantly results in the degradation of the completion rate. From this figure, we find that MBS and MBS+EWMA have higher completion rates than IEEE 802.15.4.

Figures 9 and 10 show the effects of the traffic load on the average queueing delay D_q and average MAC delay D , respectively. These figures show the intuitive results that for MBS, MBS+EWMA and IEEE 802.15.4, the average queueing and MAC delays increase as the traffic load increases. These figures also indicate that when the traffic load is light, the curves for all schemes are insensitive to the traffic load. On the other hand, in the heavy traffic load, the average delays significantly increase as the traffic load increases especially

Fig. 9. Effects of Traffic Load on Average Queueing Delay

Fig. 10. Effects of Traffic Load on Average MAC Delay

for IEEE 802.15.4. Since serious collision under the heavy traffic load results in longer delays in IEEE 802.15.4, the MBS and MBS+EWMA schemes are proposed. Furthermore, the average delays of MBS+EWMA are less than those of MBS because the contention window in the MBS+EWMA scheme can be adapted more appropriately by using the proposed EWMA approach.

Figure 11 shows the average number N_c of collisions occurred for each data frame prior to being successfully transmitted. A trivial result is observed that for all schemes under investigation, N_c increases as the traffic load increases. N_c increases more significantly for the heavy traffic load than for the light traffic load especially in IEEE 802.15.4. Furthermore, MBS and MBS+EWMA have smaller N_c values than IEEE 802.15.4. The large N_c value indicates that with a data frame arrival, the mobile station should try to send the data frame many times before the frame is successfully transmitted, which results in more power consumption of the mobile station.

IV. CONCLUSION

IEEE 802.15.4 defines the low-rate wireless transmission for personal area networks. In IEEE 802.15.4 standard, the physical and medium access control (MAC) layers are specified. In this paper, we proposed a *memorized backoff scheme* (MBS) to dynamically adjust the size of the contention window (CW)

Fig. 11. Effects of Traffic Load on the Number of Collisions for Each Data Frame

based on the network load. With the *exponential weighted moving average* (EWMA) approach, the CW value can be estimated more accurately. Our proposed scheme can be implemented in the standard IEEE 802.15.4 MAC protocol without adding any new message type and without modifying the communicating procedure. An analytic model was developed to evaluate the performance of IEEE 802.15.4 and MBS, which has been validated against the simulation experiments. The numerical results indicated that in terms of goodput, completion rate, average MAC delay and average queueing delay, MBS and MBS+EWMA significantly outperform standard IEEE 802.15.4 backoff scheme especially when the traffic load is heavy. Furthermore, the average number N_c of collisions for each data frame can be effectively decreased, which results in the reduction of power consumption for mobile stations.

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