Enhancing IEEE 802.15.4-Based Wireless Networks to Handle Loss of Beacon Frames

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SUMMARY   Even though the IEEE 802.15.4 standard defines processes for handling the loss of beacon frames in beacon-enabled low-rate wireless personal area networks (LR-WPANs), they are not efficient nor detailed. This letter proposes an enhanced process to improve the throughput performance of LR-WPANs under the losses of beacon frames. The key idea of our proposed enhancement is to make devices that have not received a beacon frame, due to packet loss, to transmit their data in the contention period and even in the inactive period instead of holding pending frames during the whole superframe period. The proposed protocol is evaluated using mathematical analysis as well as simulations, and the throughput improvement of LR-WPANs is proved.
key words: LR-WPAN, interference, WLAN, beacon

1. Introduction

Because the IEEE 802.15.4 standard-based low-rate wireless personal area networks (LR-WPANs) have unique characteristics such as low-cost device, short transmission range, low data rate, and low power consumption [1], applications utilizing LR-WPANs have been increasing in a broad range of areas such as medical services, smart home and industrial-automation systems, traffic information systems, public safety systems, wireless sensor networks, and smart grid advanced metering infrastructures (AMIs). On the other hand, as shown in previous studies [2], [3], LR-WPANs still have some critical issues to be resolved to improve network performance. One of the issues is the 'loss of beacon frame' problem arising from the fact that all devices participating in LR-WPANs transmit their data frames according to the scheduling information in the periodic beacon frames. Although reliable transmission of beacon frame is important, due to interference from 2.4 GHz-based wireless networks and collisions with transmissions from neighbor LR-WPANs, it is inevitable that devices in LR-WPANs frequently fail to receive the beacon frames. Various experiments and studies [2] show that LR-WPANs experience a 60% degradation of their performance because of WLANs in 2.4 GHz band. Nevertheless, the process for handling beacon-loss defined in the IEEE 802.15.4 standard is inefficient and not clearly defined. Therefore, in this letter, an

enhanced protocol is proposed to improve the performance of beacon-enabled LR-WPANs by amending an inefficient process of LR-WPAN when devices fail to receive the beacon frames.

2. IEEE 802.15.4-Based MAC Protocol and Process for Handling Beacon Loss

The IEEE 802.15.4 standard defines two types of LR-WPANs: non-beacon-enabled and beacon-enabled LR-WPANs. The method proposed in this letter targets beacon-enabled LR-WPANs. Based on the IEEE 802.15.4 standard, a network is composed of a piconet controller (PNC) and member devices, and the member devices are synchronized with the PNC using beacon frames. The time duration between two consecutive beacon transmissions is called a superframe, and a superframe is divided into active and inactive periods. No device is allowed to transmit its data during the inactive periods in order to save power. Active period is divided into two periods: the contention access period (CAP) and the contention free period (CFP). Devices can transmit data using the contention-based channel access method during CAP. CFP is composed of multiple guaranteed time slots (GTSs), and a device can only transmit its data in a pre-assigned GTS. A beacon includes the information necessary to manage the superframe, including the durations of CAP, GTSs, and the inactive period. Therefore, every device has to periodically receive beacon frames from a PNC to obtain information for the upcoming superframe structure.

The process when a device fails to receive a beacon frame is not clearly described in the standard, except for when GTSs are allocated in the superframe. When a device's GTSs are allocated in a superframe, but that device fails to receive a beacon frame, the device is not allowed to transmit its packet during its GTS. Since a beacon frame contains the information of the superframe structure, such as CAP, allocation of GTSs, and so on, and since the information can change in every superframe, if a device loses a beacon frame, it needs to hold its transmissions during the superframe to prevent collisions with other scheduled transmissions. For cases when the network parameters, such as the number of devices, traffic loads, and so on, fluctuate frequently, every superframe structure may change and thus devices have to hold their transmissions upon loss of beacon frames to avoid using incorrect slots for their transmissions. Furthermore, when a device does not receive beacon

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frames for consecutive *aMaxLostBeacons* times, it declares synchronization loss and starts over from scanning channels after discarding all buffered packets in the medium access control (MAC) layer.

3. Proposed Method

3.1 Motivation

As described in Sect. 2, loss of beacon frame makes devices to hold their transmissions during whole superframe period. In addition, *aMaxLostBeacons* time of beacon frame losses triggers re-association process starting from the scanning process. Both holding transmissions and starting re-association process degrades performance of LR-WPANs. There are some prior studies on how to avoid beacon frame loss from the interference coming from other LR-WPANs and 2.4 GHz-based networks [4]–[6]. These studies propose to switch operating channel to non-interfering channel or to transmit data frames using other networks' superframe which does not have high traffic load and interference. However, these require more overheads and are not scalable nor flexible. Furthermore, while there are studies to prevent from losing beacon frames, there is no study on enhancement for the process when a beacon frame is lost. Therefore, in this letter, we propose a backward-compatible and effective enhanced protocol for handling loss of beacon frames in the IEEE 802.15.4 standard.

3.2 Proposed Protocol

The fundamental idea of the proposed protocol is to let a device that fails to receive a beacon frame (hereinafter it is called 'failed-device') transmit its queued data not only in CAP, but also in inactive period. This rule is applied to only when the device cannot wait for the GTS in the next superframe to transmit queued data frames. The failed-device transmits its data frames during the possible minimum CAP period which is calculated as follows:

$$T_{CAP} = aNumSuperframeSlots - MaxNumCFPSlots, \quad (1)$$

where *aNumSuperframeSlots* is the number of slots contained in any superframe as defined in the IEEE 802.15.4 standard and *MaxNumCFPSlots* is the maximum number of slots that can be assigned for CFP in any superframe. *MaxNumCFPSlots* is set to 7 slots according to the IEEE 802.15.4 standard. T_{CAP} is guaranteed for CAP, so that any transmission during T_{CAP} will not interfere with any transmission in GTSs. Figure 1 shows data frame format defined in the IEEE 802.15.4 standard. For a data frame used in the proposed protocol, the value of *FrameType* subfield is set to 100[†] and *FramePending* subfield is utilized to make destination device wake up even in the inactive period to receive pending frames from a failed-device.
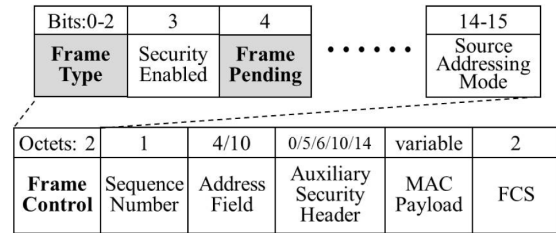
The detailed process of the proposed protocol for a

[†]An unused value in current standard.

Fig. 1 Data frame format specified in the IEEE 802.15.4 standard

failed-device is as follows.

Step 1. Once a device fails to receive a beacon frame, it checks if it has data frames that are scheduled in GTS.

Step 2. If it has any, the device check delay requirement of the queued data to decide if the data transmission can be held during the current superframe period.

> **Step 2-1.** If the transmission can be held, the device holds its data transmission and wait for the next beacon frame.
>
> **Step 2-2.** If otherwise, it moves to the next step.

Step 3. The device forms data frame by setting *FrameType* field to 100. Then, the data frames are transmitted only during T_{CAP} after *aBaseSuperframeDuration* which is a maximum duration of beacon frame that a PNC can make.

Step 4. At the end of 16 slots after *aBaseSuperframe − Duration*, if the failed device still has queued data whose delay requirement indicate that they cannot wait until the next superframe, it keeps sending data frames in upcoming inactive period in the same manner as CAP.

When the destination device receives a data frame with *FrameType* field set to 100, it processes the data frame and checks *FramePending* field. If *FramePending* field is set to 1, it expects to receive more data frames. When the device has not received next data frame in CAP, it waits even in the inactive period to receive the data frames until receiving a data frame with *FramePending* field set to 0.

After the current superframe period has completed, normal operation will be proceeded.

3.3 Discussion

Since the proposed method utilizes the inactive period to enhance throughput and reduce the latency of data delivery in case of beacon frame loss, it may incur additional energy overhead for the listening devices. However, utilization of the inactive period (Step 4 above) is invoked if and only if there are still pending data that have not finished transmission in the T_{CAP} period (Step 3 above). Furthermore, the device does *not* listen for data during the inactive period if the *FramePending* field is set to 0 in the last packet received in Step 3. Therefore, the energy wasted for Step 4 is minimal. Even if nodes do need to listen during the inactive period, use of low-power listening techniques [9] can keep the

energy cost of radio listening sufficiently low. Furthermore, if the network consists of battery-operated wireless devices and if the application does not require high-throughput or low-latency, then it is always possible to deactivate the use of the inactive period in Step 4 by replacing the *FrameType* subfield in *FrameControl* field in Fig. 1 from 100 to 001 as defined the IEEE 802.15.4 standard. Finally, there are many IEEE 802.15.4 applications such as the smart grid AMI, where each node can be connected to a power source and low energy consumption is not the uppermost requirement (low cost constraint is still valid, and low power is also valid due to regulatory reasons). Moreover, these applications need to deal with high traffic load since the network consists of a large number of nodes. Thus, we focus on throughput rather than power consumption in our evaluation.

4. Performance Evaluations

4.1 Theoretical Analysis

Even though methods in [4]–[6] are proposed to avoid the loss of beacon frames, as far as we are aware of, there is no comparative protocol that includes enhanced process for handling when beacon frames are lost. Therefore, we compare our proposed method with IEEE 802.15.4-based protocol in terms of throughput. The throughput achieved by the proposed method can be derived as

$$Thr_{pro} = \frac{D_S(1-PER_D)(1-PER_B)+D_L(1-PER_D)PER_B}{T_{SF}}, \quad (2)$$

where D_S represent the total amount of data successfully transmitted during a superframe when a beacon frame is successfully received, and D_L represent the total amount of data successfully transmitted during a superframe when a beacon frame is lost. T_{SF} denotes the duration of a superframe, and PER_D and PER_B are packet error rates of data and beacon frames, respectively. PER_D includes all possible packet losses caused by channel errors (resulted by interference, fading, etc.) and collisions in CAP. In the numerator of Eq. (2), the 1st and 2nd terms represent the portions of data transmitted when a beacon frame is successfully received and when it is lost, respectively, out of successfully transmitted total data in a superframe. On the other hand, the throughput of the IEEE 802.15.4-based WPANs is

$$Thr_{IEEE} = \frac{D_S(1-PER_D)(1-PER_B)}{T_{SF}}. \quad (3)$$

Therefore, the performance improvement obtained by using the proposed protocol is

$$Imp_{Thr} = \frac{Thr_{pre} - Thr_{IEEE}}{Thr_{IEEE}}$$
$$= \frac{D_L PER_B}{D_S(1-PER_B)} = \gamma \frac{PER_B}{(1-PER_B)}, \quad (4)$$

where γ is a ratio between the amount of data transmitted when a beacon is received and lost. Assuming that the bit
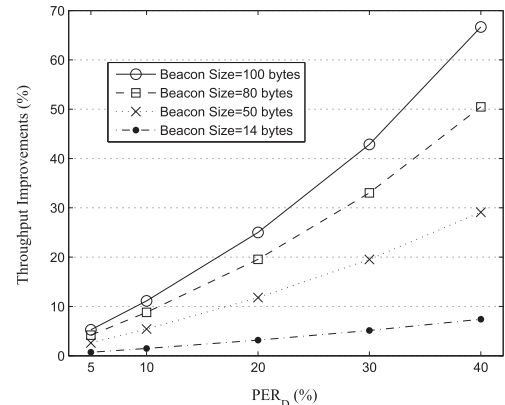

Fig. 2 Throughput improvement as a function of PER_D and beacon frame size when $\gamma = 1$

errors are independent and identically distributed, bit error rate (*BER*) represents current channel condition and PER_B is obtained from *BER* as follows [7]:

$$PER_B = 1 - (1 - BER)^M, \quad (5)$$

where *BER* is the bit error rate of the channel and M is the number of bits in a beacon frame. The *BER* is also related with PER_D as follows:

$$BER = 1 - (1 - PER_D)^{1/N}, \quad (6)$$

where N is the number of bits in a data frame. In this letter, the performance improvements obtained from the proposed method are evaluated as functions of the sizes of beacon frames and PER_D. Varying PER_D also changes PER_B under constant size of beacon frame. With $\gamma = 1$, Fig. 2 shows the enhancement in throughputs as functions of PER_D and the sizes of beacon frames. $\gamma = 1$ indicates all data frames scheduled in a GTS are transmitted in current superframe. As shown in Fig. 2, the improvements are achieved from 1% with 5% PER_D and 14-byte beacon frame, to 68% with 40% PER_D and 100-byte beacon frame. Even though 40% PER_D might be too high comparing to the 10% requirements in the IEEE 802.15.4 standard, it is worthwhile to observe the results because the PER_D due to the interference from other networks can be varied from 10^{-4} up to 1 according to the wireless environment around the network [2].

In Fig. 2, it is assumed that all data frames scheduled in GTS are transmitted in a superframe. This means that results shown in Fig. 2 is an upper-bound that can be obtained from the proposed method. However, once a beacon frame is lost, the data frames are transmitted using the contention-based channel access method unlike contention-free access used in GTS. That is, transmission of data frames can fail due to contention or collision. Therefore, for the more realistic scenario, we need to consider the case where subset of the data frames scheduled in GTS are not successfully transmitted. Therefore, as shown in Fig. 3, we observe throughput improvement as a function of γ and PER_D when the size of beacon frame is 50 bytes. It shows that, as γ decreases, improvement also decreases. However, at 40% PER_D, more than 10% improvement can be obtained.
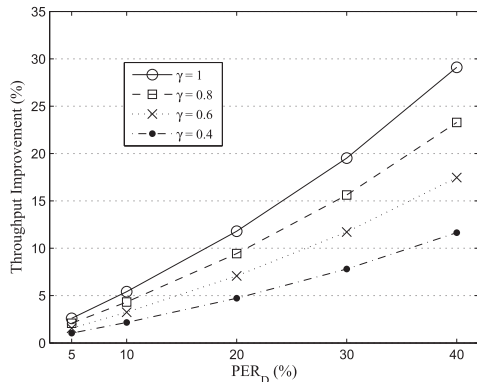
Fig. 3 Throughput improvement as a function of PER_D and γ when the size of beacon frame is 50 bytes.

Table 1 Simulation parameters.

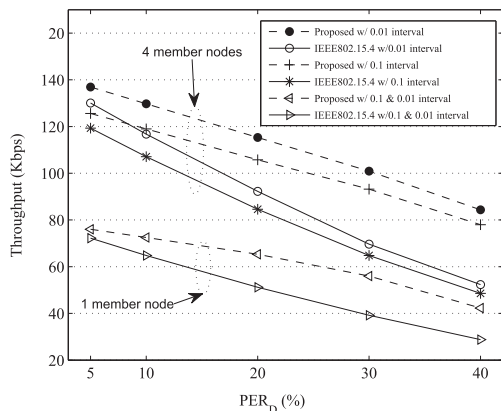| parameter	value
BO (Beacon Order)	8
symbol	16us
aBaseSlotDuration	60 symbols
aMaxLostBeacons	4
Contention Window (CW)	2
macMaxFrameRetries	3
macMinBE	3
macMaxBE	4
macMaxFrameRetries	3

Fig. 4 Throughput as a function of PER_D and frame inter-arrival time.

4.2   Analysis through Simulation

Throughput of IEEE 802.15.4-based protocol and our proposed method are compared through simulations using Network Simulator-2 (NS-2) version 2.34 [8]. For the simulations, piconets composed of one PNC and one or four member devices are considered, and network throughputs are evaluated by varying the PER_D from 5% to 40%. During the simulation, the nodes transmit data during CFP if it successfully receives a beacon frame. Otherwise, it will use CAP. Parameters used in simulation are shown in Table 1. Datarate for the simulation is set to 250 Kbps that is defined for 2.4GHz frequency in [1]. At the application layer, con-

stant bit rate (CBR) traffic is generated from the device, and the frame size is set to 100 bytes. We evaluate the network performance in 0.1 and 0.01 frame inter-arrival times. Each simulation runs 400 seconds and the results are average of 5 simulation runs. As shown in Fig. 4, throughput improvements with four member devices are achieved from 5% up to 58% for both 0.1 and 0.01 frame inter-arrival times. When there is single member device in a piconet, throughput improvements are achieved from 5.2% up to 43% for both 0.1 and 0.01 frame inter-arrival times. In the case of single member device, since the traffic load does not saturate the network, throughputs for both cases of 0.1 and 0.01 frame inter-arrival times are equal.

5.   Conclusion

The proposed protocol allows the devices to transmit their urgent data frames in CAP and inactive periods without colliding with any transmission in CFP when it loses a beacon frame. By using this protocol, average throughput performances are improved up to 68% in theoretical analysis and 59% in simulations.

Acknowledgments

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