Performance Improvement in Beacon-enabled LR-WPAN-based Wireless Sensor Networks

Hong Min Bae[1], Chan Min Park[2], Shinil Suh[2], Rana Asif Rehman[3] and Byung-Seo Kim[4]
[1]*Dept. of Electronics and Computer Eng., Hongik University, 2369 Sjongro, Sejongsi, Korea, Republic of*
[2]*Graduate School of Smart City Science Management, Hongik University, 2369 Sejongro, Sejongsi, Korea, Republic of*
[3]*Dept. of Electronics and Computer Eng., Hongik University, 2369 Sjongro, Sejongsi, Korea, Republic of*
[4]*Dept. of Computer and Information Communications Eng., Hongik University, 2369 Sejongro, Sejongsi, Korea, Republic of*

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Abstract: LR-WPANs have two types of networks: beacon–enabled and non-beacon-enabled networks. In beacon-enabled LR-WPANs, the high reliability of Beacon frame transmission is required because all transmissions is controlled by the in-formation in the Beacon frame. However, the process to handle the case for the beacon-loss is not well-defined in the standard. In this paper, an enhanced protocol for the case when a Beacon frame is lost is proposed to improve network performances. The protocol allows a device not receiving a Beacon frame to keep transmit its pending frames only within the minimum period of CAP based on the previously received Beacon frame while the standard prevents the device from sending any pending frame during a whole superframe. By simulation and evaluations, the effectiveness of the proposed protocol on improving performances is proven.

1 INTRODUCTION

IEEE802.15.4 standard (IEEE, 2011) specifies Low Rate-Wireless Personal Area Networks (LR-WPANs) for the low-cost devices' communications with a short range, low data rate, and low power consumption. Applications using such IEEE802.15.4 standards-based LR-WPANs have been increasing in broad areas including situation awareness, medical services, public safety, home entertainment system, smart home automation systems, ubiquitous building systems, traffic information systems, public safety systems, and so on. IEEE802.15.4 standard defines two types of LR-WPANs: beacon–enabled and non-beacon-enabled networks. Any transmissions of any device in the beacon-enabled LR-WPANs are controlled by the information in the Beacon frames transmitted by the central PAN coordinator. Therefore, the high reliability of Beacon frame transmission is essential for beacon-enabled LR-WPANs. Furthermore, the importance of beacon-enabled LR-WPANs also increases as multimedia traffics are served over WSNs to meet QoS.

However, Beacon frames are not successfully delivered to member devices because of collisions, interferences from other heterogeneous communication devices, and erroneous channel. The collision problems between Beacon frames have been studied in (Kim et al., 2008), (Koubaa et al., 2007), (Nam and Hwang, 2014), (IEEE, 2012). Beacon frame collisions occur when a device is in the transmission range of two PAN coordinators. In this case, the device may receive two Beacon frames from both coordinators at the same time and as a consequence the Beacon frames are in collision. To resolve this problem, researches in (Kim et al., 2008), (Koubaa et al., 2007), (Nam and Hwang, 2014), (IEEE, 2012) propose a few methods. Most of the methods are to schedule or to distribute the transmissions of Beacon frames of multiple piconets, so that the collision is prevented. Particularly, IEEE802.15.4e standard (IEEE, 2012) defines 'Beacon Scheduling" method to prevent from beacon collision. On the other hand, the loss of Beacon frame due to interference occurs because many communication networks like LR-WPANs, Wireless Local Area Networks (WLANs), and even microwaves uses same frequency bands of 2.4GHz which is called Industrial Scientific Medical (ISM) band (Lau et al., 2009). As a consequence, LR-WPANs experience severe interferences from other devices. The

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performance degradations of LR-WPAN due to interferences are reported by many experiments and studies as shown in (Howitt and Gutierrez, 2003), (Sikora and Groza, 2005), (Yoon et al., 2006), (Yuan et al., 2007), (Shin et al., 2007), (Park and Kim, 2014). As the electric power grid systems recently utilize LR-WPANs and WLANs, the interference issues in the power grid system is reported as shown in (Stanciulescu et al., 2012). Especially, as the number of deployed WLANs rapidly increases, the impacts on LR-WPANs of interferences from WLANs are actively researched in (Sikora and Groza, 2005), (Yoon et al., 2006), (Yuan et al., 2007), (Chen et al. 2015) and it is shown that LR-WPANs coexisting with WLANs experience 10~100 % degradations on the performances depending on the distances between LR-WPANs and WLANs, locations, the channels used by LR-WPANs, and the traffic loads of WLANs. There are many studies to avoid the interference. To resolve the problem, the most of methods switch the operating channels to non-interference channel. Some other methods allow piconets using interference channel to borrow some part of superframe of piconets using non-interference channel.

While all aforementioned studies propose methods to avoid a beacon loss, no aforementioned studies mentions the process itself for the case that a device fails to receive a Beacon frame. Even though many solutions have been proposed, Beacon frame can still be lost because of the channel characteristics like noise, fading, Doppler effects, and so on. Based on IEEE802.15.4 standard, devices failed to receive a Beacon frames have to hold their pending transmissions during a superframe, so that it cause performance degradations. Therefore, we need to a better way to improve the network performances when the Beacon frame is lost.

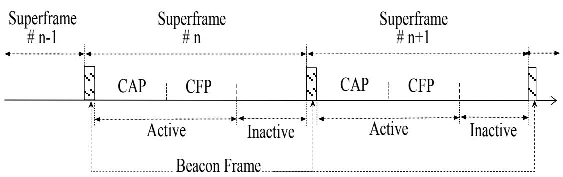

Figure 1: Superframe Structure.

In this paper, enhanced protocol is proposed to overcome the performance degradation when Beacon frames are not successfully transmitted in beacon-enabled LR-WPANs. The proposed protocol allows devices to transmit its pending frames during a Contention Access Period (CAP).

In Section 2, IEEE802.15.4 standard-based LR-WPANs and the process when the Beacon frame is lost are described. In Section 3, the proposed protocol is described and In Section 4, the performances of the proposed protocol is evaluated through extensive simulations. Finally conclusions are made in the last section.

2 PRELIMINARIES

2.1 IEEE802.15.4 Standard

Beacon-enabled LR-WPANs defined in IEEE802.15.4 standard operates within a certain time period, called 'Superframe'. The superframe is repeated and begins with Beacon frame which is transmitted periodically by a PAN coordinator. As shown in Fig. 1, a superframe is subdivided into two parts: Active and Inactive periods. During Active period, data is exchanged between devices in a piconet while nothing occurs during Inactive period. Inactive period is required to save device's energy. Therefore, even though devices have pending frames, they have to wait until upcoming active period in the next superframe. The durations of both periods can be varied. The Active period is composed of 16 slots and basic slot duration is 960us when using 2.4GHz-Direct Sequence Spread Spectrum (DSSS) mode (IEEE, 2011). The durations of superframe, Active period, and Inactive period are decided by a PAN coordinator and are informed to all member devices through Beacon frame. In addition to inform superframe structure information to all participating member device, the Beacon frame is also used to synchronize with participating devices and to identify the WPAN. As shown in Fig. 1, after Beacon frame, contention access period (CAP) and Contention Free Period (CFP) are followed in a row. CAP adopts the contention-based data transmissions like carrier sense multiple access with collision avoidance (CSMA/CA). CFP is composed of multiple Guaranteed Time Slots (GTSs). The durations of GTSs are decided by PAN coordinator and can be different in every superframe. The maximum number of GTSs in CFP is 7 and a GTS can occupy more than one slot. GTSs in CFP are also allocated by the PAN coordinator by devices' requests. The information on the GTS allocation is included in the Beacon frame. During GTS, only designated device transmits its packet without contention and collision.

Beacon Interval (BI) which is the length of the superframe is defined as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO} [symbols] \quad (1)$$

where *aBaseSuperframeDuration* is the number of symbols forming a superframe when the superframe order (SO) is equal to 0, and BO is Beacon Order that means how often the beacon is to be transmitted. *aBaseSuperframeDuration* is around 960 symbols recommended in (IEEE, 2011), BO is one value from 0 to 15 and SO is one value from 0 to BO. The active period, defined by *SuperframeDuartion* (SD), is calculated by:

$$SD = aBaseSuperframeDuration \times 2^{SO}[symbols]. \quad (2)$$

2.2 Process When Beacon Frame Is Lost

Even though we extensively research, no literature describing the process when Beacon frame is not successfully received has been found. Only both of IEEE802.15.4 and IEEE802.15.4e standards (IEEE, 2011), (IEEE, 2012) describes process for the case in which GTSs are allocated in the superframe. Based on standards, if a device requesting GTSs fails to receive Beacon frame, it has to hold its transmission during GTSs within the superframe. Even though it was assigned with GTSs in the previous superframe, it need to hold transmissions in the current superframe. Since a Beacon frame contains the information on superframe structure like period of CAP, the allocation of GTS, and so on, and the superframe structure can vary in every superframe, if a device fails to receive a Beacon frame, it can be assumed that it needs better to hold its transmissions during the superframe to prevent from collisions with other scheduled transmissions. This is ensured for the cases that the net-work parameters like the number of devices, traffic loads, etc. are frequently fluctuated.

Moreover, based on the standards, if an *aMaxLostBeacons* number of Beacon frames are not successfully received at a device, the device declares synchronization loss and starts orphan channel scan after discarding all buffered packets. That is, the device restart to associate with new piconet and this process waists lots of time.

Overall, the losses of Beacon frames cause holding devices' transmissions as well as the synchronization loss, and as consequences it severely degrades the network performances.

3 PROPOSED PROTOCOL

As mentioned in Section 2, the loss of Beacon frame makes devices to hold their transmissions during whole superframe period. In addition, *aMaxLostBeacons* time of Beacon frame losses causes re-association process starting from scanning process. Both of holding transmission and starting re-association process degrades performances of LR-WPANs. Even though many studies proposes methods to switch channels to reduce beacon loss, Beacon frames are still lost due to channel characteristics such as noise, interference, fading and so on. While preventing from losing Beacon frames has been studied a lot, there is no study on enhancement for the process when a Beacon frame is lost. Therefore, in this paper, we try to propose a backward-compatible and effective enhanced protocol.

The basic ides of the proposed protocol is to allows a device not receiving a Beacon frame (hereinafter it is called 'failed-device') to transmit its queued data not only in CAP, but also in Inactive period only if the device cannot wait GTSs in the next upcoming superframe because of delay constraints of the queued data frames. Since every superframe is guaranteed to have at least minimum CAP period which is around 7 slots, all failed-devices can safely transmit their data during the minimum CAP period.

3.1 Protocol Operations

The detailed process of the proposed protocol for a failed-device is as follows.

At the moment a device expects to receive a Beacon frame, if the frame is not received, the device declares to fail to receive a Beacon frame. Then, it checks if it has a data that was scheduled to be transmitted in a GTS. If it has ones, the device checks if the queued data can be held by the next upcoming superframe. If the transmission can be held, the device holds the data and wait for the next Beacon frame. However, if the data is delay-constraint traffic, so that it need to be transmitted in the current superframe, it transmit the data during CAP. Before transmitting the data, the device forms data frame by setting *Frame Type* field to 100 in binary number. Binary number 100 is not used in IEEE802.15.4 standard and is used to indicate that the data is transmitted by the rule of the proposed protocol. Then, the data frames are transmitted only during the possible minimum CAP period.

Based on IEEE802.15.4 standard, the minimum CAP period is defined as maximum number of slots assigned for CFP minus the number of slots in a superframe. Therefore, during CAP_{min}, the failed-device can safely transmit its data because CAP_{min} is a guaranteed period.

At the end of 16 slots which is at the end of current superframe period, if the device still has queued data to be transmitted in the current superframe, it keeps sending data frames even in upcoming Inactive period in the manner of CAP.

When transmitting a data in CAP, if a failed-device has more queued data to be transmitted, it sets *Frame Pending* field to 1. By doing this, the destination device expects more data is coming. When the device is not received next data frame in CAP, it won't go to sleep mode and waits even in Inactive period to receive the data frames until receiving a data frame with *Frame Pending* field set to 0.

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

Since our proposed method utilizes Inactive period, it may incur additional energy consumption. However, the use of inactive period is invoked only if there are still pending data that has not finished transmission in the CAP. In addition, even when listening during the inactive period, devices can minimize energy loss by using low-power listening techniques proposed in (Polastre et al., 2004). In addition, the proposed protocol targets not only to battery-powered WSNs, but also to many IEEE802.15.4 applications such as the smart grid AMI, where each device can be connected to a power source and low energy consumption is not the upper most requirement (low cost constraint is still valid, and low power is also valid due to regulatory reasons). These applications need to deal with high tra□c load since the network consists of a large number of devices. Thus, we focus on throughput rather than power consumption in our evaluation.

4 PERFORMANCE EVALUATIONS

4.1 Theoretical Analysis

The proposed protocol is compared with IEEE802.15.4-based protocol. Even though, as mentioned in Section 2, many methods to avoid from interferences are proposed, any protocol does not focus the process for the case of Beacon frame loss. Therefore, in terms of the process for beacon loss case, there is no comparative protocol, but IEEE802.15.4-based protocol.

The throughputs achieved by IEEE802.15.4 and the proposed protocol can be derived as Eq. (3) and (4), respectively.

$$Throughput_{IEEE} = \frac{D_{Succ} \cdot (1 - P_B) \cdot (1 - P_D) + D_{Loss} \cdot P_B \cdot (1 - P_D)}{T}, \quad (3)$$

$$Throughput_{proposed} = \frac{D_{Succ} \cdot (1 - P_B) \cdot (1 - P_D)}{T}, \quad (4)$$

where P_D and P_B are packet error rate of data and Beacon frames, respectively, D_{succ} is the amount of data transmitted when Beacon frame is successfully transmitted, D_{Loss} is the amount of data transmitted when it is failed to receive Beacon frame, and T is superframe duration. Therefore, comparing to IEEE802.14.5 standard-based protocol, the theoretical throughput gain obtained by the proposed protocol is

$$Throughput\_Gain = \frac{D_{Loss} \cdot P_B}{D_{succ} \cdot (1 - P_B)}. \quad (5)$$

4.2 Numerical Evaluations

4.2.1 Evaluations with Theoretical Analysis

Fig. 3 shows the throughput gains obtained from Eq. (5) as functions of Beacon frame size, P_D, and β. β is defined as D_{Loss}/D_{succ}, that is, β indicates how amount of data can be transmitted when losing Beacon frame comparing to that in normal case. When the bit errors are independently and Identically Distributed (i.i.d), the relationship between P_D and P_B is defined as follows (Rappaport, 2002), (Kim et al., 2010):

$$P_B = 1 - (1 - P_D)^{M/N}, \quad (6)$$

where M and N are the number of bits in a Beacon frame and a data frame, respectively. Varying the values of P_D emulates erroneous channel environment caused by interference, thermal noise, fading, collisions, etc. We evaluate throughput improvements by varying P_D from 5% to 40%. 40% packet error rate might be too high. However, as mentioned in Section 1, the packet error rate of LR-WPANs is widely distributed from 0% to 100%. Particularly, it is more severe when LR-WPANs coexist with WLANs. Thus, it is worthwhile to see the performances even in high packet error rate such as 40%.

As shown in Fig. 2, the proposed protocol achieves from 15% up to 67% performance improvement. When β is high, the gain is also high because the high value of β means more data transmitted during CAP even though Beacon frame is lost. When Beacon frame size is low, the proposed protocol achieves relatively low gain because the P_B is low. Since the proposed protocol enhances IEEE802.15.4

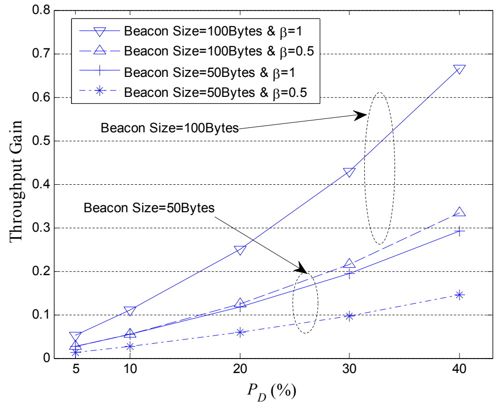

Figure 2: Throughput gain as a function Beacon frame size, β, and P_D.

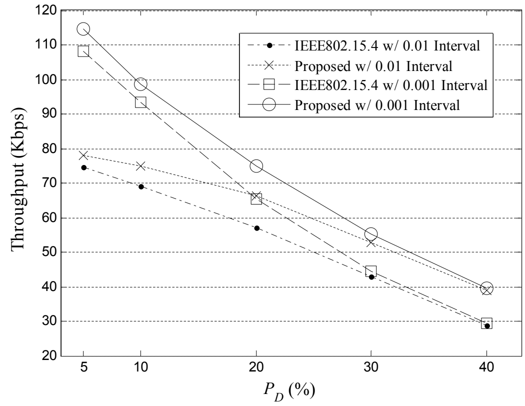

Figure 3: Throughput as a function of P_D and packet inter arrival time.

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

standard-based protocol when Beacon frame is lost, low value of P_B does not make big different in terms of performances.

4.2.2 Evaluations with Simulations

Throughputs of IEEE802.15.4-based protocol and proposed method are compared through simulations using Network Simulator-2 (NS-2) version 2.34. For the simulations, one piconet with a PAN coordinator and member devices are considered and throughputs between the PAN coordinator and the device are observed. We intentionally set P_D and change from 5% to 40% to emulate the degree of interference environment. Parameters used in simulation are shown in Table I. Data rate for the simulation is set to 125Kbps. In the application layer, constant bit rate (CBR) traffic is generated at the device, and the CBR packet size is 100bytes. The CBR packets are transmitted to the PAN coordinator through UDP/IP layer. We evaluate network performances in 0.01 and 0.001 packet inter-arrival times. Each simulation runs 100seconds. As shown in Fig. 3, throughput improvements are achieved from 4.5% up to 35% and from 5.9% to 33.6% at 0.01 and 0.001 packet inter-arrival times, respectively.

5 CONCLUSIONS

The reliability in the beacon transmissions is very critical on the performance of Beacon-enabled LR-WPANs because the loss of beacon causes for devices to hold their transmissions during the superframe. Unlike specification in the standard, the method proposed in the paper allows devices to transmit its pending packet only during the minimum period of CAP that is guaranteed in the superframe as well as Inactive period without colliding with any transmission in CFP. By using this protocol, it is proved that average performance throughputs are improved up to 65% in theoretical analysis and 35% in simulations over 40% packet error rate channel and 100-bytes Beacon frame size.

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