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Reliable beacon transmission based MAC protocol for LR-WPANs over WLAN interferences*

Ji-Hoon PARK[1], Byung-Seo KIM[‡2]
([1]ITO Business Division, Nongshim Data System, Seoul 156-709, Korea)
([2]Department of Computer and Information Communications Engineering, Hongik University, Sejongsi 339-701, Korea)
E-mail: pjh@nongshim.co.kr; jsnbs@hongik.ac.kr

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Abstract: The use of IEEE 802.15.4 standard based application systems has been rapidly increasing, for example, in medical services, sensor networks, public safety systems, and home automation systems. However, issues arise from the fact that IEEE 802.15.4 standard based low rate wireless personal area networks (LR-WPANs) use the same frequency bands as wireless local area networks (WLANs), and they interfere with each other. Based on past research on this issue, the interference has a more serious impact on LR-WPANs' performance than on WLANs' performance. In this paper we propose a method to improve LR-WPANs' performance while coexisting with WLANs, which is called the reliable beacon transmission based medium access control (MAC) protocol. Since the reliability of a beacon frame is important, in this method, only the beacon frame is transmitted in interference-free channels, and the data packets are transmitted in interfered channels instead of abandoning the channels altogether. This method increases the reliability of beacon frames as well as overall channel utilizations. The effectiveness of the proposed method was evaluated through extensive simulations, and this paper proves that this method improves the performance of IEEE 802.15.4 based wireless sensor networks (WSNs) over WLANs' interferences.

Key words: Low rate wireless personal area network (LR-WPAN), Interference, Wireless local area network (WLAN), Beacon
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1 Introduction

The IEEE 802.15.4 standard (IEEE, 2006) specifies low rate wireless personal area networks (LR-WPANs) for low-cost device communications in a short range and with a low data rate and low power consumption. Applications using such IEEE 802.15.4 standards based LR-WPANs have been increasing in broad areas, including wireless sensor networks (WSNs), medical services, smart home-automation systems, ubiquitous building systems, traffic information systems, and public safety systems. In particular, the number of WSN-based applications has increased due to emerging technologies, such as the Internet of Things (IOT) and machine-to-machine (M2M) communications. IEEE 802.15.4 specifies a total of 27 operational channels in three different frequency bands: 868 MHz, 915 MHz, and 2.4 GHz. Since the 2.4 GHz frequency band is the industrial, scientific, and medical (ISM) band, and is free to use, many communication devices, such as IEEE 802.15.1 based Bluetooth, IEEE 802.11b/g based wireless local area networks (WLANs), wireless medical devices, and 2.4 GHz cordless telephones, use the same frequency band—even microwave ovens generate radio signals belonging to this ISM band (Lau *et al*., 2009). As a consequence, IEEE 802.15.4 based devices experience severe interference from other devices. There are many studies on the performance degradation of LR-WPANs due to interference, as mentioned in Howitt and Gutierrez (2003), Shin *et al*. (2005;

‡ Corresponding author
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2007), Sikora and Groza (2005), Petrova and Gutierrez (2006), Yoon *et al*. (2006), Yuan *et al*. (2007), and Lau *et al*. (2009). Stanciulescu *et al*. (2012) showed that the performances of IEEE 802.15.4 based WSNs are significantly degraded for the Canadian power grid system. In particular, the impact of interference from WLANs on LR-WPANs were actively researched in Shin *et al*. (2005), Sikora and Groza (2005), Yoon *et al*. (2006), Petrova and Gutierrez (2006), and Yuan *et al*. (2007) because the number of deployed WLANs, popularly called Wi-Fi, has been rapidly increasing.

Fig. 1 shows the channel allocations of IEEE 802.11b/g based WLANs (IEEE, 2007) and IEEE 802.15.4 based LR-WPANs (IEEE, 2006) on a 2.4 GHz frequency band. The total number of channels for IEEE 802.11b/g is 14 and there are four non-overlapping channels, which are channels 1, 6, 11, and 14. However, since channel 14 is used only for IEEE 802.11b based systems in Japan (IEEE, 2007), it is not considered in this paper. As aforementioned, there are 27 channels specified in the IEEE 802.15.4 standard, which are allocated into three frequency bands. Channel 0 is allocated into the 868 MHz band, channels 1–10 into the 915 MHz band, and channels 11–26 into the 2.4 GHz band. Since the 2.4 GHz band is considered in this paper, only channels 11–26 are shown in Fig. 1. As a result, when excluding channel 14 used in WLANs, only four channels out of a total of 16 LR-WPAN channels allocated into the 2.4 GHz band do not overlap with channels for the WLANs. Hereinafter, any channel not overlapped with a WLAN channel is called an interference-free channel, while any channel overlapped with a WLAN channel is called an interfered channel. There are only four interference-free channels in 2.4 GHz based LR-WPANs.

When LR-WPANs coexist with WLANs in a same area, LR-WPANs experience serious degradation in their performance, while WLANs experience only a little degradation. The reason is as follows: WLAN devices cannot sense the transmission of LR-WPANs because the transmission power of LR-WPANs is too small to detect. Therefore, WLAN devices transmit their packets regardless of the on-going transmissions of LR-WPAN devices; thus, the communications between LR-WPAN devices are disabled. On the other hand, there is relatively little impact on the communications among WLAN devices, because the transmission power of WLAN devices is higher than that of LR-WPAN devices. Furthermore, when devices in LR-WPANs try to send their packets during the transmissions of WLAN devices, they can sense transmissions of WLAN devices and hold their transmissions. Therefore, it does not affect WLANs' on-going transmissions.

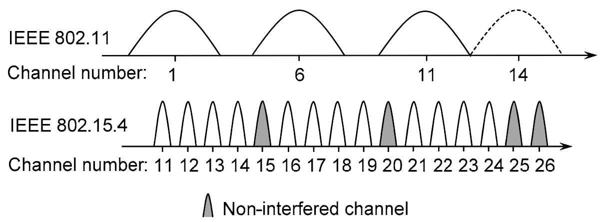

Fig. 1 Frequency plans specified in IEEE 802.11 and IEEE 802.15.4 standards

In addition, even if devices in LR-WPANs choose channels not overlapped by WLANs, new WLAN devices may set their networks using a channel that overlaps with the channel chosen by the device in LR-WPANs, because WLANs cannot sense the transmissions of LR-WPANs due to the low transmission power level.

The various experiments and studies in Howitt and Gutierrez (2003), Shin *et al*. (2005; 2007), Sikora and Groza (2005), Petrova and Gutierrez (2006), Yoon *et al*. (2006), and Yuan *et al*. (2007) show that LR-WPANs using interfered channels experience a 10%–100% degradation of their performance depending on location, the distance between LR-WPANs and WLANs, the channels used by LR-WPANs, and the traffic loads of WLANs. Furthermore, the research shows that the higher traffic loads in WLANs worsen the performances in LR-WPANs. Recently, the number of WLAN applications has grown, and the number of WLAN access points (APs) deployed in a certain area is increasing. Therefore, the probability that the channel chosen by an LR-WPAN can be interfered with by WLANs is high, and as a consequence, LR-WPANs have to use one of the four interference-free channels. However, even that is not so easy nowadays because, as previously mentioned, the number of LR-WPAN applications has also increased, used in various areas such as medical applications, location tracking, and various wireless sensors (Petrova and Gutierrez, 2006; Deylami and Jovanov, 2012). That is, it becomes more difficult for an LR-WPAN to use an interference-free channel. Thus, a way to improve the performance of an LR-WPAN with an interfered channel is needed when it coexists with WLANs.

The IEEE 802.15.4 standard defines two types of LR-WPANs: non-beacon-enabled LR-WPANs and beacon-enabled LR-WPANs. In beacon-enabled LR-WPANs, the networks require a central controller, called the piconet controller (PNC), to periodically send beacon frames. All participating devices communicate based on the information in the beacon frames. In this paper, a method is proposed to improve the performance of beacon-enabled LR-WPANs coexisting with WLANs. The method focuses on protecting the transmissions of beacon frames from interference from WLANs in the use of interfered channels. Even though LR-WPANs are interfered with by WLANs, LR-WPANs may not be seriously affected unless the traffic loads in WLANs are heavy. This means that the interfered channel does not have to be abandoned. However, there is a frame that requires high reliability, which is a beacon frame. Therefore, the loss of beacon frames has a severe impact on the performance of LR-WPANs.

2 Problem formulation

2.1 Beacon loss in the IEEE 802.15.4 standard

The method proposed in this paper targets beacon-enabled LR-WPANs. Based on the IEEE 802.15.4 standard, a network is composed of a PNC and member devices, and the member devices are synchronized with the PNC using beacon frames that are periodically transmitted by the PNC. The time duration between two consecutive beacon transmissions is called a superframe, and the superframe is divided into active and inactive periods. While the active period is used for the devices' data transmissions, no device allows for transmitting data during inactive periods in order to save power. Furthermore, the 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 the CAP, GTS, and the inactive period. Therefore, a device has to periodically receive beacon frames from the PNC to obtain information for the upcoming superframe. If the device does not receive beacon frames aMaxLostBeacons times, it declares a synchronization loss and starts an orphan channel scan after discarding all buffered packets in the medium access control (MAC) layer. The orphan channel scan will scan the channels in a specified set of logical channels to search for a PNC to re-associate with. When starting the orphan channel scan, the device sends an orphan notification command and waits for a coordinator realignment command from a PNC within the macResponseWaitTime symbol period. This process is repeated for the channels in the set of logical channels.

The process when a device loses 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 and it loses 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 and allocation of GTS), and the information can be changed 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 in which the network parameters (such as the number of devices and traffic loads) frequently vary, every superframe structure needs to be changed and the information for the changed superframe is carried by beacon frames. Therefore, the loss of beacon frames causes devices to hold their transmissions to prevent them from having unnecessary collisions with other devices' transmissions.

Overall, the loss of beacon frames causes synchronization loss and holding device transmissions, and thus degrades the network performance.

There are a few studies on the loss of beacon frames in IEEE 802.15.4 based LR-WPANs (Kim *et al*., 2008; Lau *et al*., 2009). Kim *et al*. (2008) considered the collision of beacon frames from multiple piconets. In addition to synchronization loss and halting data transmissions, Lau *et al*. (2009) claimed that the loss of beacon frames also causes the accuracy in the localizations of IEEE 802.15.4 based sensor networks to deteriorate. Based on this study, the localization errors increase by up to 141% due to beacon loss when WPANs are coexisting with WLANs.

2.2 Related works

A few studies have been conducted to resolve the aforementioned issues.

Kim *et al*. (2008) provided a way to prevent beacon frames from collisions. A channel scan was performed during an inactive period to keep track of the channel information around a PNC. When a beacon's collision was detected, the operating channel of the PNC was quickly changed. However, this method is not applicable when there is no possible interference-free channel. Furthermore, the devices need to wake up even during the inactive period, which causes more power consumption than the conventional method does. Like Kim *et al*. (2008), Yun *et al.* (2008) proposed to switch the operating channel to an interference-free channel whenever a PNC detects interferences. However, Yun *et al.* (2008) focused on the interference detection method rather than a method to avoid interferences.

Pollin *et al*. (2006) proposed two methods for non-coordinated LR-WPAN networks. In the first method, a device chooses randomly a channel in every period and sends data to a device using the same channel. The second method is to select a proper channel based on information obtained from scanning channels in every superframe period. Therefore, the operating channel is frequently changed. Methods proposed in Pollin *et al*. (2006), Kim *et al*. (2008), and Yun *et al.* (2008) are based on switching channels if any interference is detected in the used channel. The methods cause an increase of overhead to exchange channel information and piconet information after changing the channel. In addition, severe fluctuations in the network resources such as traffic loads and the number of devices cause severe negative impact on the performances of LR-WPANs.

Zhang and Shin (2011) proposed a method using a busy tone signal. A device was selected as a signaler sending a busy tone signal to member devices. The signaler needs to be close enough to the WLANs, so that the signal can be sensed by the WLANs. The signaler schedules other devices' data transmissions and sends the busy tone signal when the other device starts transmitting a data packet. Because WLANs sensing the busy tone signal hold their transmissions, collisions can be prevented. However, this method may not be effective if no signaler is close enough to the WLANs. In addition, an additional radio is required to generate the busy tone signal, and power consumption is high.

Kim *et al*. (2009) proposed a way to share an interference-free channel which is being used by a piconet (called the 'primary piconet', P-piconet for short). When a new piconet (called the 'secondary piconet', S-piconet for short) needs to use an interference-free channel already in use, the active period for the S-piconet uses some part of the inactive period in the superframe of the P-piconet without interrupting on-going operations of the P-piconet. The inactive period can be shared by multiple S-piconets. To minimize the overlapping of the active periods of multiple piconets, Kim *et al*. (2009) proposed a scheduling algorithm for the piconets. However, the algorithm is complicated, and the proposed method is applicable only in applications generating low traffic loads, such as automatic meter reading (AMR). Therefore, the proposed method is not scalable for such applications as visual sensor networks (Soro and Heinzelman, 2009) where high traffic loads are generated with a variable bit rate.

Deylami and Jovanov (2012) proposed a way to resolve the overlapping problem of the active periods of S-piconets in Kim *et al*. (2009). While an S-piconet schedules its own active periods based on the beacon frame of the PNC in the P-piconet in Kim *et al*. (2009), the S-piconets in Deylami and Jovanov (2012) schedule their active periods by obtaining sharing information from other S-piconets that are using the inactive periods of the P-piconet. Deylami and Jovanov (2012)'s method is more effective than that of Kim *et al*. (2009). However, it requires more overhead and is still not scalable or flexible.

3 Reliable beacon transmission based MAC protocol

3.1 Motivation

As mentioned in Section 2.2, some of the existing methods use inactive periods of interference-free channels of other piconets, and some methods switch a current operating channel to the other piconet's channels to experience certain levels of interference in the current channel. The former is neither flexible nor scalable. The latter requires some overhead to exchange channel information and reset the operating channel. Both types of methods experience severe performance degradation when the status of the channel is fluctuating. Furthermore, all these methods abandon the interfered channel, which leads to low overall channel utilization. Therefore, in this paper, we propose a method to improve the performances of LR-WPANs using an interfered channel without abandoning the interfered channel or changing the operating frequency for the whole active period. In addition, our method achieves scalability and flexibility by minimizing the effects on the operations of the piconets using frequencies of an interference-free channel.

Abandoning overlapped channels to avoid interferences with WLAN is not appropriate considering that the frequency spectrum is a scarce resource in wireless networks. Some previous research (Howitt and Gutierrez, 2003; Shin *et al*., 2005; 2007; Sikora and Groza, 2005; Petrova and Gutierrez, 2006; Yoon *et al*., 2006; Yuan *et al*., 2007) was performed under the assumption that the WLAN's traffic was saturated, so that the LR-WPAN performances dropped by more than 90%. However, in reality, the traffic loads in WLANs are not always saturated, so abandoning the overlapped channels is not appropriate. The method proposed in this paper allows for the use of an interfered channel by protecting the beacon frame from the interference. As mentioned above, the loss of beacon frames in an LR-WPAN causes huge performance degradations because the association is terminated between a PNC and a device, and the re-association process requires long process delays. Therefore, the main focus of this study is to maintain high reliability of beacon frame transmission over the WLAN's interferences.

In summary, in this paper we propose a reliable beacon transmission based MAC (RBT-MAC) protocol to increase the performances of LR-WPANs even using an interfered channel, while not affected by the variations of the other LR-WPANs using interference-free channels. As a consequence, this method increases the utilizations of the total channels assigned to LR-WPANs. Furthermore, this method maintains backward compatibility. In fact, our previous work Park and Kim (2014) proposed a similar method. However, Park and Kim (2014) did not consider the process of an orphan channel scan, did not contain many detailed processes or illustrations, and provided only mathematical evaluations under many environmental assumptions.

3.2 Overview of RBT-MAC

The scenario considered in this study is that a device needs to set its own piconet under the following circumstances: all four non-overlapped frequencies are used by piconets and a WLAN is operating. That is, the new piconet has to use a channel overlapped with the WLANs' operating channels. Here, two types of piconets are considered: P-piconet and S-piconet. P-piconet is a piconet using one of the interference-free channels, and S-piconet is a new piconet which has to use channels overlapping with the WLAN's channels. In this scenario, the proposed protocol provides a way to prevent beacon frames from being corrupted due to the interferences from the WLAN.

The key feature of the proposed protocol is to allow the S-piconet to transmit its beacon frames in a channel being used by a P-piconet. By doing so, the reliability on transmitting the S-piconet's beacon frames is achieved. The beacon frame is transmitted during the inactive period of the superframe of the P-piconet. On the other hand, except beacon frames, other frames including data frames and command frames are transmitted during active periods of the S-piconet's superframe in a selected channel overlapping with the WLAN's channel.

An example of constructing superframes using the proposed protocol is illustrated in Fig. 2. The first superframe is for a P-piconet using channel 15 and the lower two superframes are S-piconets using channels 11 and 12, respectively. As shown in the figure, the beacon frames of S-piconets are transmitted at the end of the inactive periods of the P-piconets' superframe, while the data frames in the S-piconets are transmitted during an active period of the superframe using channels 11 and 12. All member devices in the S-piconets switch their operating channel to channel 15 in order to listen to a beacon frame and switch back to the operating channel for data transmissions.

However, an S-piconet uses the proposed method if its channel is interfered by the WLAN's signal more than a certain threshold γ. If the interference level experienced by an S-piconet is less than γ, using the current channel is better than switching the channel to the P-piconet's channel in order to listen to its beacon.

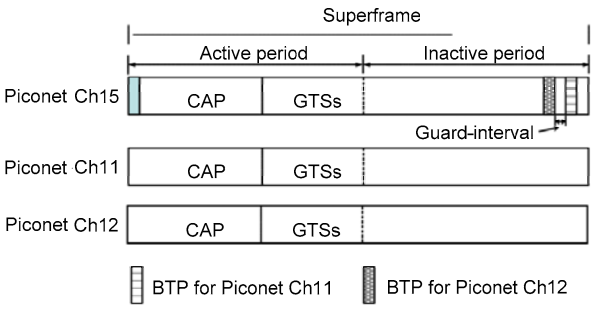

Fig. 2 An example of constructing superframes using the proposed method

The periods of transmitting beacon frames (called the beacon transmission period, BTP) of S-piconets are allocated from the end to the beginning of the inactive period of the P-piconet following the order of the requests from the S-piconets. In Fig. 2, because the BTP for S-piconetCh11 is close to the end of the superframe of the P-piconet, it is assumed that S-piconetCh11 requests the BTP earlier than S-piconetCh12. This is to cope with the cases in which the P-piconet increases the active periods.

The details on the proposed protocols are illustrated in Section 3.4.

3.3 New command frames for RBT-MAC

To operate RBT-MAC, three new command frames are designed: beacon-allocation (BA)-request, BA-response, and beacon-de-allocation (BD)-request (Fig. 3). The formats of the MAC headers of the three frames are based on the command frame format specified in the IEEE 802.15.4 standard, so that the frame type subfield in the frame control field in the MAC header is set to 011 (code number for the command frame) defined in IEEE 802.15.4 (IEEE, 2006). Command frame identifiers for BA-request, BA-response, and BD-request frames are set to 0x0A, 0x0B, and 0x0C, respectively.

The BA-request frame is used to request an admission for a device (to be a PNC of S-piconet) to use the inactive periods of the P-piconet's superframe to transmit the device's beacon frame. In Fig. 3a, the beacon length field is the number of symbols indicating the required length of the beacon frame.

(a)

Octets	1	1
MAC header	Command frame identifier	Beacon length

(b)

Octets	1	1	2	1
MAC header	Command frame identifier	Beacon ID	Beacon Tx time	Max. BTP

(c)

Octets	1	1
MAC header	Command frame identifier	Beacon ID

Fig. 3 Frame formats of BA-request (a), BA-response (b), and BD-request (c)

The BA-response frame is sent back to the device from a PNC of the P-piconet in order to inform the decision on the BA-request frame. In Fig. 3b, the beacon ID field is an identification number that the PNC of the P-piconet assigns to a PNC of the S-piconet. This is to distinguish beacon frames transmitted in an inactive period when multiple BTPs are allocated. The beacon Tx time is the number of symbols indicating the beginning of the allocated BTP in the inactive period. That is, the PNC of the S-piconet sends its beacon frame after the beacon Tx time at the end of the active period. The max. BTP is also the number of symbols indicating the maximum periods allowed for transmitting the beacon frame of the S-piconet. Therefore, the length of the S-piconet's beacon frame can be varied up to max. BTP.

The BD-request frame is sent by the PNC of the S-piconet when the S-piconet does not need to send beacons over the channel of the P-piconet anymore.

For a beacon frame of the S-piconet, one new subfield, called the actual-channel-number, is appended right after the pending address field in the beacon payload (Fig. 4). The new subfield indicates the number of the channel where actual data transmissions of the S-piconet are performed, and the field is set to a channel number from 11 to 26. To distinguish this beacon frame from a normal one, the frame type in the frame control field in the MAC header is set to 100, which is one of the unused values in the IEEE 802.15.4 standard.

Fig. 5 shows the format of the RBT-MAC coordinator realignment command sent by a PNC as a

Octets: 2	1	4/10	0/5/6/10/14	2	variable	variable	variable	2
Frame control	Sequence number	Address field	Auxiliary security header	Superframe specification	GTS field	Pending address fields	Beacon payload	FCS

1	variable
Actual channel number	Payload

Fig. 4 Format of a beacon frame for reliable beacon transmission based MAC (RBT-MAC)

Octets:	1	2	2	1	2	0/1
MAC header	Command frame identifier	PAN identifier	Coordinator short address	Logical channel	Short address	Channel page

Fig. 5 Format of an RBT-MAC coordinator realignment command

response for an orphan notification command. This is used to re-establish re-association with the PNC when a device loses synchronization with a PNC. The format in Fig. 5 is the same as that of a conventional coordinator realignment command defined in the IEEE 802.15.4 standard except for two fields. The command frame identifier field in the new command is set to 0x0D to distinguish it from a coordinator realignment command in the IEEE 802.15.4 standard. In addition, the logical channel field represents the interference-free channels, where the beacon frames for the S-piconet are transmitted, instead of the interfered channel, where data packets in the S-piconet are sent.

3.4 Operation of the RBT-MAC protocol

In this subsection, the detailed operation of the RBT-MAC protocol is illustrated. The protocol is explained in terms of setting an S-piconet and becoming a member of the S-piconet.

The procedure of generating and terminating S-piconets is as follows:

Step 1: If all the interference-free channels are being used by other piconets and all interfered channels are being occupied by interference signals more than γ, the device selects two channels with the best signal-to-noise ratio (SNR) among the interference-free channels and the interfered channels. The selected interference-free channel and interfered channel are represented by f_p and f_s, respectively.

Step 2: The device sends a BA-request frame to the PNC of the P-piconet using f_p after setting the fields of the frame as mentioned in Section 3.3. This frame is sent during the CAP of the P-piconet.

Step 3: A PNC receiving the BA-request frame decides if it accepts the request.

Step 3.1: If the possible inactive period is larger than the beacon length in the BA-request frame and the PNC decides to accept the request, it sends the BA-response frame back after setting unique beacon ID, beacon Tx time, and max. BTP fields. The PNC then records the admitted beacon frame information in a table as shown in Fig. 6.

Beacon ID	Beacon Tx time	Max. beacon period
0000 0001	0000 0000 1111 1111	0000 0000 0111 1111
⋮	⋮	⋮

Fig. 6 An example of the table recording admitted beacon frames in a PNC of P-piconet

Step 3.2: Otherwise, it ignores the request frame and does nothing.

Step 4: This step explains the process with and without receiving BA-response frame.

Step 4.1: If the device does receive the BA-response frame, it becomes a PNC of the S-piconet and sends its own beacon frame after setting the actual-channel-number field to f_s at beacon Tx time. The length of the beacon frame has to be less than the value in the max. BTP field in the BA-response frame.

Step 4.2: If the device does not receive the BA-response frame within a long inter frame space (LIFS) time defined in the IEEE 802.15.4 standard, it then retransmits the BA-request frame. The maximum number of retransmissions is set to macMaxFrameRetries defined in the IEEE 802.15.4 standard.

Step 5: If the PNC of the S-piconet wants to stop operating its own piconet, it sends the BD-request frame to the PNC of the P-piconet.

Step 6: When the PNC of the P-piconet receives the BD-request frame, it removes information of the beacon ID from the table recording admitted beacon frames (Fig. 6).

The association process with the RBT-MAC based piconet, which is for a device to associate with an S-piconet for the first time, is as follows:

Step 1: A device searches for the beacon frame providing a required service.

Step 2: When the device decides which beacon frame that it wants to associate with, it starts the association process with the PNC of the beacon frame.

Step 2.1: If the frame type field of the beacon frame is set to 100, it records the data transmission channel to f_s in the actual-channel-number field in the beacon frame.

Step 2.1.1: Even though the device receives the beacon frame at f_p, it performs associations with the PNC over f_s by exchanging the command frames defined in the IEEE 802.15.4 standard for the association.

Step 2.1.2: After association, except for the listening beacon frames at f_p, the device stays in channel f_s for its command and data transmissions.

Step 2.2: If the frame type field of the beacon frame is not set to 100, it follows the process specified in the IEEE 802.15.4 standard.

Fig. 7 shows a flow chart of the RBT-MAC protocol to configure and associate with the S-piconet. In addition, Fig. 8 shows the flow chart explaining the process of the PNC in the P-piconet.

3.5 Process for an orphan channel scan

If a device loses synchronizations with the PNC after losing the aMaxLostBeacons number of beacon frames, it starts an orphan channel scan by sending an orphan notification command in an active period in f_s. When a PNC in an S-piconet receives the commands and uses the RBT-MAC protocol, it sends the RBT-MAC coordinator realignment command shown in Fig. 5. The command frame identifier in the command format in Fig. 5 is set to 0x0D to distinguish it from a coordinator realignment command in the IEEE 802.15.4 standard. In the frame, the logical channel field represents f_p.

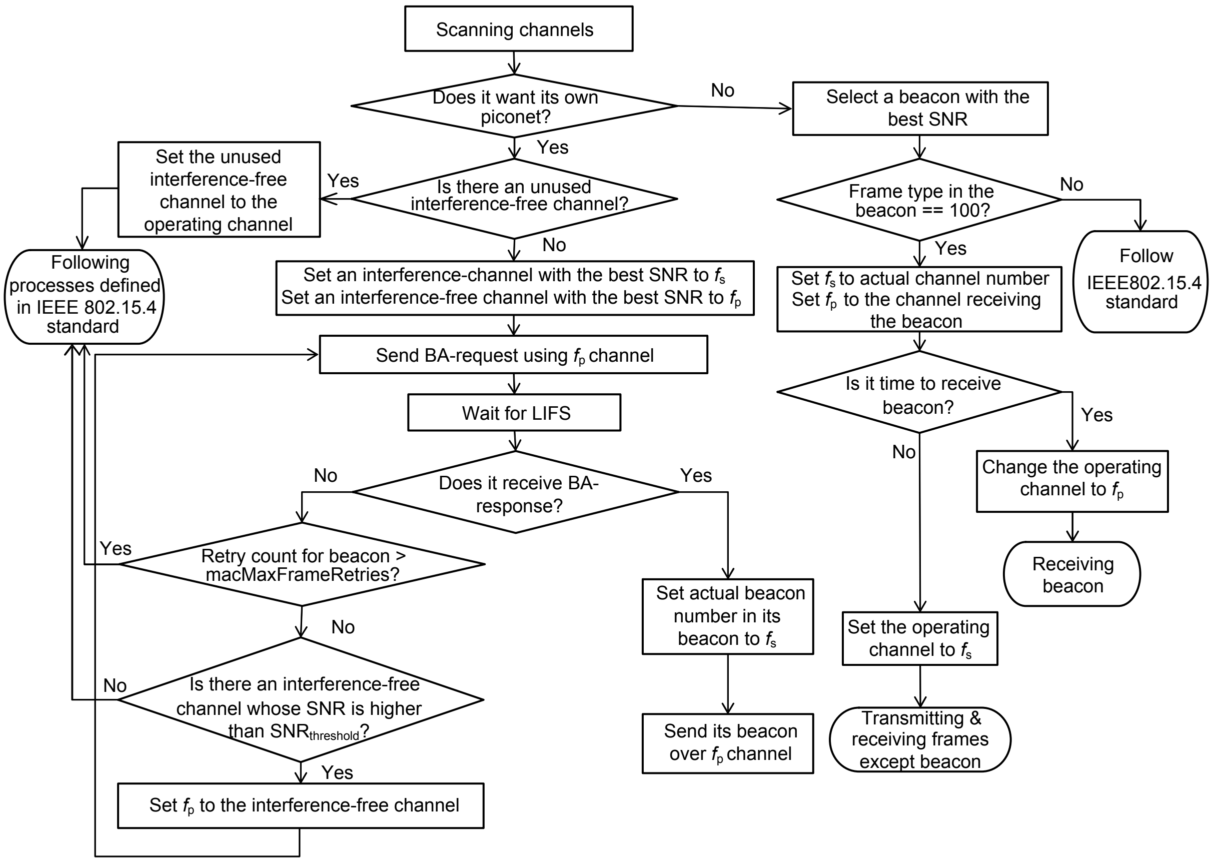

Fig. 7 Flow chart of the process that a device configures and associates with the S-piconet using the RBT-MAC protocol

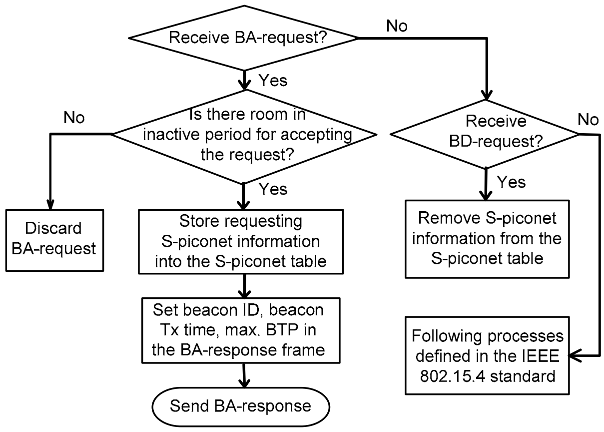

Fig. 8 Flow chart of the process at a PNC of the P-piconet

4 Performance evaluations

4.1 Simulation environments

The RBT-MAC protocol is evaluated through extensive simulations using the Network Simulator-2 (NS-2) version 2.34. The RBT-MAC protocol is compared with the IEEE 802.15.4 standard based MAC protocol. Even though a few methods have been proposed, as mentioned in Section 2.2, most of the protocols avoid the interfered channels by switching the operating channels or using the inactive periods of the pre-existing superframes. Therefore, in terms of keeping the use of interfered channels in the RBT-MAC protocol, there is no comparative protocol but the IEEE 802.15.4 based protocol.

For the simulations, one piconet with a PNC and a member device is considered as an S-piconet. The network environment for the simulations assumes that there is no available interference-free channel and other interfered channels are being interfered by the WLANs as in previous research (Deylami and Jovanov, 2012; Stanciulescu *et al.*, 2012). To analyze the performances of RBT-MAC, the communication performances between PNC and the device are observed. As mentioned in Section 1, previous research on the impact of interferences on LR-WPANs shows that the packet error rate of LR-WPANs is widely distributed from 10% to 100%, depending on the various network environments. Therefore, instead of implementing actual transmissions of WLANs, we emulate data packet errors due to the interferences of WLANs using the packet error rate (PER). That is, the PER represents the degree of interferences from WLANs. Therefore, the various interference environments are modeled by varying the PER. In this study, the performances of LR-WPANs are evaluated as varying the PER.

In this study, we vary the PER for data packets, P_{data}. When the bit errors are independent and identically distributed (i.i.d.), the PER for the beacon frames, P_{beacon}, is obtained as follows (Rappaport, 1996; Kim *et al.*, 2010):

$$P_{beacon} = 1-(1-P_b)^M, \tag{1}$$

where P_b is the bit error rate, $P_b=1-(1-P_{data})^{1/N}$, and M and N are the numbers of bits in the beacon and data frames, respectively. In these simulations, packet errors due to interferences only are considered. As mentioned before, previous experimental research reported that the PER of LR-WPANs due to the interference signals from WLANs is varying from 10% to 100% depending on the traffic loads of WLANs. Therefore, it is worthwhile to evaluate the performances of the proposed method in the worst PER cases. Therefore, the performances of RBT-MAC and IEEE 802.15.4 based MAC protocols are evaluated over PER of 20%–80%. The data rate for the simulation is set to 125 kbps. In the application layer, the constant bit rate (CBR) traffic is generated at the device associated with the PNC, and the CBR packet size is 100 bytes. The detailed simulation parameters are obtained from the IEEE 802.15.4 standard (IEEE, 2006) and are shown in Table 1.

Table 1 Simulation parameters

Parameter	Value
Symbol	16 μs
aBaseSlotDuration	60 symbols
aMaxLostBeacons	4
Contention window (CW)	2
SIFS	12 symbols
LIFS	40 symbols
CCA period	128 μs
macMaxFrameRetries	3
Number of operating channels	16
macMinBE	3
macMaxBE	4
macMaxFrameRetries	3

As defined in the IEEE 802.15.4 standard, the beacon interval, BI, is obtained by

$$BI = aBaseSuperframeDuration \cdot 2^{BO}, \quad (2)$$

where aBaseSuperframeDuration is a minimum size of the superframe in the unit of symbol, and BO is a beacon order.

4.2 Performances of the RBT-MAC protocol

Fig. 9 shows the throughputs of both protocols as a function of the packet error rate and beacon frame length. Figs. 9a and 9b show the results with 0.1 s and 0.001 s packet inter-arrival time, respectively. The packet error rate in the figures represents the error rate of the data packets caused by interference from WLANs.

In Fig. 9, the most upper line is the throughput of the RBT-MAC protocol, and the other lines are throughputs of the IEEE 802.14.5 based protocol with different sizes of beacon frames. Because beacon frames in the RBT-MAC protocol are transmitted over the interference-free channel, the throughput of RBT-MAC does not depend on the size of the beacon frame.

On the other hand, the throughput of the IEEE 802.15.4 based protocol decreases as the size of the beacon frame increases, which means the probability of loss of beacon frames increases. The loss of beacon frames causes the devices to hold their transmission during the superframe. Furthermore, as the probability of loss of beacon frames increases, the probability of synchronization loss also increases. As mentioned above, the device starts an orphan channel scan for re-association when losing synchronization. Therefore, the device stops its data transmission until re-association is completed. Since devices hold their transmissions during the re-association process, the network utilization degrades. As shown in Fig. 9, the improvement in the throughput obtained using the RBT-MAC protocol increases as beacon frame length increases. The throughput improves by more than 3 times at 0.1 s inter-arrival time and 7 times at 0.001 s inter-arrival time when the PER is 80%. When the PER is 20%, the improvement is improved from 2% at 0.1 s packet inter-arrival time to 26% at 0.001 s inter-arrival time.

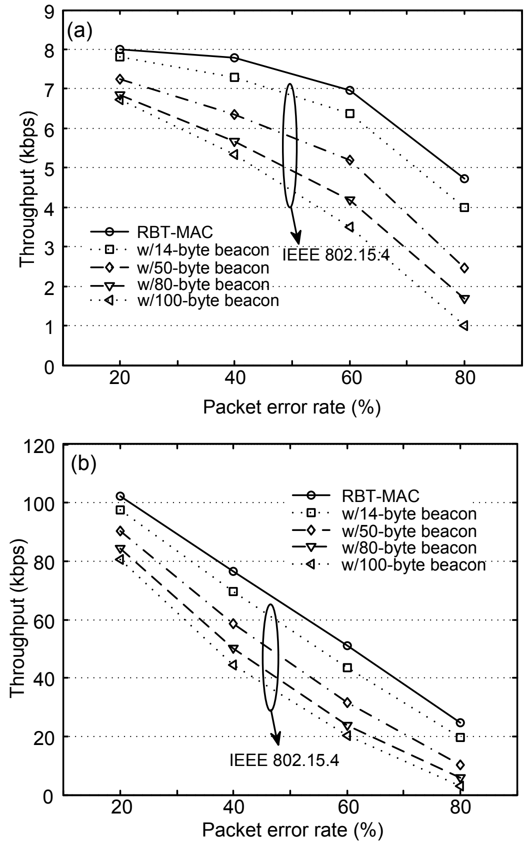

Fig. 9 Throughput as a function of the packet error rate and beacon frame length with 0.1 s (a) and 0.001 s (b) packet inter-arrival time

Figs. 10a and 10b show the throughput as a function of the packet error rate and packet inter-arrival time with a 14- and 100-byte beacon frame, respectively. Fig. 10 also shows the performance improvements obtained using the RBT-MAC protocol. The performances with 0.01 s and 0.001 s inter-arrival time are similar when the PER is larger than 40%. The reason is that the PER causes retransmissions for the erroneous packets; as a consequence, the traffics over the networks are saturated. Therefore, for the PER larger than 40%, the performances of the RBT-MAC protocol with 0.01 s and 0.001 s inter-arrival time are almost the same.

Fig. 11 shows the throughput of both protocols as a function of BO when the beacon frame size is 80 bytes and the PER is 60%. The throughput of the IEEE 802.15.4 based protocol decreases as BO decreases, which means more packets are held as synchronization losses occur more often. On the other hand, the change of BO has small impact on the throughput of the RBT-MAC protocol. The reason is that RBT-MAC does not experience any synchronization loss because the devices with the RBT-MAC protocol are not affected by interference from WLANs.

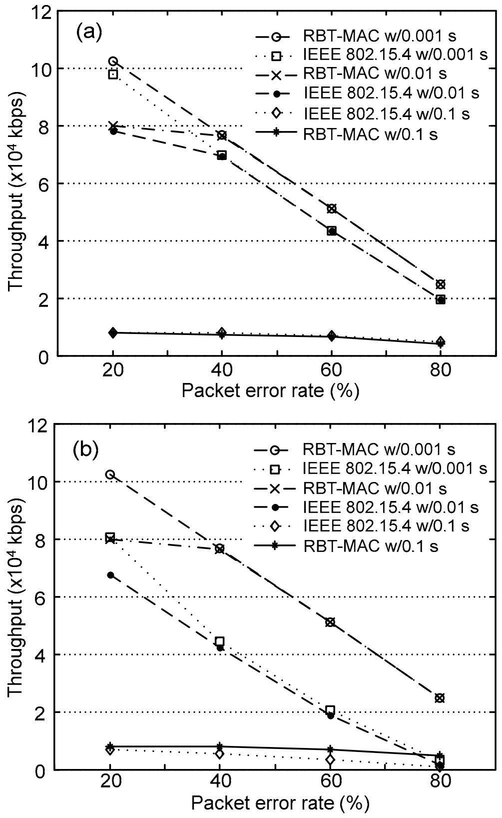

Fig. 10 Throughput as a function of the packet error rate and packet inter-arrival time with a beacon frame length of 14 bytes (a) or 100 bytes (b)

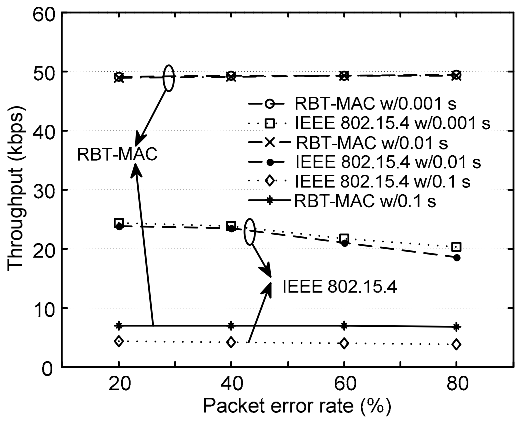

Fig. 11 Throughput as a function of the BO using a 80-byte beacon frame and 60% PER

Fig. 12 shows the number of synchronization losses in the IEEE 802.15.4 based protocol. The number of synchronization losses increases as the PER and beacon frame length increase. That is, by transmitting the beacon frame in the reliable channel, the RBT-MAC protocol can significantly reduce the probability that a synchronization loss occurs.

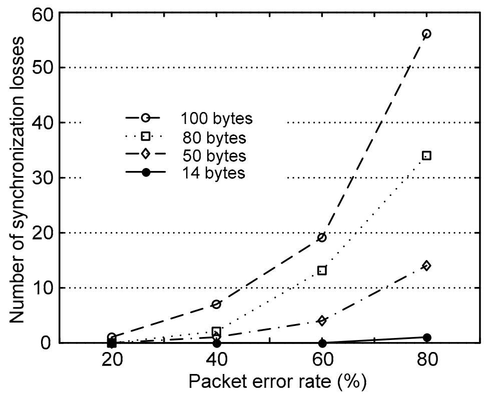

Fig. 12 Number of synchronization losses as a function of the packet error rate and beacon frame length

5 Conclusions

LR-WPAN is popularly used for implementing WSNs. Because the transmission power in the LR-WPAN is low, when coexisting with WLANs, LR-WPANs experience severe performance degradations due to the interferences from WLANs. In this paper, a method is proposed to enhance LR-WPANs' performances over the interferences from WLANs. Since LR-WPANs' performances are not severely degraded unless the traffic loads in WLANs are heavy, this method uses the interfered channel for data transmissions, instead of abandoning the channels as done in previous research. On the other hand, because the loss of beacon frames causes severe performance degradations, this method allows the beacon frame to be transmitted in an interference-free channel. Therefore, the S-piconet is not affected by the changes in the network parameters of P-piconets and can use even the interfered channels. Simulations show that the performances of this method increase by up to 7 times when compared to those using conventional LR-WPANs.

References

Deylami, M., Jovanov, E., 2012. A distributed and collaborative scheme for mitigating coexistence in IEEE 802.15.4 based WBANs. 50th Annual Southeast Regional Conf., p.1-6. [doi:10.1145/2184512.2184514]

Howitt, I., Gutierrez, J.A., 2003. IEEE 802.15.4 low rate-wireless personal area network coexistence issues. Wireless Communications and Networking Conf., p.1481-1486. [doi:10.1109/WCNC.2003.1200605]

IEEE, 2006. IEEE Std. 802.15.4:2006, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specification for Low Rate.

IEEE, 2007. IEEE Std. 802.11:2007, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

Kim, B.S., Kim, S.W., Fang, Y., *et al.*, 2010. Feedback-assisted MAC protocol for real time traffics in high rate wireless personal area networks. *Wirel. Networks*, **16**(4): 1109-1121. [doi:10.1007/s11276-009-0191-0]

Kim, J.W., Kim, J., Eom, D.S., 2008. Multi-dimensional channel management scheme to avoid beacon collision in LR-WPAN. *IEEE Trans. Consum. Electron.*, **54**(2):396-404. [doi:10.1109/TCE.2008.4560105]

Kim, T.H., Ha, J.Y., Choi, S., 2009. Improving spectral and temporal efficiency of collocated IEEE 802.15.4 LR-WPANs. *IEEE Trans. Mob. Comput.*, **8**(12):1596-1609. [doi:10.1109/TMC.2009.85]

Lau, S.Y., Lin, T.H., Huang, T.Y., *et al.*, 2009. A measurement study of ZigBee-based indoor localization systems under RF interference. 4th ACM Int. Workshop on Experimental Evaluation and Characterization, p.35-42. [doi:10.1145/1614293.1614300]

Park, J.H., Kim, B.S., 2014. Performance improvements on LR-WPANs over interference from WLANs. *IEICE Trans. Inform. Syst.*, **E97-D**(1):151-154.

Petrova, M., Gutierrez, J.A., 2006. Performance study of IEEE 802.15.4 using measurements and simulations. Wireless Communications and Networking Conf., p.487-492. [doi:10.1109/WCNC.2006.1683512]

Pollin, S., Ergen, M., Timmers, M., *et al.*, 2006. Distributed cognitive coexistence of 802.15.4 with 802.11. 1st Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications, p.1-5. [doi:10.1109/CROWNCOM.2006.363456]

Rappaport, T.S., 1996. Mobile radio propagation: large-scale path loss. *In*: Wireless Communications: Principles and Practices. Upper Prentice Hall, NJ, USA, p.69-185.

Shin, S.Y., Choi, S., Park, H.S., *et al.*, 2005. Packet error rate analysis of IEEE 802.15.4 under IEEE 802.11b interference. *LNCS*, **3510**:279-288. [doi:10.1007/11424505_27]

Shin, S.Y., Park, H.S., Kwon, W.H., 2007. Mutual interference analysis of IEEE 802.15.4 and IEEE 802.11b. *Comput. Networks*, **51**(12):3338-3353. [doi:10.1016/j.comnet.2007.01.034]

Sikora, A., Groza, V.F., 2005. Coexistence of IEEE802.15.4 with other systems in the 2.4 GHz-ISM-band. Instrumentation and Measurement Technology Conf., p.1786-1791. [doi:10.1109/IMTC.2005.1604479]

Soro, S., Heinzelman, W., 2009. A survey of visual sensor networks. *Adv. Multim.*, Article ID 640386. [doi:10.1155/2009/640386]

Stanciulescu, G., Farhangi, H., Palizban, A., *et al.*, 2012. Communication technologies for BCIT smart microgrid. IEEE PES Innovative Smart Grid Technologies, p.1-7. [doi:10.1109/ISGT.2012.6175669]

Yoon, D.G., Shin, S.Y., Kwon, W.H., *et al.*, 2006. Packet error rate analysis of IEEE 802.11b under IEEE 802.15.4 interference. 63rd Vehicular Technology Conf., p.1186-1190. [doi:10.1109/VETECS.2006.1683022]

Yuan, W., Wang, X., Linnartz, J.P.M.G., 2007. A coexistence model of IEEE 802.15.4 and IEEE 802.11b/g. 14th IEEE Symp. on Communications and Vehicular Technology, p.1-5. [doi:10.1109/SCVT.2007.4436237]

Yun, J., Lee, B., Li, J., 2008. A channel switching scheme for avoiding interference of between IEEE 802.15.4 and other networks. Int. Multisymp. on Computer and Computational Sciences, p.136-139. [doi:10.1109/IMSCCS.2008.41]

Zhang, X., Shin, K.G., 2011. Enabling coexistence of heterogeneous wireless systems: case for ZigBee and WiFi. 12th ACM Int. Symp. on Mobile Ad Hoc Networking and Computing, p.6-11. [doi:10.1145/2107502.2107510]