LETTER

Performance Improvements on LR-WPANs over Interference from WLANs

Ji-Hoon PARK†, Nonmember and Byung-Seo KIM††, Member

SUMMARY To reduce performance degradations of LR-WPANs due to interference from WLANs, this letter proposes a protocol to allow a piconet to switch an operating channel to an interference-free channel only for transmitting beacon frames. The proposed method does not only increase network performances because of high reliability of the beacon frames, but also increase overall channel utilizations because of using even interfered-channels.

key words: LR-WPAN, interference, WLAN, beacon, ISM

1. Introduction

The performances of IEEE 802.15.4-based low rate wireless personal area networks (LR-WPANs) are seriously degraded about 10~100% due to the interference from wireless local area networks (WLANs) reported in [1], [2]. To resolve the issue, most methods proposed in [3]–[5] abandon the interfered-channels and switches a non-interfered channel being already used by other piconets. However, the methods are neither flexible nor scalable when traffic loads vary. Furthermore, if the non-interfered channel is being fully utilized, a new piconet cannot be established. The proposed method in this letter utilizes even the interfered-channels because the interference level is not always severe and fluctuates depending on the WLANs’ traffic loads. On the other hand, the proposed protocol allows beacon frames to be transmitted over the non-interfered channel. This is in order to increase reliability of beacon transmissions because losing beacon frames cause IEEE802.15.4-capable nodes (for simplicity, hereinafter, it is called just ‘node’.) to hold their transmissions and to deteriorate the accuracy up to 141% in the localizations as previously claimed [6].

2. Overview of the Proposed Protocol

Two types of piconets are considered: Primary-Piconet (P-Piconet) (a piconet using one of interference-free channels) and Secondary-Piconet (S-Piconet) (a piconet which has to use channels overlapped with WLAN’s channels). The key feature of the proposed protocol is to allow S-Piconet to transmit its beacon frames over a frequency being used by P-Piconet to achieve high reliability on receiving beacon frames. The beacon frames are transmitted during the inactive period of the superframe of the P-Piconet. On the other hand, other frames except beacon frames are transmitted during active period of S-Piconet’s superframe in a selected channel interfered with WLANs. An example of constructing superframes using the proposed protocol is illustrated in Fig. 1. In Fig. 1, the first superframe is for P-Piconet, and the lower two superframes are S-Piconets using Channel 1 and 2 (interfered-channels), respectively. As shown in the figure, the beacon frames of S-Piconets are transmitted at the end of inactive period of P-Piconets’s superframe while the data frames in S-Piconets are transmitted during an active period of the S-Piconets’ own superframe. All member nodes in S-Piconets switch their operating channel to P-Piconet’s channel in order to listen a beacon frame and switch back to the operating channel for the data transmissions. However, S-Piconet uses the proposed method if its channel is interfered by WLAN’s signal more than a certain threshold, $\gamma$. The periods transmitting beacon frames, called Beacon Transmission Period (BTP), for S-Piconets are allocated from the end to the beginning of inactive period of P-Piconets’s superframe while the data frames in S-Piconets are transmitted during an active period of the S-Piconets’ own superframe. All member nodes in S-Piconets switch their operating channel to P-Piconet’s channel in order to listen a beacon frame and switch back to the operating channel for the data transmissions. However, S-Piconet uses the proposed method if its channel is interfered by WLAN’s signal more than a certain threshold, $\gamma$. The periods transmitting beacon frames, called Beacon Transmission Period (BTP), for S-Piconets are allocated from the end to the beginning of inactive period of P-Piconet following the order of the received requests. The example of this is also shown in Fig. 1. In Fig. 1, because the BTP for the S-Piconet-1 is close to the end of the superframe of the P-Piconet, the S-Piconet-1 requests the BTP earlier than the S-Piconet-2. This is to cope with the cases that P-Piconet increases the active period.

3. Operation of the Protocol

When a node decides to create its own piconet, process using the proposed method is as follows:

- **Step 1.** If all interference-free-channels are being used by other piconets and all interfered-channels are occu-

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†The author is with ITO Business Division, Nongshim Data System, Seoul, Korea.

††The author is with the Faculty in Department of Computer and Information Communications Eng., Hongik University, Sejongsi, Korea.

a) E-mail: jsnbs@hongik.ac.kr

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Step 5. The PNC receiving the BA-Request frame decides if it accepts the request. If the PNC cannot accept the request, it ignores the request. If the possible inactive period is larger than Beacon Length in the BA-Request frame and the PNC decides to accept the request, it sends BA-Response frame shown in Fig. 2 back with setting unique Beacon ID, Beacon Tx Time, and Max. BTP fields. Beacon ID field is an identification number of S-Piconets assigned by the PNC of P-Piconet. Beacon Tx Time is the number of symbols indicating the beginning of allocated BTP in inactive period. That is, the PNC of S-Piconet sends its beacon frame after Beacon Tx Time at the end of active period. Max. BTP is also the number of symbols indicating the maximum periods allowed for transmitting the beacon frame of S-Piconet. Therefore, the length of the S-Piconet’s beacon frame can be varied up to Max. BTP.

Step 4. If the node receives BA-Response frame, it becomes a PNC of S-Piconet and sends its own beacon frame after setting Actual Channel Number field to \( f_p \) after setting Beacon Length field to the required length of beacon frame. This frame is sent during contention access period (CAP) of P-Piconet.

Step 3. The PNC receiving the BA-Request frame decides if it accepts the request. If the PNC cannot accept the request, it ignores the request. If the possible inactive period is larger than Beacon Length in the BA-Request frame and the PNC decides to accept the request, it sends BA-Response frame shown in Fig. 2 back with setting unique Beacon ID, Beacon Tx Time, and Max. BTP fields. Beacon ID field is an identification number of S-Piconets assigned by the PNC of P-Piconet. Beacon Tx Time is the number of symbols indicating the beginning of allocated BTP in inactive period. That is, the PNC of S-Piconet sends its beacon frame after Beacon Tx Time at the end of active period. Max. BTP is also the number of symbols indicating the maximum periods allowed for transmitting the beacon frame of S-Piconet. Therefore, the length of the S-Piconet’s beacon frame can be varied up to Max. BTP.

Step 2. The node sends Beacon-Allocation (BA)-Request frame as shown in Fig. 2 to the piconet coordinator (PNC) of P-Piconet using \( f_p \) after setting Beacon Length field to the required length of beacon frame. This frame is sent during contention access period (CAP) of P-Piconet.

Step 1. When a node chooses a beacon frame that it wants to associate with after scanning channels, it starts association process with the PNC that owns the beacon frame. If the node is conventional IEEE802.15.4-based node, it tries to associate other conventional PNC after checking Frame Type field of the beacon frame. Therefore, backward-compatibility is achieved.

Step 6. When the PNC of P-Piconet receives the BD-Request frame, it removes information of the Beacon ID from the table recording admitted beacon frames.

The association process for a node to associate with S-Piconets for the first time is as follows:

1. If Frame Type field of the beacon frame is not set to 100, it follows the process specified in IEEE802.15.4 standard. Otherwise, it records the data transmission channel to \( f_p \) in Actual-Channel-Number field in the beacon frame. Actual-Channel-Number field is appended right after Pending Address Field in Beacon payload to indicate the channel number where actual data transmissions of S-Piconet are operated. Even though the device receives the beacon frame at \( f_p \), it performs association with the PNC over \( f_s \) by exchanging the command frames defined IEEE802.15.4 for the association.

2. After association, except for listening beacon frames at \( f_p \), the device stays in \( f_s \) for its command and data transmissions.

If a device loses synchronization with PNC after losing aMaxLostBeacons number of beacon frames as defined in IEEE802.15.4 standard, it starts orphan channel scan by sending an orphan notification command in an active period in \( f_s \). When a PNC in a S-Piconet receives the commands and uses the proposed MAC protocol, then it sends the coordinator realignment command after setting Command Frame Identifiers field to 0x0D to distinguish it from a conventional coordinator realignment command. In the frame, Logical Channel field represents \( f_p \).

4. Performance Evaluations

The throughput enhancements by using the proposed method are evaluated. Even though methods in [3]–[5] are proposed, in terms of keeping the use of the interfered-channels, there is no comparative protocol, but IEEE802.15.4-based protocol. Therefore, the proposed protocol is compared with IEEE802.15.4-based protocol. The throughput of the proposed method is

\[
Thr_p = \frac{D(1 - PER_D)}{T},
\]

where \( D \) represents the amount of data transmitted during an active period when a beacon frame is successfully received, \( T \) means the duration of a superframe, and \( PER_D \) is the PERs of data frames. The throughput of the IEEE802.15.4-base WPANs is
where \( \text{PER}_B \) is the PERs of beacon frames. \((1 - \text{PER}_B^4)\) represents the probability that consecutive four beacon frames are missed which cause a synchronization loss. Therefore, the performance enhancements obtained by using the proposed method is

\[
E_{\text{Thr}} = \frac{\text{Thr}_{IEEE} - \text{Thr}}{\text{Thr}_{IEEE}} - 1.
\]

Even though the performance enhancement depends only on \( \text{PER}_B \) according to (3), it eventually depends on Bit Error Rate, \( \text{BER} \). The reason is because assuming that the bit errors are independent of each other, \( \text{BER} \) represents current channel condition and \( \text{PER}_B \) is obtained from \( \text{BER} \) as follows [7]:

\[
\text{PER}_B = 1 - (1 - \text{BER})^M,
\]

where \( \text{BER}_B \) is the bit error rate and \( M \) is the number of bits in beacon frame. The \( \text{BER} \) also defines \( \text{PER}_D \). Therefore, once \( \text{PER}_D \) is given, \( \text{BER} \) is obtained as follows:

\[
\text{BER} = 1 - (1 - \text{PER}_D)^{1/N},
\]

where \( N \) is the number of bits in data frame. In this letter, the performance enhancements using the proposed method are evaluated as functions of the sizes of beacon frames and \( \text{PER}_D \)s. Varying \( \text{PER}_D \) means variations of \( \text{PER}_B \) under constant size of beacon frame. With 100-byte data frame, Fig. 3 shows the enhancements in the throughputs as functions of \( \text{PER}_D \) and the lengths of beacon frames. As shown in Fig. 3, the enhancements are achieved from 1% with 5% \( \text{PER}_D \) and 14-byte beacon frame to 71% with 40% \( \text{PER}_D \) and 100-byte beacon frame. Even though 40% \( \text{PER}_D \) might be too high comparing to the 10% requirements in IEEE802.15.4 standard, it is worthwhile to observing the results because the \( \text{PER}_D \) due to the interferences from WLANs is time-varying from 0 to 100% based on the network environments.

In Fig. 3, the beacon frame’s \( \text{PER} \) of S-Piconet in the proposed method is assumed to be 0 because it is transmitted over non-interference-channel. This provides an upper-bound in the enhancement obtaining from the proposed method. However, for the more realistic scenario, even non-interference channel may have channel errors. Now, we evaluates the case when the beacon frames transmitted in the non-interference-channel have errors. When the \( \text{PER} \) of the beacon frame of S-Piconet, \( \text{PER}_{SB} \), is not zero, then Eq. (3) is changed as follows:

\[
E_{\text{Thr}} = \frac{(1 - \text{PER}_{SB})(1 - \text{PER}_B^4)}{(1 - \text{PER}_B)(1 - \text{PER}_B^4)} - 1.
\]

We define \( \beta \) as \((\text{PER}_B - \text{PER}_{SB})/\text{PER}_B\) to indicate how different \( \text{PER}_{SB} \) is in terms of \( \text{PER}_B \). That is, \( \beta = 1 \) means \( \text{PER}_{SB} \) is zero which is the case in Fig. 3, and \( \beta = 0 \) means \( \text{PER}_{SB} \) is \( \text{PER}_B \) which is the worst channel environment. In Fig. 4, throughput improvement as a function of \( \text{PER}_B \) and \( \beta \) is shown. As shown in Fig. 4, when \( \text{PER}_B \) is 40% and \( \beta \) is 0.2 that means P-Piconet’s channel is erroneous closely as bad as S-Piconet’s channel, the proposed method still achieves more than 15% comparing to the conventional method.

5. Conclusion

The proposed method allows only beacon frame of the piconet to be transmitted over non-interfered channels, so that piconets can utilize even interfered-channel reliably. Therefore, by achieving the high reliability of beacon frame over severe interference environments due to WLANs, the performances and channel utilizations of WPANs increase.
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References

[1] I. Howitt and J.A. Gutierrez, "IEEE 802.15.4 Low Rate - Wireless Personal Area Network Coexistence Issues," Proc. IEEE WCNC’06, 2003.

[2] S.Y. Shin, H.S. Park, and W.H. Kwon, “Mutual interference analysis of IEEE 802.15.4 and IEEE 802.11b,” Computer Networks, vol.51, Issue 12, pp.3338–3353, Aug. 2007.

[3] M. Deylami and E. Jovanov, “A distributed and collaborative scheme for mitigating coexistence in IEEE 802.15.4 based WBANs,” Proc. ACM-SE’12, 2012.

[4] X. Zhang and K.G. Shin, “Enabling coexistence of heterogeneous wireless systems: Case for ZigBee and WiFi,” Proc. MobiHoc’11, 2011.

[5] T.H. Kim, J.Y. Ha, and S. Choi, “Improving spectral and temporal efficiency of collocated IEEE 802.15.4 LR-WPANs,” IEEE Trans. Mobile Comput., vol.8, no.12, pp.1596–1609, Dec. 2009.

[6] S.-Y. Lau, T.-H. Lin, T.-Y. Huang, I.-H. Ng, and P. Huang, “A measurement study of Zigbee-based indoor localization systems under RF interference,” Proc. WINTER ’09, pp.35–42, 2009.

[7] B.-S. Kim, S.W. Kim, Y. Fang, and T. Wong, “Feedback-assisted MAC protocol for real time traffic in high rate wireless personal area networks,” ACM Wireless Networks, vol.16, no.4, pp.1109–1121, May 2010.