

Experimental Evaluation of Coexistence Method for ZigBee under WLAN Interference

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Abstract—ZigBee has attracted attention for constructing the sensor network such as home energy management system. Both ZigBee and wireless LAN (WLAN) use a 2.4GHz band, called the industrial, scientific, and medical unlicensed band; therefore, ZigBee faces severe interference problems in the presence of WLAN. Frame collisions are serious problems between ZigBee and WLAN. Both employ a carrier sense mechanism to avoid collision, but both use different channel access mechanisms. The primary problem is the competition that exists between WLAN data frames and ZigBee ACK frames, i.e., because of WLAN interference, ZigBee may not receive any given ACK frame; therefore, the ZigBee transmission success ratio is degraded. To overcome this problem, the authors propose an interference avoidance method that improves ZigBee and WLAN coexistence and utilizes actual equipment to present the experimental evaluation. The experimental results reveal that the ZigBee transmission success ratio increases as the WLAN transmission rate increases. In addition, we clarified the distance in which the proposed method can effectively operate.

Index Terms—Wireless LAN, ZigBee, CSMA, interference, frame collisions

I. INTRODUCTION

The home energy management system for smart houses has attracted attention as a way to both protect the environment and provide comfortable living. In the development of smart houses, the ZigBee specified in the IEEE802.15.4 standard [1] is widely used for controlling the solar power system and electronic devices. ZigBee uses a common 2.4GHz band, called the industrial, scientific, and medical (ISM) unlicensed band. The wireless LANs (WLANs) specified in the IEEE802.11 standard [2] also use the ISM band and have already been introduced into smart homes, and electrical devices equipped with WLAN, such as PCs and smartphones, are widely used in homes. Furthermore, both ZigBee and WLAN use different channel access mechanisms. Because ZigBee and WLAN use the same 2.4GHz band, competition occurs between them [3]. This competition degrades the ZigBee transmission success ratio.

Fig. 1 shows ZigBee and WLAN channels in the 2.4GHz band. All the ZigBee channels overlap WLAN channels. Therefore, it is impossible to avoid interference between ZigBee and WLAN even if the frequency band is changed. To overcome this problem, we focus on the time domain and propose an interference avoidance method for ZigBee and WLAN coexistence that is aimed at improving the ZigBee transmission success ratio; we present the effectiveness of our proposed method by experimenting with actual equipment.

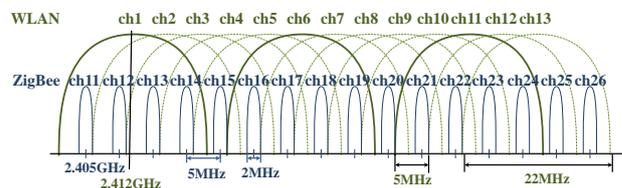


Fig. 1. ZigBee and WLAN channels.

The rest of the paper is organized as follows. Section 2 describes the channel access mechanisms. Section 3 reviews related work. Section 4 describes the problem of ZigBee and WLAN coexistence, and Section 5 describes our proposed interference avoidance method for coexistence. Section 6 presents experimental results. The conclusions are presented in Section 7.

II. CHANNEL ACCESS MECHANISMS

A. Channel Access Mechanism in ZigBee

The IEEE802.15.4 standard specifies two types of channel access mechanisms, based on the network configuration used. When there is no beacon synchronization, the channel access mechanism is an unslotted CSMA-CA, which is what we focus on because the beacon synchronization is not required.

An example operation of the unslotted CSMA-CA is shown in Fig. 2. The unslotted CSMA-CA uses two variables, NB and BE. NB is the number of times the unslotted CSMA-CA mechanism is required to backoff while attempting the current transmission. BE is the backoff exponent, which is related to how many backoff periods a ZigBee device shall wait before attempting to access a channel. When the ZigBee device attempts to transmit data frames, it waits for the backoff time. The

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unit of the backoff time is the backoff period, which is uniformly chosen in the range $[0, 2^{BE}-1]$. The ZigBee device performs clear channel assessment (CCA) analysis during the CCA detection time after the backoff time has elapsed. If the channel is found to be idle, the ZigBee device transmits its data frame after the $aTurnaroundTime$. Only if the acknowledgment (ACK) option is enabled, the ZigBee device whose data frame is received transmits an ACK frame after the T_{ACK} . After receiving the ACK frame, the data transmission is completed. If the channel is found to be busy during CCA analysis, the NB value is incremented. If the value of NB is less than $macMaxCSMABackoff$, the ZigBee device waits for a new backoff time before trying to access the channel again. If the value of NB is greater than $macMaxCSMABackoff$, it discards the data frame.

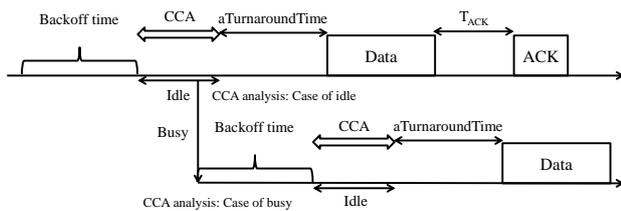


Fig. 2. Channel access mechanism in ZigBee.

B. Channel Access Mechanism in WLAN

The 802.11 standard specifies a DCF based on the CSMA/CA. An example operation of CSMA/CA is shown in Fig. 3. When the WLAN device attempts to transmit data frames, it checks the channel state during the distributed interframe space (DIFS) period. If the channel is found to be idle, the WLAN device selects the backoff time as the following equation:

$$\text{Backoff time} = \text{random}() \times aSlotTime \quad (1)$$

where $\text{random}()$ is an integer randomly chosen from a uniform distribution over the range $[0, CW]$. For example, the minimum contention window (CW_{min}) and the maximum CW (CW_{max}) values are 15 and 1023, respectively in the IEEE802.11g standard.

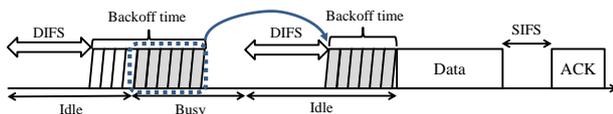


Fig. 3. Channel access mechanism in WLAN.

The WLAN device checks the channel state in each $aSlotTime$. If the channel is found to be idle, the backoff time is decremented in every $aSlotTime$. If the backoff time reaches zero, the WLAN device transmits a data frame. If the channel is found to be busy during the backoff time, the WLAN device stops the backoff time's decrement. After the channel is found to be idle during the DIFS period, the decrement of the backoff time is resumed. After transmitting the data frame, the WLAN device whose data frame is received transmits the ACK frame after a short interframe space (SIFS) period. If the

WLAN receives the ACK frame, the data frame transmission is completed.

III. RELATED WORKS

Several interference avoidance methods for ZigBee and WLAN coexistence have been proposed. These works focus on either the time domain or the frequency domain to avoid interference.

Some works that focused on the time domain [4]–[6] separate the time domain into two periods: one for ZigBee and one for WLAN. In addition, these works assume a beacon network for ZigBee. The configuration of these works is such that the ZigBee coordinator is connected to the WLAN access point (AP), and these operate cooperatively. Ref. [4] uses the point coordination function (PCF) period and the distributed coordination function (DCF) period specified in the IEEE802.11 standard. This work uses a two-part time domain to avoid interference between ZigBee and WLAN, based on the idea that ZigBee uses only the PCF period and WLAN uses only the DCF period. Specifically, the active period specified in the IEEE802.15.4 standard corresponds to the PCF period, and the inactive period corresponds to the DCF period. Note that only the beacon network uses both the active and inactive periods. Refs. [5], [6] use the network allocation vector (NAV) specified in the IEEE802.11 standard to create a dedicated period for ZigBee. The function of NAV postpones the transmission of WLAN. Before the ZigBee coordinator transmits a beacon, the WLAN AP transmits either a request-to-send (RTS) frame or a clear-to-send (CTS)-to-self frame to use the NAV.

Conversely, some works focus on the frequency domain to avoid ZigBee and WLAN interference. Ref. [7] uses the characteristics of ZigBee and WLAN channels, as shown in Fig. 1. One WLAN channel overlaps with four ZigBee channels. Thus, ref. [7] applies a special function to ZigBee that is capable of transmitting a busy tone. When the ZigBee detects a ZigBee signal, it uses the neighboring channel of the reception channel to transmit the busy tone, and thus informs the neighboring WLANs of the ZigBee signal. However, this work needs a special function not specified in the IEEE802.15.4 standard. Refs. [8]–[11] use multiple ZigBee channels, applying a channel selection algorithm that enables them to detect interference and adaptively switch to a channel with less interference.

As mentioned above, the configuration of the works in refs. [4]–[6] uses the beacon network specified in the IEEE 802.15.4 standard. In addition, the ZigBee coordinator and WLAN AP need to synchronize with each other because they use a beacon. Therefore, these works cannot apply to the non-beacon network in the IEEE 802.15.4 standard. Ref. [7] uses a special function that is not specified in the IEEE802.15.4 standard and, thus, lacks versatility. Refs. [8]–[11] employ multiple ZigBee channels. As shown in Fig. 1, all ZigBee channels

overlap WLAN channels. Therefore, the ZigBee channels may not separate from the WLAN channels.

In [12], the authors investigate the interference generated by WLAN over ZigBee in overlapping frequency band using actual equipment. The frame error has been reported to be strongly affected by the percentage of WLAN utilization, but the method to overcome the frame error is not proposed. In [13], the authors analyze the throughput performance in the ZigBee and WLAN coexistence by a mathematical model. However, the channel access mechanism is the slotted CSMA-CA, and the mathematical model does not apply to the unslotted CSMA-CA. In [14], the authors focused on the discard of ZigBee data frames when the value of NB was greater than macMaxCSMABackoff. To prevent this discard, the authors propose the extension of the DIFS period, but this method is not specified in the IEEE802.11 standard. In addition, the performance is evaluated via only computer simulation. As mentioned above, to the best of our knowledge, a coexistence method between WLAN and ZigBee using unslotted CSMA-CA that is completely compatible with the IEEE802.15.4 and IEEE802.11 standards has not yet been proposed.

In this paper, we focus on the non-beacon network in which ZigBee channels overlap with WLAN channels. In addition, the ZigBee and WLAN used in this paper are fully compatible with the standards.

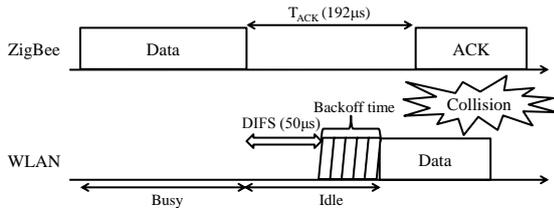


Fig. 4. Coexistence problem.

IV. ZIGBEE AND WLAN COEXISTENCE PROBLEM

A problem in the coexistence of ZigBee and WLAN is shown in Fig. 4. As shown, frame collisions between ZigBee and WLAN occur because both have different channel access mechanisms. The primary problem is the frame collision that occurs between ZigBee ACK frames and WLAN data frames. As a result of those collisions, the ZigBee transmission success ratio tends to be degraded. Since a sensor usually gathers information periodically, a higher transmission success ratio is required. The cause of these frame collisions is the fact that the T_{ACK} is longer than the DIFS period. Note that the value of DIFS in the IEEE802.11g standard is $50 \mu s$ and the value of T_{ACK} in the IEEE802.15.4 standard is $192 \mu s$. Specifically, when the channel is to be idle during the DIFS period within the T_{ACK} , it is possible for the WLAN device to transmit a data frame. For this reason, frame collisions occur between ZigBee ACK frames and WLAN data frames.

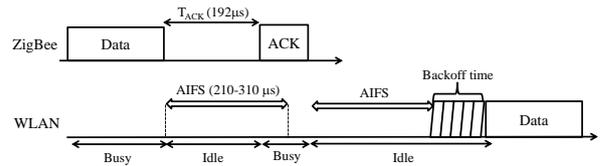


Fig. 5. Proposed coexistence method.

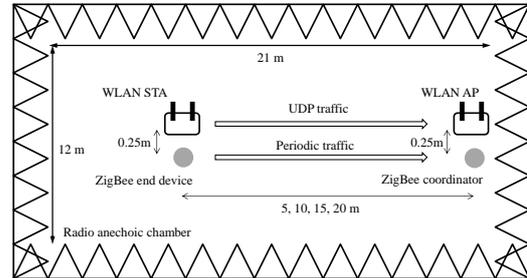


Fig. 6. Experimental environment.

V. PROPOSED COEXISTENCE METHOD

The original idea has been proposed in [15]. In [15], the proposed method has evaluated only by computer simulation. This paper also uses the proposed method, but the proposed method is evaluated by actual equipment. Therefore, this paper considers the actual radio propagation.

As mentioned above, the primary cause of frame collisions is that the T_{ACK} is longer than the DIFS period. To overcome this problem, the DIFS period in WLAN has to be longer than the T_{ACK} in ZigBee. Because the IEEE802.15.4 standard supports the fixed length of T_{ACK} , we utilize the arbitration interframe space (AIFS) specified in the IEEE802.11e standard. Because we focus on frame collisions between ZigBee ACK and WLAN data frames, we set an AIFS value greater than T_{ACK} . Similar to the related works discussed above, we assume a hybrid device (such as home gateway) that is equipped with both the WLAN AP and the ZigBee coordinator; however, synchronization between them is not required. The operation of the proposed method is such that the WLAN AP sets an AIFS value greater than the T_{ACK} if it detects a ZigBee frame. If a ZigBee frame is not detected (i.e., ZigBee end devices do not exist), the AIFS value is set to DIFS value. Since the AIFS number (AIFSN) value for setting the AIFS value is included in the beacon transmitted by the WLAN AP, the WLAN station (STA) changes the AIFS value after receiving the beacon. The relationship between the AIFS value and the AIFSN value is expressed as follows:

$$AIFS = aSlotTime \times AIFSN + aSIFSTime \quad (2)$$

where $aSlotTime$ is $20 \mu s$, the AIFS number (AIFSN) value is the range from 2 to 15, and $aSIFSTime$ is $10 \mu s$. Therefore, the AIFS value is the range $[50 \mu s, 310 \mu s]$. The short slot time option is disabled. These parameters are in the IEEE802.11g standard. Since ZigBee's T_{ACK} is $192 \mu s$, the minimum AIFS value that is greater than the T_{ACK} is $210 \mu s$. An example operation of the proposed

method is shown in Fig. 5. Since AIFS is greater than the T_{ACK} , frame collisions between the ZigBee ACK frame and the WLAN data frame do not occur.

VI. EXPERIMENTAL EVALUATIONS OF PROPOSED COEXISTENCE METHOD

To examine the effectiveness of the proposed method, we conduct an experimental evaluation using actual equipment. In addition, we clarify the relationship between the ZigBee transmission success ratio and the WLAN transmission rate, because the transmission rate is changeable.

Both ZigBee and WLAN employ the carrier sense mechanism, but the preamble signal between them is different. The presence of frames in the other is detected by the signal power, i.e., energy detection. If the distance between ZigBee and WLAN is too long, energy detection will not work well. For this reason, WLAN may not detect the ZigBee ACK frame and frame collisions may occur. Therefore, we investigate the effectiveness of the proposed method using varying distances between ZigBee and WLAN.

A. Experimental Conditions

We evaluate the performance of the proposed method in a radio anechoic chamber to block any radio waves from outside. The experimental environment is shown in Fig. 6. Cisco AIR-AP1242AG-P-K9 [16] is used for the WLAN devices (WLAN station and WLAN AP). Air Micro AM-206 [17] is used for the ZigBee devices (ZigBee coordinator and ZigBee end device). Air Micro AM-206 is developed using the STM32W module supplied by STMicroelectronics. Each device is connected to the PC, which then operates the devices. We set WLAN to channel 6 and ZigBee to channel 18. The transmission powers of ZigBee and WLAN are 7 and 14 dBm, respectively. These channels overlap, as shown in Fig. 1. We do not use the hybrid device in the experimental environment because WLAN coexists with ZigBee in this environment. This is the situation after detecting the ZigBee frame.

The difference between the conventional and proposed methods is the AIFS value. The conventional method uses an AIFS value of 50 μ s because the IEEE802.11g standard specifies a DIFS value of 50 μ s; meanwhile, the proposed method uses an AIFS value of 210 or 310 μ s, which is longer than ZigBee's T_{ACK} . The 210 μ s value is the minimum AIFS value that is still longer than the T_{ACK} , and the 310 μ s value is the maximum possible AIFS value. As mentioned in Section V, the range of AIFS is specified in the standard. To the best of our knowledge, the coexistence method between WLAN and ZigBee using unslotted CSMA-CA that is completely compatible with the IEEE802.15.4 and IEEE802.11 standards has not yet been proposed. To clarify the effectiveness of the proposed method, we use the default parameters specified in these standards for the conventional method.

WLAN parameters are set as follows. We utilize the traffic generator application Jperf [18]. The WLAN STA generates UDP traffic to the WLAN AP. The parameter of Jperf is the default value, i.e., the packet size and buffer size are 1470 bytes and 70 bytes, respectively. ZigBee parameters are set as follows. The ZigBee payload is 127 bytes and the ACK option is enabled. The ZigBee end device generates traffic to the ZigBee coordinator every one second.

We define two evaluation scenarios concerning the WLAN transmission rate and the distance between the WLAN AP and the WLAN STA; these scenarios are called "Scenario 1" and "Scenario 2," respectively. The ZigBee coordinator is placed near the WLAN AP and the ZigBee end device is placed near the WLAN STA. The distance between them is 25 cm, as shown in Fig. 6. The measurement time is 100 s, and measurements are taken three times.

To clarify the performance of the proposed method, we define the following four evaluation criteria.

- WLAN throughput:
A value measured by Jperf.
- ZigBee data frame reception ratio:
The ratio of the number of data frames transmitted by the ZigBee end device and the number of data frames received by the ZigBee coordinator.
- ZigBee transmission success ratio:
The ratio of the number of data frames transmitted by the ZigBee end device and the number of ACK frames received by the ZigBee end device.
- ZigBee non-received ACK frame ratio:
Relates to ZigBee's ACK collisions and is calculated by the following equation: $(1 - \text{number of ACK frames received by the ZigBee end device}) / \text{number of data frames received by the ZigBee coordinator}$.

B. Experimental Results for Scenario 1

We clarify the performance of the proposed method when the WLAN transmission rate is different. In Scenario 1, the distance between the WLAN AP and the WLAN STA is 5 m. The WLAN transmission rates are 24 and 54 Mbps. Other conditions are as specified in the previous sub-section.

First, we evaluate WLAN throughput performance. Fig. 7 and Fig. 8 show the throughput characteristics with transmission rates of 24 and 54 Mbps, respectively. As shown in these figures, the throughput is degraded in the case of high UDP traffic as the AIFS value increases, because long AIFS values lead to high overhead in frame transmissions. This overhead is increased as the WLAN transmission rate increases because the transmission time of WLAN data frames is changed by the transmission rate. Note that the AIFS value is not changed. Therefore, the degradation of WLAN throughput is increased as the WLAN transmission rate increases. The cause of degradation is the fact that the AIFS remains a high value even though ZigBee data frames do not need to be received. Automatically changing the AIFS value only

when a ZigBee data frame is received solves this problem. However an adaptive control of AIFS is required; moreover, it is necessary to develop a cooperation system between ZigBee and WLAN to apply this adaptive control. Therefore, automatically changing the AIFS value is out of the scope of this paper. In high UDP traffic and AIFS values, generated data frames are lost in the WLAN STA's buffer and the load in the channel differs depending on the AIFS value. We have to evaluate the ZigBee performance in the range in which the throughput is the same among all AIFS values. Therefore, the UDP traffic ranges for 24 and 54 Mbps are [2 Mbps, 12 Mbps] and [8 Mbps, 18 Mbps], respectively.

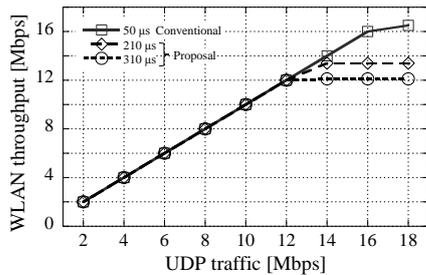


Fig. 7. WLAN throughput with a WLAN transmission rate of 24 Mbps (Scenario 1).

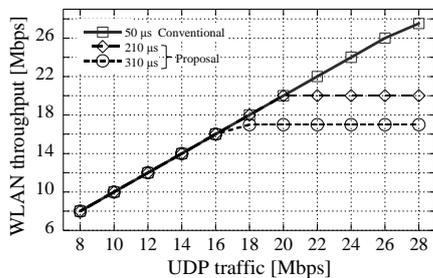


Fig. 8. WLAN throughput with a WLAN transmission rate of 54 Mbps (Scenario 1).

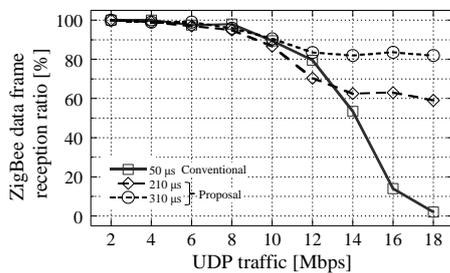


Fig. 9. ZigBee data frame reception ratio with a WLAN transmission rate of 24 Mbps (Scenario 1).

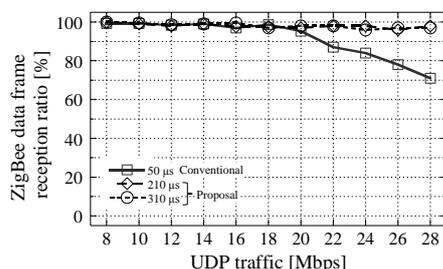


Fig. 10. ZigBee data frame reception ratio with a WLAN transmission rate of 54 Mbps (Scenario 1).

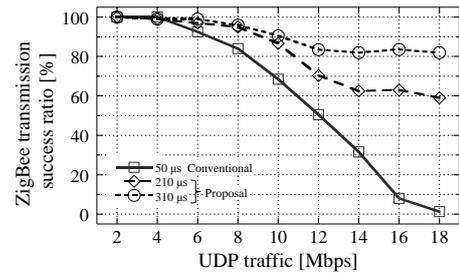


Fig. 11. ZigBee transmission success ratio with a WLAN transmission rate of 24 Mbps (Scenario 1).

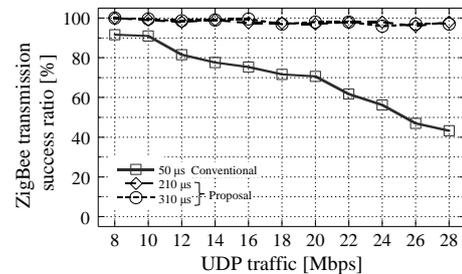


Fig. 12. ZigBee transmission success ratio with a WLAN transmission rate of 54 Mbps (Scenario 1).

Fig. 9 and Fig. 10 show the ZigBee data frame reception ratio characteristics when the WLAN transmission rate is 24 and 54 Mbps, respectively. As shown in these figures, only the conventional method is significantly decreased in high UDP traffic because the load in the channel is higher than in the proposed method. In the UDP traffic range [8 Mbps, 12 Mbps] in Fig. 9, the data frame reception ratio of an AIFS value of 50 μs outperforms that of a 210 μs AIFS value. Considering the buffer status of the WLAN STA, the WLAN STA has some pending data frames in case the throughput is saturated. In this case, the interval between a WLAN ACK frame and the subsequent WLAN data frame depends on the AIFS and the backoff time. Frame collisions between the WLAN STA's data frames and the ZigBee end device's data frames relate to the total time of the CCA duration time and aTurnaroundTime. We examine the possibility of frame collisions when the AIFS value is 50, 210, and 310 μs. In the saturated state, if the total time of the AIFS and backoff time is less than the total time of the CCA duration time and aTurnaroundTime, the possibility of frame collisions is high. In the unsaturated state, this interval depends on frame arrival because the WLAN STA does not necessarily have pending data frames. The longer this interval is, the lower is the possibility of frame collisions. As shown in Fig. 7, the throughput with an AIFS value of 50 μs is unsaturated and that with an AIFS value of 210 μs is nearly completely saturated. Therefore, the possibility of frame collisions when the AIFS value is 50 μs is smaller than that when the AIFS value is 210 μs, because the WLAN STA does not necessarily have pending data frames.

The data frame reception ratio of 54 Mbps obtained with all AIFS value outperforms that of 24 Mbps

obtained with all AIFS value. Because the WLAN data frame length is fixed, the transmission time of WLAN data frames depends on the WLAN transmission rate. A longer transmission time for WLAN data frames has a higher detection possibility during the ZigBee CCA detection time. Therefore, the data frame detection ratio depends on the WLAN transmission rate.

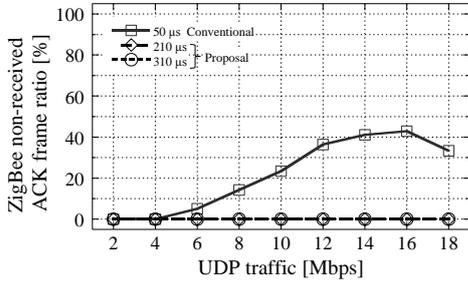


Fig. 13. ZigBee non-received ACK frame ratio with a WLAN transmission rate of 24 Mbps (Scenario 1).

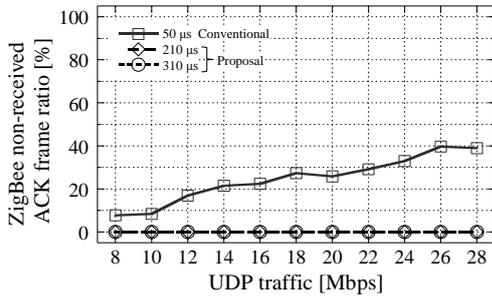


Fig. 14. ZigBee non-received ACK frame ratio with a WLAN transmission rate of 54 Mbps (Scenario 1).

Fig. 11 and Fig. 12 show the ZigBee transmission success ratio with WLAN transmission rates of 24 and 54 Mbps, respectively. Likewise, Fig. 13 and Fig. 14 show the ZigBee non-received ACK frame ratio with WLAN transmission rates of 24 and 54 Mbps, respectively. The ZigBee transmission success ratio increases as the AIFS value increases, which is similar to the data frame reception ratio characteristics. The ZigBee non-received ACK frame ratio in the proposed method is zero. Thus, we verify that the proposed method can avoid frame collisions during the T_{ACK} . Furthermore, as mentioned above, we verify that the proposed method outperforms the conventional method.

C. Experimental Results for Scenario 2

The distance between the WLAN AP and the WLAN STA is expanded in Scenario 2. The ZigBee coordinator is placed near the WLAN AP and the ZigBee end device is placed near the WLAN STA. Because ZigBee and WLAN are different systems, each detects the presence of frames in the other by signal power, i.e., energy detection. The threshold of WLAN's energy detection level, called the CCA threshold, is -65 dBm according to Cisco systems' published documents [19]. Since ZigBee and WLAN both have bandwidths of 2 and 20 MHz, the minimum received power in WLAN to detect ZigBee signals is -55 dBm. The relationship between the

propagation distance d and the propagation loss $L(d)$ in the IEEE802.15.4 standard is expressed as the following equations [20].

$$L(d) = \begin{cases} 40.2 + 20\log_{10}(d) & d < 8m \\ 58.5 + 33\log_{10}(d/8) & d \geq 8m \end{cases} \quad (3)$$

Since the transmission power of ZigBee is set to 7 dBm, WLAN can detect the energy of the ZigBee signal within a distance of approximately 10 m from the ZigBee transmitter. Therefore, the distance between the WLAN AP and the WLAN STA is set to 5, 10, 15, and 20 m.

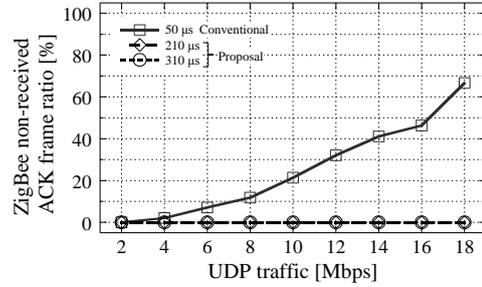


Fig. 15. ZigBee non-received ACK frame ratio with a distance of 10 m (Scenario 2).

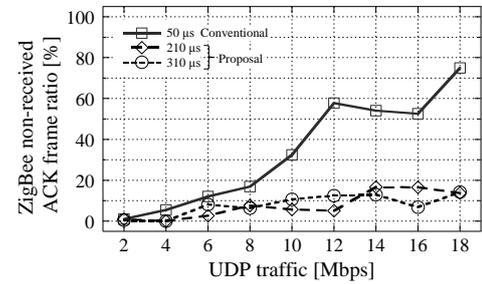


Fig. 16. ZigBee non-received ACK frame ratio with a distance of 15 m (Scenario 2).

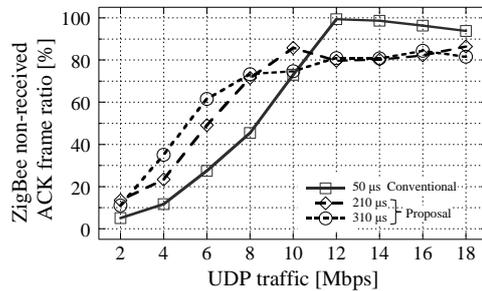


Fig. 17. ZigBee non-received ACK frame ratio with a distance of 20 m (Scenario 2).

Unlike the previous sub-section, we show the results of the ZigBee non-received ACK frame ratio and the ZigBee transmission success ratio because the WLAN throughput and the ZigBee data frame reception ratio are mostly not affected by distance. Results from a distance of 5 m are shown in the previous sub-section. The ZigBee non-received ACK frame ratio characteristics with distances of 10, 15, and 20 m are shown in Fig. 15, Fig. 16, and Fig. 17, respectively. In Figs. 13 and 15, the ZigBee non-received ACK frame ratio in the proposed method is extremely improved because the distance is within 10 m. However, the ZigBee non-received ACK

frame ratios in the proposed method with distances of 15 and 20 m are degraded compared with those with distances of 5 and 10 m. In this case, the WLAN STA cannot detect the energy of the ZigBee coordinator's ACK frame, because the ZigBee signal is less than the CCA threshold of WLAN. As a result, frame collisions occur. Therefore, the performance of the proposed method depends on distance; the proposed method is effective when ZigBee and WLAN are placed within a short distance of each other.

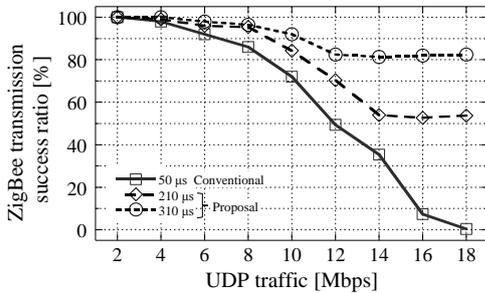


Fig. 18. ZigBee transmission success ratio with a distance of 10 m (Scenario 2).

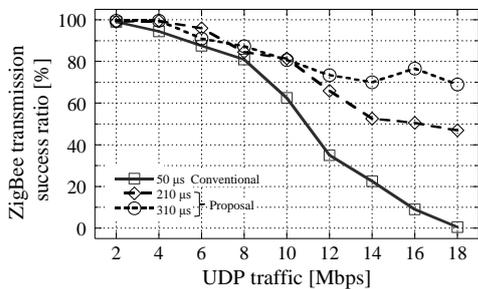


Fig. 19. ZigBee transmission success ratio with a distance of 15 m (Scenario 2).

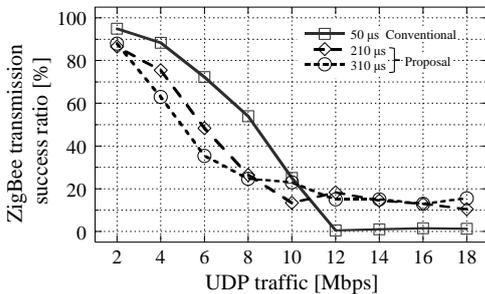


Fig. 20. ZigBee transmission success ratio with a distance of 20 m (Scenario 2).

Fig. 18, Fig. 19, and Fig. 20 show the ZigBee transmission success ratios with distances of 10, 15, and 20 m, respectively. As shown in these figures, the proposed method outperforms the conventional method except at distances of 20 m. This phenomenon can be analyzed as follows. The main cause of degradation is ZigBee ACK frame collisions. If UDP traffic is less than 10 Mbps, the throughput in the proposed method is unsaturated, as shown in Fig. 7. Unlike in the saturated state, the WLAN STA does not necessarily have pending data frames. The possibility of detecting ZigBee frames is higher in the proposed method than in the conventional

method because the total time of the AIFS and backoff time is longer. As shown in an example operation of Fig. 21, the probability that the WLAN STA detects the energy of the data frame transmitted by the ZigBee end device during the backoff countdown is higher than that in the conventional method. In the proposed method, the WLAN STA transmits a data frame and, as a result, frame collisions occur. In the conventional method, the probability that the WLAN STA detects the energy of the data frame transmitted by the ZigBee end device during the backoff countdown is low. Since the probability that the WLAN STA transmits a data frame after transmitting data frames from the ZigBee end device is low, the ZigBee transmission success ratio is lower than that with the conventional method. However, if UDP traffic is greater than 12 Mbps, the throughput in the proposed method is saturated, as shown in Fig. 7. For this reason, the ACK frame reception ratio of 20 m in the proposed method is a constant. In the proposed method, the probability that the WLAN STA detects the energy of the data frame transmitted by the ZigBee end device during the backoff countdown is higher than it is with lower UDP traffic. Because the total time of the AIFS and backoff time is smaller than the proposed method (as shown in an example operation in Fig. 22), the possibility of frame collisions is higher than that with the proposed method. Therefore, the ACK frame reception ratio is higher than that with the conventional method.

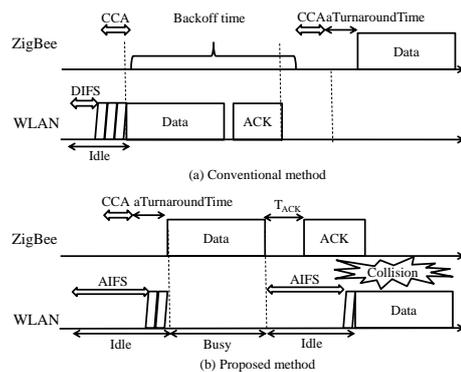


Fig. 21. Example operation showing that the ZigBee transmission success ratio is lower than that of the conventional method when the UDP traffic is less than 10 Mbps.

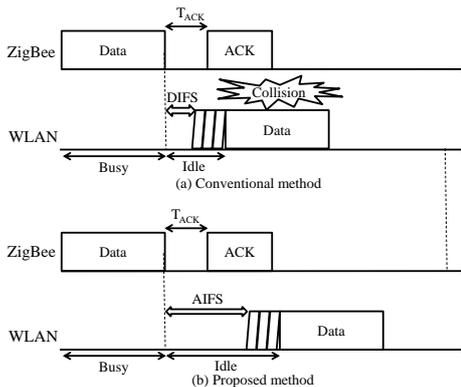


Fig. 22. Example operation showing that the ZigBee transmission success ratio is higher than that of the conventional method when the UDP traffic is greater than 12 Mbps.

As mentioned above, we confirm that the proposed method is effective in situations where ZigBee and WLAN are placed within a relatively short distance of each other, such as within a home.

VII. CONCLUSIONS

We have proposed an interference avoidance method for coexistence between ZigBee and WLAN and present an experimental evaluation that employs actual equipment. To clarify the effectiveness of the proposed method, we conducted two types of evaluations: 1) evaluations of the relationship between the ZigBee transmission success ratio and the WLAN transmission rate, and 2) evaluations of the distance between the WLAN AP and the WLAN STA. In this environment, the ZigBee coordinator is placed near the WLAN AP and the ZigBee end device is placed near the WLAN STA. The experimental results reveal that the ZigBee transmission success ratio increases as the WLAN transmission rate increases. In addition, we clarified the distance in which the proposed method can effectively operate. The proposed method is effective in situations where ZigBee and WLAN are placed within a relatively short distance, such as within a home. For further study, we will examine a collision avoidance method that corresponds to the IEEE802.11n (or latest) standard. In addition, to the best of our knowledge, the mathematical model between WLAN and ZigBee using unslotted CSMA-CA has not yet been proposed. This is a challenging issue for future work.

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