Evaluation of DSSS WLAN Beacon Caused by Interference with BLE Advertising Packet Considering the Difference in Frequency

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Abstract  Smartphones with Bluetooth low energy (BLE, marketed as Bluetooth Smart) have been widely used. The BLE is a part of Bluetooth 4.0. It utilizes the 2.4 GHz band known as the industrial, scientific, and medical (ISM) band. The IEEE802.11 wireless local area network (WLAN) utilizes the same ISM band as BLE. Therefore, radio-frequency interference may arise with BLE and WLAN coexistence. In this paper, we focus on the interference between the WLAN beacon and the BLE advertising packet. We evaluate the bit error rate (BER) of the WLAN signal on the direct sequence spread spectrum (DSSS) modulation caused by interference with the BLE signal on the Gaussian minimum shift keying (GMSK) modulation by computer simulation. Additionally, we focus on the difference in frequency to investigate the effect of overlapping channels. Furthermore, we examine BER estimation by using the signal-to-interference ratio (SIR) assuming that the BLE signal is modeled as an additive white Gaussian noise (AWGN). Concerning the characteristic of the difference in frequency, we confirm the validity of these simulation results by experimental evaluation in the coexistence of the WLAN beacon and the BLE advertising packet. These results of simulation and experiment have shown that the difference in frequency is correlated with the interference of the BLE signal on the WLAN signal. Moreover, we have verified that the estimation of BER characteristics considering the difference in frequency by using SIR is possible.

Keywords: wireless LAN, Bluetooth low energy, DSSS, radio-frequency interference

1. Introduction

Bluetooth low energy (BLE) [1] supported in the Bluetooth 4 standard has attracted attention. To realize location services, smartphones with BLE have been widely used. As a service using BLE, iBeacon [2] has appeared. BLE utilizes the 2.4 GHz band called the industrial, scientific and medical (ISM) band. In addition, the wireless local area network (WLAN) built by IEEE802.11 [3] has been widely used in homes and offices. WLAN also utilizes the ISM band. Therefore, the problem of radio-frequency interference may arise in the coexistence between BLE and WLAN. Figure 1 shows the channel allocation in BLE and WLAN. Because every channel of BLE overlaps with any WLAN channel, it is likely that the BLE signal interferes with the WLAN signal.

WLAN transmits a beacon at regular intervals, i.e., beacon intervals. Currently, the direct sequence spread spectrum (DSSS) is still used in the beacon. BLE also periodically transmits an advertising packet. From the above, we focus on the interference between the DSSS wlan beacon specified in the original IEEE802.11 and the BLE advertising packet.

In this paper, on the basis of our previous studies [4], [5], we evaluate bit error rate (BER) characteristics by computer simulation to clarify the interference effect of the BLE signal as the advertising packet on the DSSS WLAN signal as the WLAN beacon considering the difference in frequency. Moreover, we also confirm the validity of simulation results by the experimental evaluation.

In addition to our previous study [5], we investigate the reason why the difference in frequency causes a
difference in BER characteristics. Furthermore, we also examine the estimation method of BER characteristics of the WLAN signal being interfered by the BLE signal.

The rest of the paper is organized as follows. In Sect. 2, we review related works on the interference between Classic Bluetooth and WLAN. In Sect. 3, we present the evaluation of the WLAN signal being interfered by the BLE signal considering the difference in frequency by computer simulation and the examination of the BER estimation method. In Sect. 4, we verify the simulation results by experimental evaluation. Finally, we conclude our work in Section 5.

2. Related Works

Since the WLAN and Bluetooth systems have been widely used in various environments, such as an office or home, these systems may cause mutual interference. The effect of mutual interference caused by WLAN and Classic Bluetooth coexistence has been evaluated [6], [7]. The IEEE802.11b WLAN interference with Bluetooth systems has been evaluated using actual equipment [6]. Akiyama et al. described the BER and throughput characteristics of Bluetooth in the case of interference by DSSS and the frequency hopping spread spectrum (FHSS) WLAN system. They showed that the Bluetooth throughput does not degrade even if the DSSS or FHSS WLAN is present. Mikulka and Hanus [7] focused on the physical layer and evaluated the effect of mutual interference caused by Bluetooth 2.1 +EDR and IEEE802.11b/g WLAN coexistence by computer simulation. Mikulka and Hanus performed the baseband simulation of Bluetooth 2.1 +EDR interference on IEEE802.11b/g and vice versa. In this study, they showed that the degradation of IEEE802.11b/g caused by interference with Bluetooth depends on the Bluetooth data rate. In the study, they also show that the interference affecting Bluetooth depends on the IEEE802.11b/g data rate.

Because WLAN utilizes the 2.4 GHz band known as the ISM band, WLAN is interfered by not only Bluetooth but also electromagnetic waves radiated by electronic devices. Therefore, the effect of electromagnetic waves radiated by microwave ovens interfering with WLAN was evaluated [8], [9]. In Refs. [8] and [9], the impact on error rate characteristics by interference is different when the frequency of electromagnetic waves differs from that of WLAN. Additionally, it was pointed out that the impact on the error rate characteristics of DSSS communication systems depends on the frequency of a disturbance [10]. To apply the estimation method of error rate characteristics to DSSS communication systems, it has to consider the difference in disturbance frequency. In Ref. [11], the packet error rate (PER) estimation method of DSSS communication systems was examined in consideration of the difference in frequency. Tomita et al. examined the estimation method using the amplitude probability distribution (APD). They focused on the disturbance as continuous wave and Bluetooth 2.1 +EDR. Their study has verified the PER estimation method by experimental measurements, considering the difference in frequency.

As mentioned above, the effect of mutual interference caused by WLAN and Classic Bluetooth coexistence has been evaluated in several studies. However, to the best of our knowledge, the effect of the BLE signal on the WLAN signal has not yet been evaluated. In this paper, as well as Ref. [11], we focus on the difference in frequency between the WLAN channel and the BLE advertising channel. The contributions of this paper are the following three points. First, we clarify the effect of the BLE signal on the WLAN signal in terms of the BER characteristics of the WLAN signal by computer simulation. Next, we clarify the effectiveness of BER estimation using a signal-to-interference ratio (SIR) assuming that the BLE signal is modeled as an additive white Gaussian noise (AWGN). Finally, we clarify the effect of the BLE advertising packet on the WLAN beacon in terms of the WLAN beacon loss ratio by

![Simulation model](image)

### Table 1: Simulation parameters

<table>
<thead>
<tr>
<th></th>
<th>BLE signal</th>
<th>WLAN signal</th>
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<tbody>
<tr>
<td>Modulation</td>
<td>GMSK</td>
<td>DSSS</td>
</tr>
<tr>
<td>Channel [ch]</td>
<td>38</td>
<td>2 - 6</td>
</tr>
<tr>
<td>Channel Width [MHz]</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>Data Rate [Mbps]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Barker Code Length</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Rolloff Factor</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$P_{\text{AWGN}}$ [dB]</td>
<td>-30 to 20</td>
<td></td>
</tr>
<tr>
<td>AWGN $E_b/N_0$ [dB]</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>$\Delta f$ [MHz]</td>
<td>-9, -4, 1, 6, 11</td>
<td></td>
</tr>
</tbody>
</table>
actual experiment, and then we verify the validity of the simulation result from the experimental evaluation.

3. Simulation Evaluations

3.1 Simulation conditions

We configure the coexistence environment between the WLAN signal and the BLE signal using a simulation model with MATLAB Simulink. The simulation model is shown in Fig. 2 and parameter settings are given in Table 1. In this simulation, we use the BLE signal as the disturbance against the WLAN signal. The bandwidths of the WLAN channel and advertising channel are 22 and 2 MHz, respectively. To overlap the advertising channel in the WLAN channel, we set both channels as follows: the advertising channel is 38 ch and the WLAN channel is any one of 2 to 6 ch.

Before being transmitted, the WLAN signal is band-limited by the square-root-raised cosine filter. The band-limited width depends on rolloff factor $\alpha$. WLAN signal spectra with the difference in $\alpha$ are shown in Fig. 3. We can confirm that the width of the WLAN signal is different from each other owing to the difference in $\alpha$.

We define $\Delta f$ [MHz] as the difference in the center frequency between the WLAN channel and the advertising channel. We show the relationship of $\Delta f$ between the WLAN channel and the advertising channel in Fig. 4. For example, if the advertising channel is 38 ch and the WLAN channel is 2 ch, $\Delta f$ is -9 MHz. We also define $P_{WBR}$ [dB] as the ratio of the signal power of the WLAN signal to that of the BLE signal, to evaluate BER versus $P_{WBR}$.

3.2 Simulation results

Simulation results in the case of the rolloff factor $\alpha = 0.5$ are shown in Fig. 5. As for the WLAN channel, the largest effect of the BLE signal is at 4 ch, followed by 3, 5, 2 and 6 chs. In other words, the effect of the BLE signal on WLAN signal becomes larger as the value of $\Delta f$ becomes closer to 0 MHz. Thus, the closer the center frequency of the advertising channel is to the center frequency of the WLAN channel, the greater the extent of the interference becomes.

![Fig. 3 Difference in WLAN signal width by $\alpha$](image1)

![Fig. 4 Relationship between WLAN and BLE channels, and $\Delta f$](image2)

![Fig. 5 BER characteristics in simulation results](image3)

![Fig. 6 Received signal spectrum [$\Delta f = 11$MHz](image4)
To investigate the BER characteristics shown in Fig. 5, we measure the radio-frequency spectrum of received signal at the WLAN receiver. Figure 6 shows one of radio frequency spectra when $\Delta f$ is set to 11 MHz. To clarify the effect of interference, we set $P_{WBR}$ to 0 dB. As shown in Fig. 6, we can confirm that the BLE signal is interfering outside the band of the WLAN signal. In this case, the effect of the interference is the lowest among 2 to 6 ch. Focusing on the the power spectrum density (PSD), the noise floor caused by the effect of AWGN is approximately -78 dBm/Hz. PSDs in each WLAN channel are shown in Fig. 7. When $\Delta f$ is -9, -4, 1 and 6 MHz, approximate PSDs are -75, -40, -39 and -44 dBm/Hz, respectively. The descending order of the PSD corresponds to the ascending order of $|\Delta f|$. Because the WLAN signal is band-limited by the raised cosine filter, PSD decreases the farther from the center frequency.

### 3.3 Effect of the difference in frequency of interference wave

In order to show that the band limitation by the square-root-raised cosine filter causes a difference in BER characteristics, we compare the simulation results to characteristics when the rolloff factor $\alpha$ is 0.3 and 0.7. Figure 8 shows simulation results for $\alpha = 0.3$ and 0.7. By comparing Fig. 8 with Fig. 5, we find that the result when $\alpha = 0.3$ in terms of BER characteristics is the same as that when $\alpha = 0.5$. However, when $\Delta f$ is -9 MHz, the result when $\alpha = 0.7$ differs from that when $\alpha = 0.5$. This difference results from the bandwidth of the WLAN signal becoming larger. Figures 9 and 10 show the received signal spectrum of $\alpha = 0.3$ and 0.7, respectively, when $\Delta f$ is -9 MHz. In Fig. 9, the BLE signal does not overlap with the WLAN signal. On the other hand, Fig. 10 shows that the BLE signal overlaps with the WLAN signal. Thus, we confirm that the difference in the band limitation of WLAN signal causes the difference in the...
BER characteristics.

SIR is one of the criteria on the impact of interference on communication quality. When SIR becomes higher, the impact of interference becomes lower. Then, we calculate SIR in this simulation in order to investigate the effect on BER characteristics the difference in frequency of the interference wave. SIR is described as follows:

$$SIR = \frac{P_{DSSS}}{P_{GMSK}} \quad (1)$$

where $P_{DSSS}$ and $P_{GMSK}$ are the power of the DSSS signal (i.e., WLAN) and the GMSK signal (i.e., BLE) after despreading, respectively. Note that we obtain the power of these signals by calculating the value of root-mean-square of these signals and we exclude the effect of noise floor. Figure 11 shows the SIR characteristics in this simulation. All the SIR characteristics are exponentially proportional to $P_{WBR}$. The largest SIR characteristic is $\Delta f = 11$ MHz, followed by $\Delta f = -9, 6, -4$ and 1 MHz. Note that the SIR characteristics of $\Delta f = -4$ and 1 MHz overlap with by each other because they have almost the same values. This order matches the reverse order of $\Delta f$ in BER characteristics as shown in Fig. 8. Furthermore, as the center frequency of the BLE channel moves away from that of the WLAN channel, SIR becomes greater. Therefore, the impact of the WLAN signal caused by interference with the BLE signal is so small that BER characteristics of $\Delta f = -9$ and 11 MHz improve. Conversely, when SIR becomes lower, the impact of the interference is so great that the BER characteristics of $\Delta f = -4, 1, and 6$ MHz deteriorate. Hence, the difference in disturbance frequency results in obtaining a different SIR.

### 3.4 Examination of BER estimation method considering SIR

We have shown the relationship between the difference in frequency and the BER characteristics because SIR is different for each value of $\Delta f$. In this section, we examine whether the BER characteristics can be estimated using SIR and the same method as in Ref. [11].

We assume that the amplitude of the BLE signal is modeled as the AWGN distribution. In this paper, we consider a signal obtained by DSSS processing using the Barker code for the DQPSK signal as the WLAN signal. Thus, we focus on applying the estimation method to BER characteristics for DQPSK. The BER approximation formula for QPSK is described as [12]:

$$P_{BER(QPSK)} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{SIR}{2}} \right) \quad (2)$$

where $\text{erfc}(x)$ is the complementary error function. Because DQPSK is required to be a value larger than 2.3 dB in order to obtain the BER equal with QPSK [11], Eq. (2) is rewritten as:

$$P_{BER(DQPSK)} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{SIR}{2a}} \right) \quad (3)$$

where $a$ is a constant satisfying $2.3 = 10\log_{10} a$. According to Eq. (3), we can estimate the BER characteristics of the WLAN signal being interfered by the BLE signal by using SIR.

Simulation results in the case of the rolloff factor $a =...$
0.5 and estimation results obtained using Eq. (3) are shown in Fig. 12. In this paper, we use the SIR characteristics shown in Fig. 11 in Eq. (3). In Fig. 12, we can confirm that the estimation results agree well with the simulation results. Therefore, we verified that estimating BER is possible by considering the difference in the frequency of interference wave by SIR.

4 Experimental Evaluations

4.1 Experimental conditions

In order to verify the simulation results concerning the difference in frequency between the WLAN channel and the BLE advertising channel, we evaluate the interference effect using actual equipment. The experimental environment is shown in Fig. 13. To exclude external electromagnetic waves as much as possible, we apply a basement floor as the experimental environment. In this place, we build the environment of BLE and WLAN devices coexistence.

We use Elecom WRH-H300WH as the WLAN access point (AP) and a laptop connected with AirPcap as the WLAN station (STA). The WLAN AP sets the beacon interval to 100 ms. We set the transmission power of the WLAN AP to 15%. Note that the power setting unit is not dBm. This is a constraint of the product. The WLAN AP transmission channel is set to any one of 2 to 6 ch, as in the simulation parameter. We also use Raspberry Pi 3 Model B connected with a USB Bluetooth dongle (Buffalo BSBT4D09BK) as a BLE transmitter. In order to increase the possibility of interference, the BLE transmitter transmits an advertising packet at intervals of 20 ms, and the data length of advertising packet is set to 31 bytes. To overlap the advertising channel with the WLAN channel, we set the advertising channel to 38 ch.

In this experiment, we define the STA-BLE distance as the distance between the WLAN STA and the BLE transmitter. We set the STA-BLE distance as 0.25, 0.50, 0.75 and 1 m. The distance between the WLAN AP and the WLAN STA (AP-STA distance) is fixed at 7.60 m. At this point, the received power of the WLAN beacon is relatively lower because of the low transmission power and the large AP-STA distance.

Evaluation criteria are as follows: Number of lost beacons and beacon loss ratio. We define the number of lost beacons as the difference between the number of WLAN beacons captured near the WLAN AP and the WLAN STA. Note that we capture WLAN beacons for 60 s three times. We also define the beacon loss ratio as the ratio of the number of lost beacons to the number of WLAN beacons captured near the WLAN AP. We verify the trend of the effect of the frequency between the WLAN channel and the BLE advertising channel compared with simulation results, in terms of the beacon loss ratio versus the STA-BLE distance.

![Fig. 13 Experimental environment](image1)

![Fig. 14 WLAN and BLE RSSI characteristics](image2)

![Fig. 15 Beacon loss ratio](image3)
4.2 Experimental results

Figure 14 shows the RSSI characteristics of the BLE advertising packet and the WLAN beacon measured at the WLAN STA versus the STA-BLE distance. As shown in Fig. 14, the RSSI characteristics of the WLAN beacon are almost constant to the fixed AP-STA distance. On the other hand, the RSSI characteristics of the advertising packet are reduced as the STA-BLE distance increases. Hence, the STA-BLE distance is regarded as the magnitude of the interference signal.

We show experiment results concerning the beacon loss ratio in Fig. 15. In WLAN channel 4 and advertising channel 38 (4 ch in Fig. 15), the beacon loss ratio decreases as the STA-BLE distance increases. Since the magnitude of the interference signal is decreased, the number of received WLAN beacons increases. The same is true for the results of other WLAN channels. The descending order of the beacon loss ratio is 4, 3, 5, 2 and 6 chs in the WLAN channel. The reason why the beacon loss ratios of 2 and 5 chs at 1 m are larger than those at 0.75 m is the many lost beacons occurred. Therefore, except for the results at 1 m, these results are the same as the trend of the simulation result. Consequently, the effect of the advertising packet on the WLAN beacon depends on the difference in frequency between the WLAN and BLE channels.

5 Conclusions

In this paper, we evaluated the effect of the BLE signal used in the advertising packet on the WLAN signal used in the DSSS WLAN beacon. In addition, we considered the difference in advertising channel. We have evaluated the BER characteristics in the coexistence between BLE and WLAN signals by computer simulation. By this simulation, we showed that the effect of the WLAN signal caused by interference with the BLE signal is different when the frequency of the BLE channel is different. Furthermore, we have showed whether the estimation of BER characteristics by using SIR is possible. We also evaluated the beacon loss ratio in the coexistence between the advertising packet and the WLAN beacon using actual equipment. On the basis of the above, we concluded that the difference in frequency is correlated with the effect of the advertising packet on WLAN beacon.

Our study was the effect of interference on the DSSS WLAN system. Therefore, the evaluation of the impact of other WLAN systems, such as OFDM being interfered by disturbance of the BLE signal will be the topic of our future study. In addition, although we showed that the interference effect in terms of the difference in frequency using the experimental and simulation evaluation, we did not consider the operation of the media access control (MAC) layer. Therefore, the simulation evaluation considering the MAC layer will also be the topic of our future work.

References


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