BER ANALYSIS OF Bluetooth SYSTEM INTERFERED BY MICROWAVE OVEN NOISES

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Abstract: Electromagnetic disturbances emitted from microwave ovens may cause serious interference with Bluetooth systems in the 2.4 GHz ISM (Industrial, Scientific and Medical) band. In this paper, the bit error rate (BER) performance of Bluetooth systems interfered by microwave oven noises is analyzed using a microwave oven noise model which consists of FM periodic tone-bursts. Employing Bennett’s method, BER of the GFSK demodulation with a frequency discriminator is theoretically evaluated. Numerical simulations are also conducted to verify the validity of the analysis. The results show that 1) BER is strongly affected by the probability density of the oven noise frequency, and that 2) the FM tone-bursts model for the oven noise yields better BER performance than the conventional pulsed Gaussian noise model (ε-mixture model) under high CNR conditions.

Key words: EMI, Microwave oven, ISM band, Bluetooth, Bit error rate

1. Introduction

Bluetooth system [1] has been developed as a short-range wireless communication system utilizing the 2.4 GHz band. However, this frequency band is shared with industrial, scientific, and medical (ISM) equipment such as microwave ovens. Since a large number of ovens are used for domestic purposes; electromagnetic emission from the ovens causes serious interference with Bluetooth air links.

Many studies have been investigated on the performance of Bluetooth system in the presence of electromagnetic interference. Many of them focus on the interferences generated from Wireless LANs operated in the same band [2], and only a few experimental investigations have been reported on the impact of microwave oven noises [3]. Hence theoretical bases are needed in order to estimate the performance degradation by oven noises and to improve the quality of interfered wireless links.

To carry out theoretical analysis, one of the most important issues is the modeling of the interfering oven noise. Middleton’s class-A impulse noise model applied in [4]. The disadvantage of such a statistical noise model is difficulty in evaluating the BER in a short duration or the packet error rate, because the statistical model provides no information about the time-domain noise waveform. In [5], pulsed Gaussian noise (ε-mixture model) is employed to represent an inverter-type oven noise. In order to apply this model to a frequency-hopped SS system, such as Bluetooth, different noise waveform is needed when the signal frequency is hopped to a different channel, because the waveform of an oven noise generally depends on the receiving frequency.

Recently, the authors of this paper developed a time-domain oven noise model which consists of periodic tone-bursts with frequency fluctuation [6], and demonstrated the validity of the model with respect to the noise waveform and spectrum.

In this paper, we employ the oven noise model to analyze the BER performance of GFSK demodulation with a frequency discriminator by using the Bennett’s method. Numerical simulations are also conducted to compare with the theoretical results.

2. Analysis

2.1 System model

The block diagram of a Bluetooth link is shown in Fig. 1. NRZ pulses \(a_n\) (n: integer), which have a value of +1 or –1 and a duration \(T_s=1\ \mu s\), are shaped by a Gaussian low pass filter (LPF) with \(BT_s=0.5\). Then the shaped pulses are inputted to a frequency modulator. The modulation index \(h\) is specified to be from 0.28 to 0.35 in Bluetooth system. In this paper, we assume \(h=0.32\). The transmitted GFSK signal \(S(t)\) is expressed as

\[
S(t) = A \exp \left[ 2\pi f_c (t + \Delta f \int_{-\infty}^{t} a(\xi) d\xi) \right]
\]

where \(f_c\) and \(\Delta f\) (=160kHz) are the carrier frequency and frequency deviation respectively, and \(a(t)\) is filtered pulse train represented as

\[
a(t) = \sum_{\text{odd}} a_{n} \cdot \left[ \text{erfc} \left( \frac{t - (2n-1)T_s}{\sqrt{2}B_t} \right) - \text{erfc} \left( \frac{t - (2n+1)T_s}{\sqrt{2}B_t} \right) \right],
\]

\[
f_c = \frac{2}{\ln 2} B_t.
\]

In (2), \(B_t (=0.5\ \text{MHz})\) is the 3-dB bandwidth of LPF.

At the receiver, the GFSK signal, an oven noise, and a thermal noise are band-limited by a Gaussian band pass filter (BPF) whose 3-dB bandwidth is 1
Fig. 1. System model of a Bluetooth link interfered by a microwave oven noise.

MHz, and are inputted to a frequency discriminator. The output of the discriminator is sampled at the bit rate, and the bit decision is made. In order to simplify the analysis, an ideally synchronized system is assumed.

2.2 Microwave oven noise model [6]

The oven noise \( I(t) \) can be described as a combination of FM and nonlinear AM [6];

\[
I(t) = I_0 V(t) \exp \left\{ 2\pi \int f_0 + f_{\text{lin}} \int V(t) \, dt \right\}. \tag{3}
\]

Note that \( f_0 \) (around 2.4 GHz) is carrier frequency, and \( f_{\text{lin}} \) (typically 10 ~ 40 MHz) is the maximum frequency deviation for the frequency modulation. The maximum amplitude of the noise envelope is \( |I_0| \) and the phase of \( I_0 \) is assumed to be uniformly distributed within \([0, 2\pi]\). The instantaneous frequency \( f_i(t) \) is given by \( f_i(t) = f_0 + f_{\text{lin}} V(t) \) \( (V \geq V_0) \). \tag{4}

The amplitude modulation with a cut-off threshold voltage \( V_0 \) is defined by

\[
U(V) = \begin{cases} 
V, & (V \geq V_0) \\
0, & (V < V_0).
\end{cases}
\tag{5}
\]

\( V(t) \) is the magnetron driving voltage normalized by its maximum value as represented by

\[
V(t) = \begin{cases} 
\cos(2\pi f_1 t), & \text{transmitter - type} \quad (6-a) \\
\cos(2\pi f_2 t) \cos(2\pi f_1 t), & \text{inverter - type I} \quad (6-b) \\
\cos(2\pi f_1 t) \cos(2\pi f_2 t), & \text{inverter - type II}. \quad (6-c)
\end{cases}
\]

Note that (6-a) is applied to a transformer-type oven in which AC mains voltage is applied directly to a magnetron through a step-up transformer, and that (6-b) and (6-c) are applied to inverter-type ovens with a switching circuit followed by a step-up transformer. Equation (6-c) is applied to an inverter-type oven having a full-wave rectifying circuit following a step-up transformer. A variable frequency (50 or 60 Hz) and inverter switching frequency (typically from 50 to 50 kHz) are denoted by \( f_1 \) and \( f_2 \), respectively.

The received oven noise is band-limited at the BPF as shown in Fig. 1. The band-limited noise \( I_b(t) \) can be approximated in accordance with the bandwidth \( B_0 \) compared to the criterion bandwidth \( B \), defined by

\[
B_0 = \left\lfloor \max\left\{ f_{\text{lin}}, V(t) \right\} \right\rfloor. \tag{7}
\]

Case 1) \( B > B_0 \):

\[
I_b(t) = I_0(t - \tau) H_{\text{BP}}(f_0 + f_{\text{lin}} V(t - \tau)) \tag{8}
\]

where \( H_{\text{BP}}(f) \) is the frequency response of the BPF, and \( \delta \) is the delay time of BPF.

Case 2) \( B << B_0 \):

\[
I_b(t) = \sum \left( -j f_{\text{lin}} V(t_i) \right) h_{\text{BP}}(t - t_i) I(t_i) \tag{9}
\]

where \( t_i \) is the time when the instantaneous frequency of the oven noise \( f_i(t) \) is coincident with the center frequency of the filter, and \( h_{\text{BP}}(t) \) denotes the complex impulse response of the BPF.

2.3 BER evaluation

Based on the noise model, an oven noise can be regarded as periodic tone-bursts with frequency fluctuation. Since theoretical BER of an FSK interfered by a CW is known, we can apply it to the evaluation of BER of a GFSK in microwave oven interference. For demodulation with a frequency discriminator, the BER was analyzed by Mizutani [7] by using a method presented by Bennett [8].

\[
P_c(\{I, J\}, f_i) = \frac{1}{2} \left\{ P_c(\{I, J\}, f_i) + P_c(\{\bar{I}, \bar{J}\}, f_i) \right\}, \tag{10}
\]

\[
P_c(\{I, J\}, f_i) = \frac{1}{2} \times \frac{1}{2\pi \sigma_1 \sigma_2} \times \int \left\{ \int \partial \mu \left[ H_{\text{BP}}(\omega) \right] d\omega \right\} \tag{11}
\]

where \( f_i \) is the frequency offset of the CW from the carrier frequency of the FSK signal. In (11), \( f_{\text{SK}} \) is instantaneous frequency deviation of the signal at the instance of bit decision. The variables \( \lambda \) and \( \mu \) denote the phase differences of the Gaussian noise and of the CW from the signal, respectively. The noise power \( \sigma_1^2 \) and \( \sigma_2^2 \) are defined as

\[
\sigma_1^2 = \int N_0 |H_{\text{BP}}(\omega)|^2 d\omega, \tag{12}
\]

\[
\sigma_2^2 = \int \alpha^2 N_0 |H_{\text{BP}}(\omega)|^2 d\omega \tag{13}
\]

where \( N_0 \) is the power spectral density of the thermal Gaussian noise. \( P_c \) in (10) can be obtained by changing the sign of \( f_i \) in (11).

Since the instantaneous frequency (4) and the amplitude of the oven noise (8) or (9) are given, time-dependent BER can be obtained directly by substituting them into (10) and (11). Note that it is necessary to consider the effect of inter-symbol interference (ISI) caused by the LPF in the transmitter and the BPF in the receiver shown in Fig. 1.
BPF can be approximated to that by an equivalent LPF. Due to the ISI, the value of the instantaneous frequency deviation \( f_{\text{FSK}} \) depends on the transmitted bit pattern. Calculated values of \( f_{\text{FSK}} \) taking the ISI effects among the adjacent bit pulses are listed in Table 1. The time dependent BER can be obtained by substituting the values of \( f_{\text{FSK}} \) into (14), and averaging the \( P_e \) weighted with the occurrence probability of the corresponding bit pattern.

\[
P_e(t) = \frac{1}{4} P\left[|f(t)|, f(t)\right]_{f_{\text{FSK}}=f_1} + \frac{1}{2} P\left[|f(t)|, f(t)\right]_{f_{\text{FSK}}=-f_1} + \frac{1}{4} P\left[|f(t)|, f(t)\right]_{f_{\text{FSK}}=f_2} + \frac{1}{4} P\left[|f(t)|, f(t)\right]_{f_{\text{FSK}}=-f_2}.
\]

3. Calculated results

Before discussing the effects of the amplitude and frequency variations of microwave oven noise on BER degradation, BER in the case of CW interference was calculated from (14), and is shown in Fig. 2 as a function of the offset frequency of the CW from the carrier frequency of signal \( f_c \). Since the amplitude of the interfering CW is defined by \( |I_0| \), the value of amplitude \( |I_0| \) in (14) is given by \( |H_{\text{in}}(f_0)||I_0| \). CNR and INR are defined as \( |A|^2/2 \sigma_0^2 \) and \( |I_0|^2/2 \sigma_0^2 \), respectively. As shown in the figure, the BER has very strong dependence on the frequency offset of the interfering CW. With the offset frequency around 0.5 MHz, the BER is worst.

Then, average BER affected by microwave oven interference was calculated using the noise parameters in Table 2. The power of oven noise is expressed in terms of INR given by \( |I_0|^2/2 \sigma_0^2 \). The approximation (8) was applied to obtain the band-limited oven noise waveform. For the inverter-type oven noise, the approximation (9) was also employed. For comparison, BER was calculated by using the \( \varepsilon \)-mixture model [5], in which the oven noise is assumed as a Gaussian noise with the same RMS amplitude as the oven noise \( |\mathcal{A}(0)|/2 \). To verify the validity of the theoretical values, numerical simulations were conducted using Monte Carlo method.

The calculated BER with the transformer-type oven noise is shown in Fig. 3. It is found that the theoretical values obtained from (14) are in an excellent agreement with the simulated values, and that the BER with the \( \varepsilon \)-mixture model is generally worse than the simulated ones, especially in high CNR conditions.

Fig. 4 shows the BER affected by the inverter-type oven noise. The BER calculated with approximation (8) is slightly (about 2 dB) worse than the simulated one. It is considered that the difference is caused by the amplitude error of the oven noise given by approximation (8). Calculated BER with approximation (9) is quite different from the simulated values. This is because the band limited oven noise approximated by (9) is assumed to have a constant frequency \( f_c \) (carrier frequency of the signal), at which the BER becomes minimal as shown in Fig. 2. Comparing BER performances in Figs. 3(a) and 4(a), it can be concluded that BER degradation due to transformer-type oven noise is worse than that given by inverter-type oven noise for the same INR. One reason is the difference in the probability density of the instantaneous frequency of oven noises. Around a frequency offset of 0.5 MHz, at which the BER is worst as shown in Fig. 2, the transformer-type oven noise has higher probability density than the inverter-type oven noise. In Figs. (3) and (4), BER at \( f_c=2440 \) MHz is generally better than that at 2460 MHz because the oven noise inputted to the demodulator has a smaller peak amplitude at 2440 MHz.

4. Conclusion

BER performance of Bluetooth system interfered by microwave oven noises were analyzed assuming the oven noise being frequency-modulated periodic bursts. Theoretical and numerical analyses were conducted for GFSK demodulation with a frequency discriminator. It was found that the proposed noise model yields a smaller BER compared with conventional pulsed Gaussian (\( \varepsilon \)-mixture) noise model for high CNR cases. It can be also concluded...
that the probability distribution of the instantaneous frequency of the oven noise strongly affects the BER performance. The BER is dominated by the probability density around the frequency offset of 0.5 MHz from the carrier frequency of the signal. Theoretical analyses for other demodulation schemes and experimental analyses will be future works.

References