

Compensation of frequency selectivity and antenna effect for the energy detection Gaussian frequency-shift keying ultra-wideband system

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Abstract: The energy detection (ED) Gaussian frequency-shift keying (GFSK) ultra-wideband (UWB) system, transmits bit 0 and 1 using different-order derivatives of the Gaussian pulse. The spectra of the two pulses are separated entirely in the frequency domain, so it generates the orthogonality of these two pulses. This orthogonality in the frequency domain makes the GFSK system more robust in multipath channels and in the presence of synchronisation errors, so it shows a better bit error rate performance than the ED pulse-position modulation UWB system. However, the effect of frequency selectivity and antenna has not been discussed in earlier publications. In this study, the authors will analyse the effect of these two factors and propose a method to compensate the effect.

1 Introduction

Ultra-wideband (UWB) is a promising technology for short distance, low power, and high speed transmission [1, 2]. UWB systems transmit sub-nanosecond pulses to carry information. The short pulse duration leads to the fine time-resolution multipath components, which can be combined using a Rake receiver. However, the implementation of Rake receiver is very challenging in UWB systems, because the receiver needs a large number of fingers to capture the multipath components. This increases the complexity of receiver and the burden of channel estimation [3, 4]. Rake receivers also need extremely accurate synchroniser to align the template signal and received signal to perform correlation [4]. A slight synchronisation error also can cause the system performance to degrade dramatically. Energy detection (ED) is a popular non-coherent technology for UWB communication systems. Although ED is a sub-optimal technology, it has many advantages when it is compared to Rake receivers. Its receiver structure is very simple and channel estimation is not required. Also ED does not need to be as accurate on synchronisation as a Rake receiver because ED does not perform correlation. In recent years, ED was applied to UWB systems for on-off keying [5–8] and pulse-position modulation (PPM) systems [6, 7, 9].

In our previous publication [10], a new ED technology, Gaussian frequency-shift keying (GFSK), was proposed. GFSK transmits bit 0 and 1 based on using different-order derivatives of the Gaussian pulse. This new technology shows great performance improvement in multipath channels and in the presence of synchronisation errors when compared to PPM. However, the research results in [10] do not consider the effect of frequency selectivity and antenna. So we will analyse the system performance under the effect of frequency selectivity and antenna in this paper. In this paper, we will discuss the effect of these two factors and the method to compensate the effect.

The structure of this paper is as follows. Section 2 introduces the system model. Section 3 discusses the effect of channel frequency selectivity and antenna, and the method to compensate the effect. Section 4 shows the numerical results. Section 5 is the conclusion of this paper.

2 System model

The transmitted signal of this new system is [10]

$$s(t)_{\text{GFSK}} = \sum_j \sqrt{E_p} (b_j p_1(t - jT_f) + (1 - b_j) p_2(t - jT_f)) \quad (1)$$

where $p_1(t)$ and $p_2(t)$ denote the energy-normalised pulses with different-order derivatives, and E_p is the signal energy. The b_j denotes the j th transmitted bit. The frame period is denoted by T_f . When bit 1 is transmitted, the values of b_j and $1 - b_j$ are 1 and 0, respectively, so $p_1(t)$ is transmitted. When bit 0 is transmitted, the transmitted pulse is $p_2(t)$. In this paper, we use the same pulses as that in [10]. In Fig. 1, the spectra of the two pulses and the Federal Communications Commission (FCC) emission mask are shown. The two pulses are the 10th- and 30th-order derivatives of the Gaussian pulse, respectively. The shape factor of the pulse is $\alpha = 0.365 \times 10^{-9}$. The PSD of the pulses and the FCC mask in Fig. 1 are plotted by using logarithmic scale, so the overlapped section of the signal spectra include very low signal energy and hence we can say that the signal spectra are separated. A linear scale version of Fig. 1 is shown in Fig. 2, where it is easier to observe the separation of the spectra.

The receiver is depicted in Fig. 3. It includes two energy detection branches. The passband frequency ranges of filters in these two branches are different. Filter 1 allows the signal energy of $p_1(t)$ to pass and rejects that of $p_2(t)$. In contrast, Filter 2 passes $p_2(t)$ and rejects $p_1(t)$. The sum of signal $s(t)$ and the additive white Gaussian noise (AWGN) $n(t)$, is denoted by $r(t)$. The integration interval is $T \leq T_f$. The decision statistic is defined as $Z = Z_1 - Z_2$, where Z_1 and Z_2 are the outputs of branches 1 and 2, respectively. Finally, Z is compared to a threshold γ . If $Z \geq \gamma$, we can determine that the transmitted bit is 1, otherwise it is determined to be 0.

3 Effect of frequency selectivity and antenna

Fig. 4 shows the frame structure of the GFSK signal in multipath channels. The GFSK system shows better performance than PPM in multipath channels. The decision threshold and bit error rate (BER) equation are [10]

$$\gamma = 0 \quad (2)$$

$$P_e = Q\left(\frac{\lambda E_b / N_0}{\sqrt{2TW + 2\lambda E_b / N_0}}\right) \quad (3)$$

where λ denotes the ratio of the captured energy to the total bit energy. The value of λ depends on the integration time. If the integration time is equal to the maximum channel delay, the integrator captures the energy of all multipath components and the value of λ is 1.

When the signal travels through the antenna and the channel, there is no difference in the energy loss respective to the transmission

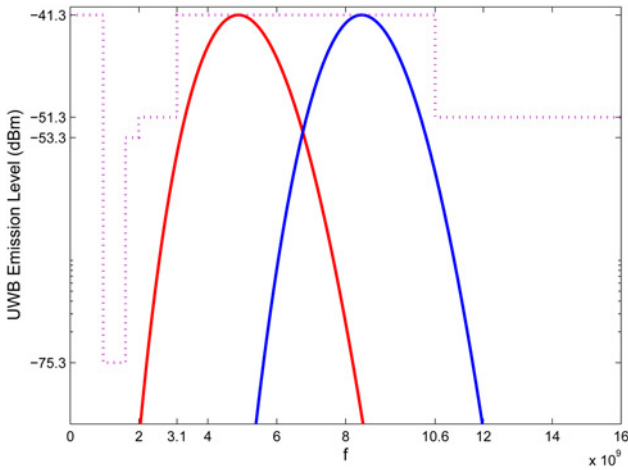


Fig. 1 Spectra of two pulses and the FCC emission mask (logarithmic scale)

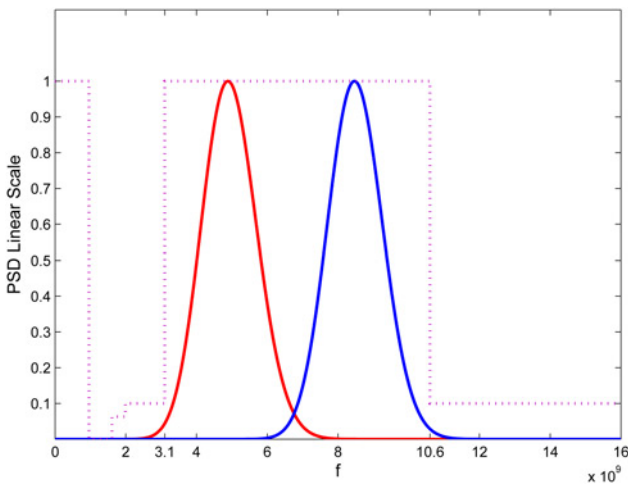


Fig. 2 Spectra of two pulses and FCC emission mask (linear scale)

distance between bit 0 and 1. However, the effect of antenna and frequency selectivity on bit 0 and 1 is different. The analysis in [10] does not consider the effect of the frequency selectivity of the channel and the effect of the antenna. The spectra of the two pulses in GFSK are located in different frequency bands, so the path loss is different. In addition, the antenna also causes different energy loss to signals with different frequencies. So the energies of bit 0 and 1 at the receiver are unbalanced, and this leads to the decision threshold to deviate from 0. So (3) is not valid any longer. Although the effect of frequency selectivity and antenna in narrow band frequency-shift keying (FSK) systems is not so apparent, it cannot be neglected in the FSK-UWB system. This is a common issue in FSK-UWB systems and has been discussed in [11]. The FSK-UWB system in [11] uses the pulsed sine waveform, $e^{j(2\pi(f_c + b\Delta)t + \Phi)}$, to achieve FSK modulation, where Δ is the frequency

shift, $b \in [-1, 1]$, Φ is the phase, and f_c is the centre frequency. Although the method to achieve modulation in [11] is different from that in [10], they both suffer the effect of frequency selectivity and antenna. The authors in [11] have pointed out that the effect of antenna to path loss is deterministic and can be calculated, so the system can compensate the effects of the antenna by transmitting 0 and 1 with different power, according to the calculation results. However, the effect of frequency selectivity is difficult to achieve by calculation because it depends on the channel environment.

The idea to transmit bit 0 and 1 with different power is a good method to compensate the different energy losses. However, how to estimate the energy loss relationship of bit 0 and 1 is the issue. In this paper, we propose a method to estimate the ratio of energy loss of bit 0 and 1, and then use this ratio to adjust the transmitting powers for bit 0 and 1. We use the GFSK system in [10] to evaluate the performance of this method.

To simplify the analysis, we consider scenarios with only two communication nodes. The detailed procedure of this method is as follows. The transmitter of node 1 transmits N consecutive 1 s and then N consecutive 0 s as a training sequence. This training sequence is known by both nodes 1 and 2. The receiver of node 2 calculates the average power for bit 0 and 1. It adjusts its transmitting power for bit 0 and 1 inversely proportional to the power ratio of the received 0 and 1. The reason why we can use the estimation of the received signal to adjust the transmitting power, can be explained as follows. The signals transmitted from nodes 1 to 2 and the signals transmitted from nodes 2 to 1 pass through the same antennas and channels, so the energy loss is the same. So the estimation of the received signals can be used to adjust the power of the transmitted signals.

The implementation of the power estimation for the received signal does not increase the complexity of the system, and it can use the receiver in Fig. 3 to achieve this estimation. First, we discuss the procedure to estimate the power of the received signal for bit 1. When the training sequence is transmitted, branch 1 of the receiver estimates the average power of the first N received symbols, which includes the signal of bit 1 and noise. Second, branch 1 continues to estimate the average power of the second N received symbols including noise only, since the signal of bit 0 is rejected by the filter of branch 1. Then we deduct the estimated average power of the second N symbols from that of the first N symbols, and the remainder is the estimation of signal average power of bit 1. Similarly, we can use branch 2 to achieve the estimation of average power for bit 0. The only difference is that the first N symbols include noise only, and the second N symbols include the signal of bit 0 and noise.

To prove the validation of the above estimation method, we derive the mathematical equation as follows. First, we use branch 1 to analyse the estimation for bit 1

$$Y_1 = \frac{1}{N} \sum_{i=1}^N (s_i + n_i)^2 \quad (4)$$

$$Y_2 = \frac{1}{N} \sum_{j=1}^N n_j^2 \quad (5)$$

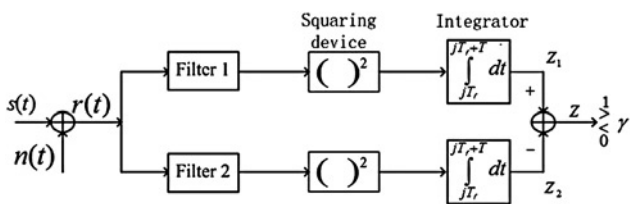


Fig. 3 Structure of the receiver of a GFSK system

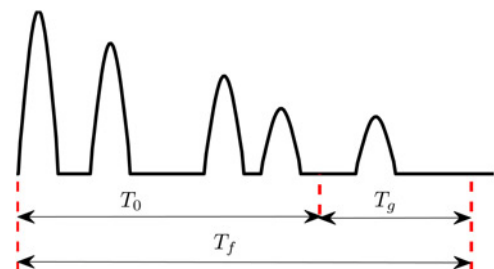


Fig. 4 GFSK frame structure in multipath channel

where s_i denotes the signal, n_i and n_j denote the Gaussian noise. Y_1 and Y_2 denote the average power of the first and the second N symbols, respectively. Equation (4) can be separated into several terms

$$Y_1 = \frac{1}{N} \sum_{i=1}^N s_i^2 + \frac{1}{N} \sum_{i=1}^N n_i^2 + \frac{1}{N} \sum_{i=1}^N 2s_i n_i \quad (6)$$

Hence $s_1 = s_2 = \dots = s_i$, we will have

$$\frac{1}{N} \sum_{i=1}^N 2s_i n_i = 2s_1 \left(\frac{1}{N} \sum_{i=1}^N n_i \right) \quad (7)$$

where $(1/N) \sum_{i=1}^N n_i$ is the expectation value of the N samples of Gaussian noise. When N is large enough, we have $(1/N) \sum_{i=1}^N n_i = 0$. So (7) also equals to 0 when N is large. Finally, the estimation of the average power of bit 1 can be achieved by

$$Y = Y_1 - Y_2 = \frac{1}{N} \sum_{i=1}^N s_i^2 + \frac{1}{N} \sum_{i=1}^N n_i^2 - \frac{1}{N} \sum_{j=1}^N n_j^2 \quad (8)$$

where $(1/N) \sum_{i=1}^N n_i^2$ and $(1/N) \sum_{j=1}^N n_j^2$ both denote the average power of the N sample of Gaussian noise. When N is large enough, they are equal. Finally, we can achieve

$$Y = \frac{1}{N} \sum_{i=1}^N s_i^2 \quad (9)$$

In the estimation of the average power of the signal, an important parameter is the training sequence length N . When N is large enough, the expectation of the noise approaches to 0 and the average power approaches to a constant. Then we can achieve an accurate estimation. However, we should not choose too large a value, since it increases the computation burden. So it is very important to choose a suitable value for N .

Similarly, we can use branch 2 to achieve the estimation for bit 0. The only difference is that $Y_1 = (1/N) \sum_{i=1}^N n_i^2$ and $Y_2 = (1/N) \sum_{j=1}^N (s_j + n_j)^2$. Thus the average power is calculated by $Y = Y_2 - Y_1$.

4 Numerical results and analysis

Fig. 5 shows the BER curves of GFSK in multipath channels. We use the CM4 model of IEEE 802.15.4a channel [12] in simulation. The bandwidth of the filters is 3.52 GHz, and the pulse duration is 0.876 ns. The integration time is set to the maximum channel delay 80 ns. Under this configuration, the integrators capture all signal energy, so the parameter λ in (3) equals 1. Then (3) is reduced to

$$P_e = Q\left(\frac{E_b/N_0}{\sqrt{2TW + 2E_b/N_0}}\right) \quad (10)$$

The training sequence is composed of $N=30$ consecutive 1s followed by $N=30$ consecutive 0s. The longer the training sequence is, the more accurate the estimation is. The value of $N=30$ already can generate an accurate estimation without inducing too much computation burden.

In Fig. 5, the analytical BER curve along with four simulated BER curves is shown. The analytical curve is generated using (10). We choose two different ratios of energy loss in simulation. The ratio of 1:0.9 mimics the small difference of energy loss between bit 1 and 0. The ratio of 1:0.7 simulates the large difference of energy loss between bit 0 and 1. For each ratio of energy loss, we

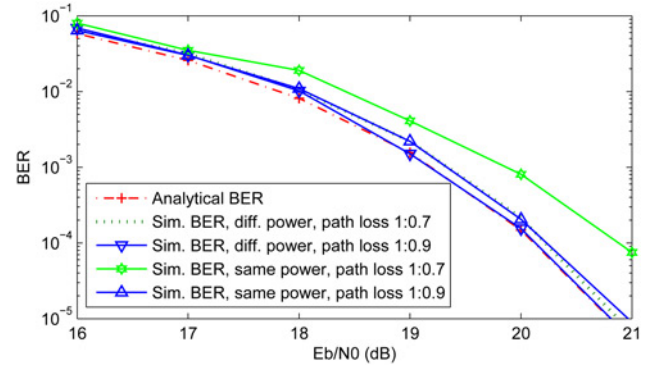


Fig. 5 BER curves in the CM4 channel of IEEE 802.15.4a

simulate two cases. Case 1 simulates the case that the bit 0 and 1 are transmitted using different powers to compensate the difference of energy loss. Case 2 simulates the case that the signals are transmitted with the same power. We can see from Fig. 5 that the simulated BER curves match the analytical curves very well when the signals are transmitted with different power to compensate the difference of energy loss. The curve of the ratio 1:0.9 has a better match than the curve of ratio 1:0.7. However, the difference is very small and the curve of 1:0.7 already matches the analytical curve very well. If the signals are transmitted using the same power, the system BER performance is degraded. When the ratio is 1:0.9, the degradation is not too severe since the difference of energy loss is not too large. However, when the ratio is 1:0.7, the degradation is about 0.7 dB at the BER = 10^{-4} . So the performance improvement by transmitting signals with different power is significant.

5 Conclusions

In an ED Gaussian FSK UWB system, the received signal energies of bit 0 and 1 are unbalanced due to the effect of frequency selectivity and antenna. This leads to the decision threshold deviating from 0 and causes decision error. To compensate the effect, the system transmits N consecutive 1s followed by N consecutive 0s as a training sequence to estimate the average received power of bit 1 and 0. Then the system compensates the transmitting power for bit 0 and 1 inversely proportional to the ratio of the received power. After compensation, the signals of bit 0 and 1 arrive at the receiver with the same energy. The numerical results show that the systems can use a short training sequence to achieve an accurate estimation without increasing the computation burden and system complexity.

6 References

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