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Performance analysis of GFSK modulation over AWGN channel

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Abstract. This paper analyses the performance of Gaussian Frequency Shift Keying (GFSK) modulation in Additive White Gaussian Noise (AWGN) channels. Using MATLAB 2022b for simulations, the study explores GFSK modulation principles, the role of Gaussian low-pass filters, the characteristics reflected by Power Spectral Density (PSD), and the influence of Bit Time-Bandwidth Product (BT) on Bit Error Rate (BER). It has been observed that the Gaussian filter restricts sidelobe amplitudes and enhances spectral efficiency. Through varying BT values, it is observed that higher BT values correlate with lower BER. Additionally, the study successfully reconstructs original baseband signals through sampling decisions, confirming GFSK modulation effectiveness.

Keywords: Gaussian Frequency Shift Keying, Bit Time-bandwidth Product, Power Spectral Density, Gaussian Low-pass Filter.

1. Introduction

In wireless communication systems, the data to be transmitted is usually in the form of binary data streams. Due to the channel's bandwidth characteristics, it is not feasible to directly transmit baseband signals. This is because digital baseband signals contain abundant low-frequency components. Hence, it is necessary to modulate the digital baseband signals onto carrier waves to make them suitable for transmission within the passband channel. Frequency Shift Keying (FSK) is a widely used modulation technique that encrypts digital data by altering the carrier signal's frequency. One continuous-phase frequency shift keying modulation method that evolved from FSK is called Gaussian Frequency Shift Keying (GFSK). To decrease the transmission bandwidth in current low-data-rate applications, GFSK modulation uses Gaussian functions as pulse-shaping filters [1].

In the realm of wireless communication, the pursuit of high efficiency, robustness, and reliable signal transmission has driven researchers to explore various modulation techniques. GFSK modulation finds its applications across a diverse range of domains, including but not limited to wireless sensor networks, Bluetooth communication, state-of-the-art backscatter systems (RBLE) [2], AMR (Automatic Meter Reading) for smart home and RF Energy Harvesting systems [3] and data telemetry [4]. The constant-envelope property of GFSK, which leads to efficient power amplifier utilization, further enhances its attractiveness for power-constrained communication scenarios [5].

One of the crucial challenges in wireless communication is the presence of noise and interference, which degrade the quality of transmitted signals. For assessing the effectiveness of communication systems, the Additive White Gaussian Noise (AWGN) channel model has been widely utilized as a fundamental abstraction of this noise. In this context, the study of GFSK modulation's performance in an AWGN channel assumes paramount importance. Analyzing its behaviour in the presence of noise will provide insights into its suitability for real-world communication scenarios, allowing us to assess its robustness and potential limitations.

Through MATLAB simulations, this research provided comprehensive insights into GFSK modulation, including its underlying principles, the role of Gaussian filters, the implications of PSD analysis, and the influence of BT on BER performance. The insights garnered from this analysis can guide the design and optimization of GFSK-based communication systems, contributing to the advancement of wireless communication technologies.

2. GFSK modulation

GFSK modulation is a continuous phase frequency shift keying (CPFSK) modulation technique. It is a digital modulation scheme that involves pre-modulating the input data through a Gaussian low-pass filter and then performing FSK modulation [6]. Figure 1 depicts the block diagram of GFSK modulator.

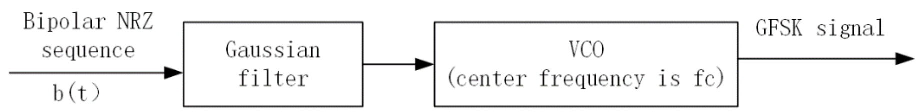

Figure 1. GFSK modulator.

Due to the uncertain phase transitions in the NRZ sequences, resulting in a wide spectrum and poor out-of-band characteristics, it is necessary to pass them through a pulse-shaping filter to truncate and limit their bandwidth. Here, a Gaussian filter is employed as the pulse-shaping filter, and its impulse response is as equation (1).

$$h(t) = \frac{1}{\sqrt{2\pi}\sigma T} e^{-\frac{t^2}{2\sigma^2 T^2}} \tag{1}$$

where

$$\sigma = \frac{\sqrt{ln2}}{2\pi BT} \tag{2}$$

The product of the 3dB bandwidth (B) and the symbol period (T) — known as the BT product — is a key design factor for GFSK modulation. The smaller the BT value, the narrower the bandwidth occupied by the Gaussian low-pass filter signal in the frequency domain. This leads to higher spectral efficiency. In contrast, in the time domain, the signal delay increases, causing more interference to other signals. Therefore, to minimize inter-symbol interference while maintaining a higher spectral efficiency, the BT value chosen for Bluetooth Low Energy (BLE) is 0.5 [7].

After the bipolar NRZ sequence passes through a Gaussian low-pass filter, the signal waveform becomes smoother. When the smoothed waveform is fed into a VCO (f_c is the centre frequency) for frequency modulation, the phase trajectory of the VCO output constant-envelope continuous phase modulation signal becomes smoother. As a result, the sidelobe attenuation of the power spectrum occurs more rapidly [8].

The input bipolar NRZ sequence can be expressed as (3):

$$b(t) = \sum_{n=-\infty}^{\infty} a_n g_T(t - nT_b) \tag{3}$$

where $a_n \in \{\pm 1\}$, $g_T(t) = rect\left(\frac{t}{T} - \frac{1}{2}\right) = \begin{cases} 1, & 0 \le t \le T \\ 0, & else \end{cases}$

GFSK signal can be described as (4):

$$s_{GFSK} = cos[2\pi f_c t + \theta(t)] \tag{4}$$

where A is the amplitude, $\theta(t)$ is the phase of GFSK signal:

$$\theta(t) = 2\pi h \int_{-\infty}^{t} \sum_{n=-\infty}^{\infty} a_n h(\tau - nT_b)\, d\tau \tag{5}$$

h is the modulation index defined as (6):

$$h = 2f_d T \tag{6}$$

where f_d is the frequency offset.

The frequency difference between the modulated carriers increases with increasing modulation index. The GFSK is comparable to the Gaussian Minimum Shift Keying (GMSK) at h=0.5. The range for h allowed by the DECT standard is 0.35 to 0.7. The value of Bluetooth varies from 0.28 to 0.35 [9].

3. Principle

The procedure of this study is shown in Figure 2.

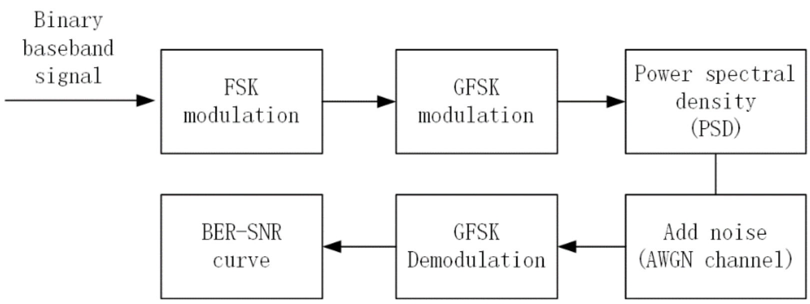

Figure 2. Procedure of the study.

First, perform FSK modulation and GFSK modulation on the input signal to obtain the GFSK signal and its power spectral density. Add AWGN to the GFSK signal to get a noisy GFSK signal, and then demodulate the signal to recover the original input signal. Finally, calculate the BER between the input signal and the demodulated signal, and plot the BER-SNR curve.

3.1. Power spectral density (PSD)

PSD is a measure that expresses the relationship between the power content of a signal and its frequency. PSD is frequently employed to explain the properties of wideband random signals. The frequency resolution of digitized signals is used to normalize the amplitude of the PSD. The mathematical expression for PSD is as follows:

$$P_x = \int_{-\infty}^{\infty} \lim_{T\to\infty} \frac{|X_T(f)|^2}{T} df \tag{7}$$

where $X_T(f)$ is the Fourier transform of the truncated power signal $x_T(t)$.

$$x_T(t) = \begin{cases} x(t), & |t| \le \frac{T}{2} \\ 0, & |t| > \frac{T}{2} \end{cases} \tag{8}$$

The amplitude of a signal is directly related to its power. Larger signal amplitudes lead to higher power values on the PSD plot. Through PSD, we can also determine the bandwidth of a signal, which represents the main frequency range encompassed by the signal. A wider bandwidth indicates that the signal contains a greater variety of frequency components, resulting in a more complex signal behaviour.

3.2. AWGN

AWGN stands for "Additive White Gaussian Noise." It is a commonly used noise model in communication systems and signal processing. AWGN is characterized by being additive, having a white spectrum, and following a Gaussian (normal) distribution. It represents random noise that is added to a signal during transmission, typically to simulate the effects of various sources of interference and noise in a communication channel. The "white" in AWGN refers to its constant power spectral density across all frequencies, and "Gaussian" refers to its statistical distribution, which follows a Gaussian distribution. AWGN is a fundamental concept in analyzing and designing communication systems to assess their performance under noise conditions. We use that model because it is close to the real-world BLE signal transfer situation [2].

3.3. Bit error rate (BER)

BER is a crucial performance metric used to quantify the quality of digital communication systems, especially in the presence of noise and interference. It measures the fraction of bits that are received incorrectly compared to the total number of transmitted bits. In other words, it provides insights into how reliably a receiver can correctly decode the transmitted information.

Mathematically, BER is expressed as the ratio of the number of bits received in error to the total number of bits transmitted. It is usually represented as a decimal value between 0 and 1, or sometimes expressed as a fraction, percentage, or logarithmic form (dB) to facilitate analysis and comparison of different communication schemes and channel conditions.

The energy per bit to noise power spectral density ratio, abbreviated E_b/N_0, is frequently represented as a function of the normalized carrier-to-noise ratio measure in noisy channels. A lower BER signifies better communication system performance, indicating fewer bit errors and improved data integrity. BER can be experimentally determined by comparing the received bits with the transmitted bits, allowing designers to assess the system's performance under different conditions and make informed decisions to enhance its reliability. It is standard practice to use BER(dB) vs. SNR(dB) graphs to illustrate how well a digital communication system performs.

4. MATLAB simulation

4.1. Simulation environment

The GFSK modulation and demodulation uses MATLAB R2022b which is a powerful numerical computing and simulation software that offers a wide array of tools and capabilities for solving various scientific, engineering, and mathematical problems.

Table 1 displays the simulation parameters used in this study:

Table 1. Simulation parameters.

Parameters	Value
Simulator	MATLAB 2022b
Number of bits	10
Number of samples per bit	100
Bit width	10^{-3} s
Bit rate	10^{3} s^{-1}
Sampling interval	10^{-5} s

Table 1. (continued).

Sampling frequency	10^5 Hz
Carrier frequency 1	11kHz
Carrier frequency 2	25kHz
BT	0.5
SNR of AWGN	20 dB

4.2. GFSK modulation

In order to simulate the modulation process of GFSK more easily, a method of discontinuous phase modulation is adopted here. Since the phase is discontinuous, transitioning from the output of one frequency generator to another will result in significant sidelobes in the signal spectrum. Using this approach for modulation requires a wider bandwidth. The block diagram of GFSK modulation using MATLAB R2022b is shown in Figure 3.

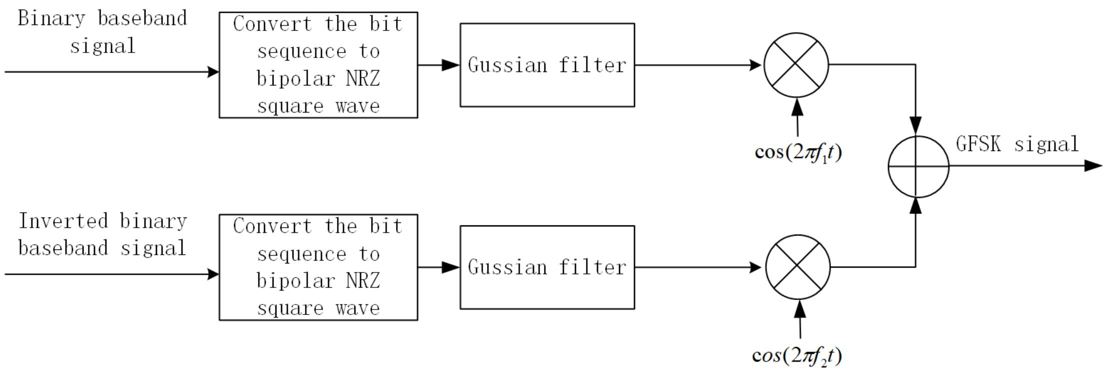

Figure 3. GFSK modulation block diagram.

The digital signal at the transmitter is transmitted in the form of bits in GFSK modulation. The randomly generated input baseband signal 1011110001 is shown in Figure 4. These bits must be transformed into actual electrical signal waveforms in order to be converted into the proper modulation format. The widely used bipolar NRZ coding stands out because of its small bandwidth and zero-crossing property in the frequency spectrum of the bit [10]. This zero-crossing characteristic is essential for the GFSK modulation demodulation procedure at the receiving end. Consequently, the bit stream needs to be transformed into bipolar NRZ code before passing Gaussian filters.

Then separately pass the bipolar NRZ code and its inverted code through Gaussian filters and multiply them with two carrier waves with different frequencies (equivalent to assigning higher carrier frequency to 1 and lower carrier frequency to 0). Finally, add them together to obtain the GFSK signal. Figures 5 & 6 show the modulated FSK and GFSK signal waveforms which indicate that applying a Gaussian filter before FSK modulation would make the output signal from FSK smoother.

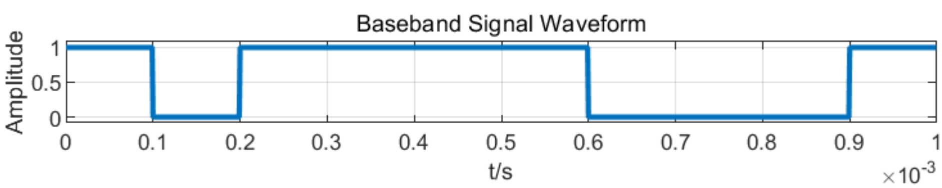

Figure 4. Baseband signal.

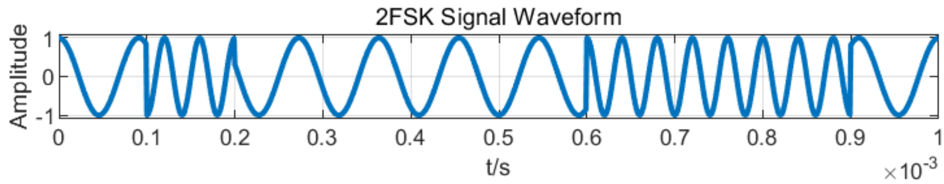

Figure 5. FSK signal.

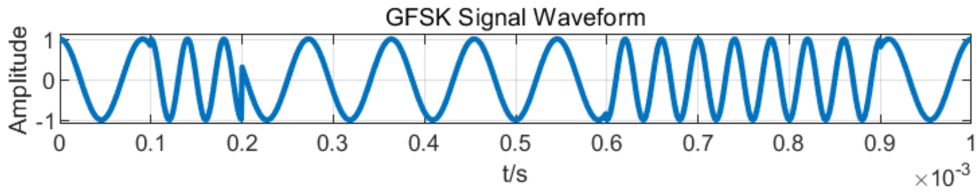

Figure 6. GFSK signal.

To get the PSD of FSK and GFSK, use the Fast Fourier Transform (FFT) function in MATLAB to convert the time-domain signal into the frequency domain. The FFT result gives the spectrum ranging from 0 Hz to the sampling frequency. To have the spectrum centred at 0 Hz, use the fftshift function to shift the spectrum.

The results of FSK and GFSK PSD can be seen in Figures 7-9. It can be observed that the Gaussian filter's shaping of the digital data considerably reduces the size of the side lobes in the frequency spectrum of the GFSK signal, thereby improving the spectral efficiency.

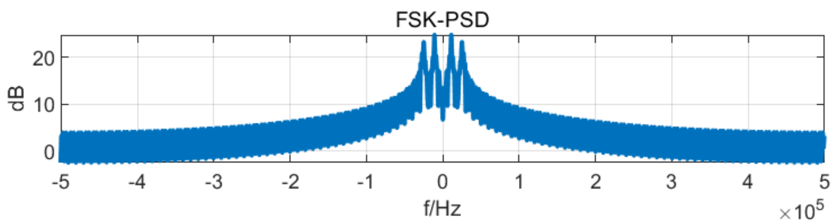

Figure 7. PDS of FSK.

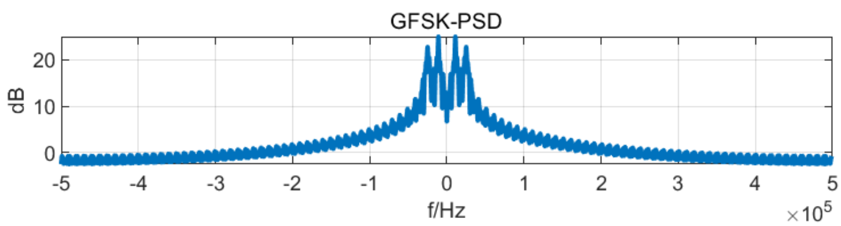

Figure 8. PDS of GFSK.

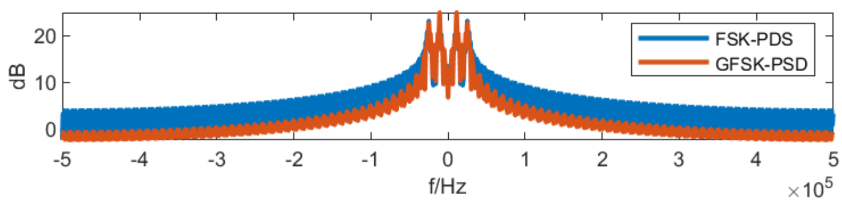

Figure 9. FSK-PSD vs GFSK-PSD.

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4.3. GFSK demodulation

The GFSK demodulation block diagram is shown in Figure 10. After passing through an AWGN channel, the received GFSK signal is split into upper and lower paths and passed through bandpass filters to eliminate out-of-band interference. Subsequently, the outputs of the bandpass filters are multiplied by their corresponding carriers. The products then undergo low-pass filters to remove high-frequency components. Finally, by employing sampling and decision-making techniques, the original baseband signal can be recovered [11].

The GFSK signal has been demodulated correctly as shown in Figure 11 (1011110001).

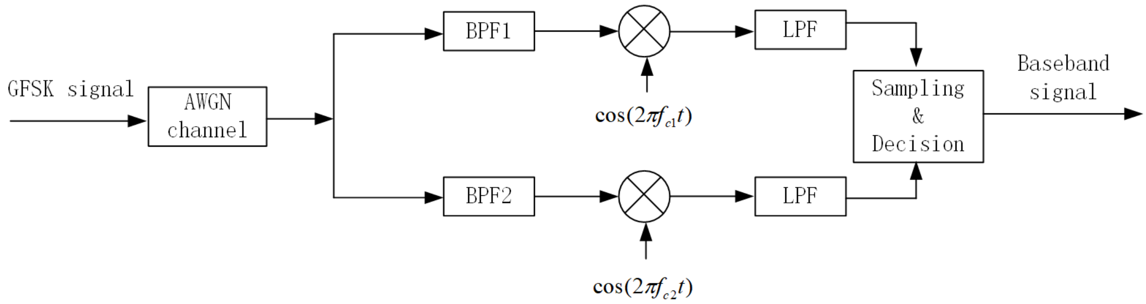

Figure 10. GFSK demodulator.

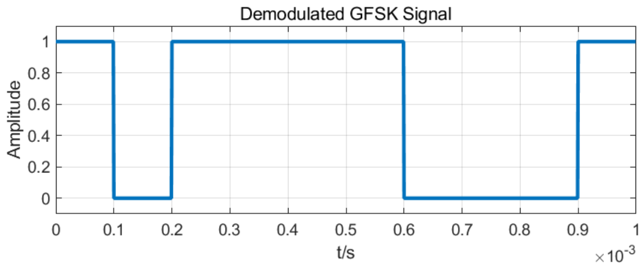

Figure 11. Demodulated GFSK signal

4.4. SNR-BER in different BT values

In this study, the BER was investigated in relation to the BT of GFSK modulation. The SNR-BER curves were plotted for varying BT values while keeping other conditions constant. The results from Figure 12 indicate that as the BT value increased, the BER exhibited a decrease. This trend implies that GFSK performance improves as BT increases, resulting in a reduced likelihood of bit errors. This finding underscores the importance of considering the BT parameter when designing GFSK communication systems, as a higher BT value can contribute to enhanced signal quality and more reliable data transmission.

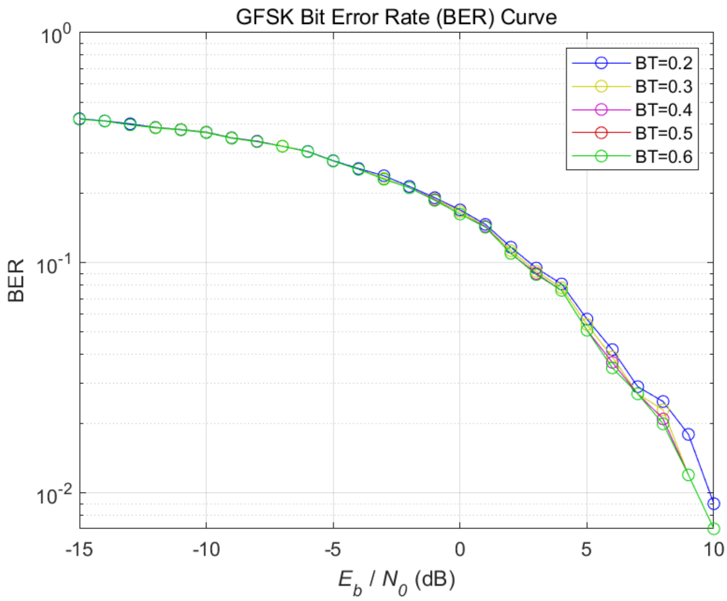

Figure 12. SNR-BER in different BT values.

5. Conclusion

The study was conducted using MATLAB 2022b, focusing on various performances of GFSK modulation. The utilization of Gaussian lowpass filter was investigated, revealing its crucial role in smoothing the FSK signal and reducing side lobes in the frequency spectrum. The PSD of GFSK provided insights into signal power distribution across different frequencies and aided in understanding signal bandwidth and spectral properties. The study also examined the impact of BT on the BER of GFSK signals. As the BT value increased, the BER exhibited a decreasing trend, emphasizing the pivotal role of BT in influencing signal quality and reliability. GFSK modulation has the advantages of easy implementation, high bandwidth efficiency, and good noise resistance performance. It can be used in low-data-rate and low-cost personal wireless communication systems and modern communication devices.

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