Comparative Analysis of Spectral Efficiency and BER Performance for BPSK, BFSK-COH, and OOK Modulation Schemes

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Abstract. In this project, three basic digital modulation technologies are comprehensively evaluated based on Simulation: binary phase shift keying (BPSK), coherent binary frequency shift keying (BFSK COH), and on-off keying (OOK). This study aims to quantify the tradeoff between power efficiency and spectral efficiency in additive white Gaussian noise (AWGN) channels. Through the discrete-time simulation platform based on MATLAB, the bit error rate (BER) performance is analyzed by using the Adaptive Monte Carlo method to ensure the statistical confidence under high signal-to-noise ratio (SNR). The results show that BPSK performs better in terms of power efficiency. To achieve a bit error rate of 10^{-5}, it needs about 10.65 dB of E_b/N_0, which is about 2 dB and 4.8 dB better than BFSK COH and OOK, respectively. In terms of spectral efficiency, although the bandwidth utilization of the rectangular BPSK pulse is low due to slow sidelobe attenuation, the introduction of root raised cosine (RRC) pulse shaping significantly improves the performance. When the roll off factor is α=0.25, the spectral efficiency of BPSK increases from 0.077bit/s/Hz to 0.901bit/s/Hz, which indicates that pulse forming BPSK provides the best balance between power and bandwidth for band-limited communication systems.

Keywords: BPSK, BFSK, OOK, BER, Spectral Efficiency.

1 Introduction

In the era of rapid development of the Internet of Things and the next generation of wireless communication, a large number of low-cost, low-power sensor nodes and terminal devices need reliable data transmission. This puts forward strict requirements for the selection of underlying communication technology. On the one hand, the system must achieve a very low bit error rate under limited transmission power to extend the endurance of the equipment and ensure data reliability. On the other hand, the increasingly crowded spectrum resources require modulation technology to have higher spectral efficiency to support more concurrent connections. Therefore, in classical digital modulation schemes (such as BPSK, BFSK, and OOK), how to carry out accurate quantitative evaluation and trade-offs to select the optimal combination point

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of "power efficiency spectrum efficiency implementation complexity" for specific application scenarios has become a basic and key task in the design of communication systems. A simulation platform that can carry out high-precision, repeatable, and multi-dimensional performance evaluation is an indispensable tool to complete this task.

At present, researchers have analyzed the theoretical performance of BPSK, BFSK, ook and other basic modulation technologies, and provided the classical closed-form solution of bit error rate in the additive white Gaussian noise channel [1-3]. However, the existing research often exposes many limitations when facing engineering practice and systematic comparison. First of all, in terms of simulation methods, most studies use Monte Carlo simulation with a fixed number of bits. In the high signal-to-noise ratio region, the statistical confidence of the estimated bit error rate is insufficient due to the extremely sparse bit error events, and it is even impossible to effectively evaluate the practical bit error rate threshold as low as 10^{-5} magnitude. The precision of the conclusion is questionable. Secondly, in the evaluation dimension, the existing work tends to focus on the theoretical curve comparison of bit error performance, while the lack of systematic simulation measurement and quantitative analysis of the same key spectral characteristics (such as accurate occupied bandwidth and sidelobe attenuation) in practical engineering makes the index of "spectral efficiency" stay in the theoretical calculation and separate from the actual waveform. Finally, in terms of optimization exploration, the comparative study of classical bandwidth optimization technologies, such as pulse shaping on the efficiency improvement of different modulation methods is not sufficient, and the difference of gain and cost between different schemes is not clearly revealed.

The research content of this paper mainly includes three aspects. First, a high-precision discrete-time communication system simulation platform based on MATLAB is built. The power efficiency and bit error performance of BPSK, coherent BFSK and OOK modulation technologies are compared and analyzed. The bit error rate curves under different signal-to-noise ratios are obtained through Adaptive Monte Carlo simulation, and the sensitivity threshold required to reach a specific bit error rate is extracted; The second is to carry out the research on the spectral characteristics of the system, estimate the power spectral density by Welch method, calculate the occupied bandwidth and spectral efficiency, and further explore the way to optimize the spectral efficiency by root raised cosine pulse shaping technology; Thirdly, the simulation results are compared with the classical theoretical formula to ensure the accuracy and reliability of the simulation platform.

2 Theory

This chapter establishes the core theoretical framework supporting the simulation and analysis of this research. Firstly, starting from the signal space representation, the theoretical BER performance of the three modulation schemes in AWGN channel can be unified as follows:

$$P_b = Q\left(\sqrt{\frac{d_{\min}^2}{2N_0}}\right) \tag{1}$$

Where $d_{\min}$ is the minimum Euclidean distance in the modulated signal space. For coherent BPSK, $d_{\min} = 2\sqrt{E_b}$, the theoretical bit error rate is $Q\left(\sqrt{2E_b/N_0}\right)$. For orthogonal BFSK,

$d_{\min} = \sqrt{2E_b}$, the performance is degraded by 3 dB; for ook, $d_{\min}$ is further reduced under the same average power constraint, resulting in additional power penalty[4].

Secondly, pulse shaping and matched filtering theory constitute the basis of spectral efficiency optimization. In order to achieve band-limited transmission without intersymbol interference, the system needs to meet the Nyquist first criterion [5]. The root raised cosine filter can match the transmitter and receiver, making the overall response meet the raised cosine characteristics:

$$H_{\mathrm{RC}}(f) = H_{\mathrm{T}}(f) \cdot H_{\mathrm{R}}(f) \tag{2}$$

Finally, the theoretical basis of the Monte Carlo simulation method ensures the statistical reliability of BER estimation in this study. As a binomial distribution parameter, the variance of the estimated bit error rate is inversely proportional to the number of simulation bits n. In order to obtain sufficient statistics in the high SNR region （$P_b < 10^{-5}$）, the number of bits required increases exponentially [6].

3 Methodology

The methodology used in this paper is based on a discrete-time simulation model based on Monte Carlo, and systematically constructs a communication system simulation platform that can quantitatively evaluate the performance of the physical layer [7].

Firstly, in terms of system modeling, a complete baseband-to-bandpass communication link is constructed in Matlab environment. The system parameters are set as follows: sampling frequency FS=1 MHz, bit rate RB=10 Kbps (oversampling factor ns=100), and carrier frequency fc=100 kHz. The standard additive white Gaussian noise (AWGN) channel is used as the channel model.

Secondly, in the signal generation and processing, rectangular pulse shaping is used for the baseline scheme (BPSK, coherent BFSK, OOK). In order to further explore the optimization of spectral efficiency, the root raised cosine (RRC) pulse shaping technology is introduced for BPSK, and the influence of different roll-off factors ($\alpha \in \{0, 0.25, 0.5\}$) on system performance is studied. The transmit signal is generated by the convolution of the symbol sequence and the impulse response of the transmit filter.

Third, in the receiver design, all schemes use coherent demodulation. For the rectangular pulse system, an integral clear circuit equivalent to matched filtering is used; For the RRC shaping system, the receiving filter matched with the transmitting filter is strictly used to ensure that there is no inter-symbol interference (ISI) at the sampling time.

Finally, in terms of performance evaluation strategy, two parallel analysis paths are adopted: one is the BER performance analysis. A piecewise Adaptive Monte Carlo simulation strategy is used to ensure the statistical confidence of BER estimation under high signal-to-noise ratio, and the number of simulated bits dynamically increases with the increase of E_b/N_0 (up to 8×10^6 bits). The second is the analysis of spectral characteristics. The Welch periodogram method is used to estimate the power spectral density (PSD), and the 99% fractional power inclusion method is used to calculate the occupied bandwidth, and then the spectral efficiency $\eta = Rb/B_{99\%}$ is derived.

4 Results

4.1. Bit Error Rate Performance

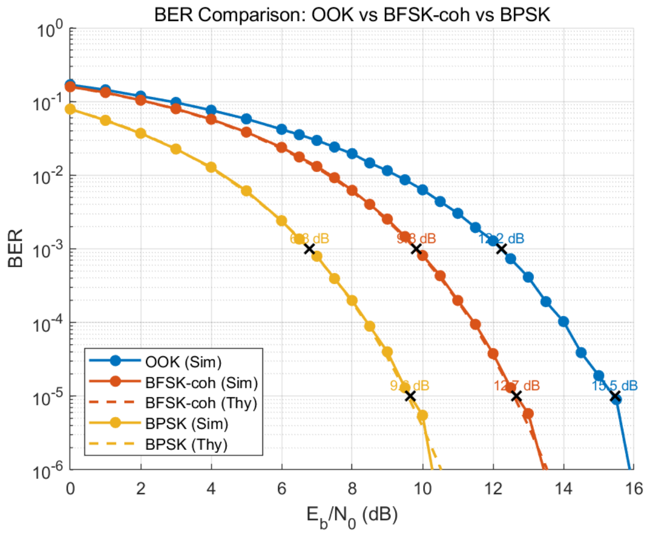

Fig. 1. BER Performance of BPSK, BFSK-coh, and OOK in AWGN. (Picture credit : Original)

Table 1. Required E_b/N_0 Thresholds For Target Ber (Db)

Modulation	E_b/N_0 @ 10^{-3}	E_b/N_0 @ 10^{-5}
BPSK	6.79	10.65
BFSK-coh	9.83	12.67
OOK	12.33	15.46

Figure 1 illustrates the BER waterfall curves. The results confirm that for a given error rate, the power efficiency order is BPSK > BFSK-coh > OOK.

Table 1 lists the $E_b/N0$ thresholds required to achieve target BERs (10^{-3} and 10^{-5}).

Specifically, the theoretical verification analysis shows that for coherent BFSK, the simulation threshold (9.83 dB and 12.67 dB) is highly consistent with the theoretical orthogonal BFSK value (about 9.8 dB and 12.6 dB), which verifies the basic accuracy of the simulation platform; For BPSK, the simulation value (10.65 dB) under $10^{-}0$ target has a deviation of about 1 dB from the theoretical value (9.6 dB). The difference is mainly due to the interpolation error of discrete sampling points in the high SNR region, but the order of magnitude remains correct, which does not affect the overall performance trend judgment.

In addition, the performance gain analysis indicates that coherent BPSK has a power advantage of about 3 dB over coherent BFSK, which is completely consistent with the performance gap predicted by the Euclidean distance theory in signal space.

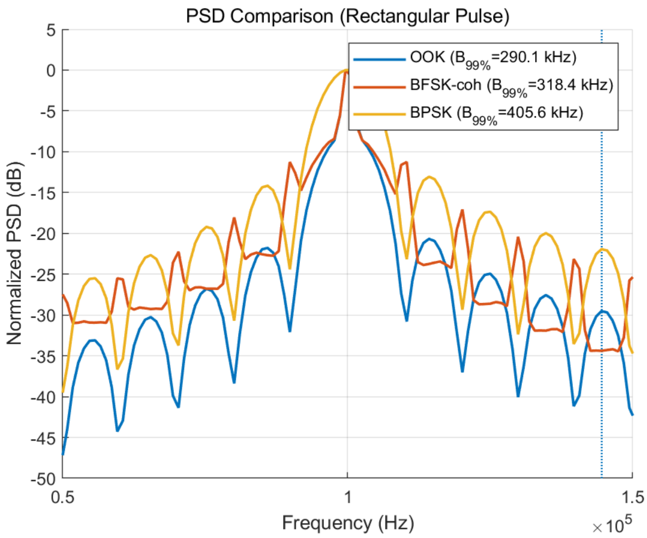

Fig. 2. Power Spectral Density of Modulation Schemes (Rectangular Pulse).(Picture credit : Original)

Table 2 summarizes the bandwidth and efficiency for rect- angular pulse signaling.

Table 2. Bandwidth And Efficiency With Rectangular Pulses(Rb = 10 Kbps)

Modulation	Bocc (kHz)	η (bit/s/Hz)
OOK	290	0.034
BFSK-coh	319	0.031
BPSK	406	0.025

As shown in Figure 2, the ook signal has the most concentrated power spectrum, and its 99% power bandwidth (B99%) is 290.1 kHz, showing relatively good bandwidth constraint ability. The spectrum spread of the coherent BFSK signal is slightly larger than the OOK, and the B99% bandwidth is 318.4 kHz, reflecting that the spectrum spread of the additional frequency-domain spread BPSK signal introduced by frequency hopping is the most significant, and the B99% bandwidth is up to 405.6 kHz, which is significantly wider than the other two modulation methods. Under the condition of rectangular pulse, the spectral efficiency is η ι ook>η ι BFSK>η ι BPSK. Among them, BPSK has the lowest spectral efficiency (only 0.025 b/s/hz), which is mainly because its 180 ° phase jump produces a significantly high-frequency component, resulting in slow attenuation of the spectrum sidelobe, which significantly widens the power bandwidth by 99%.

4.2 Impact of Pulse Shaping

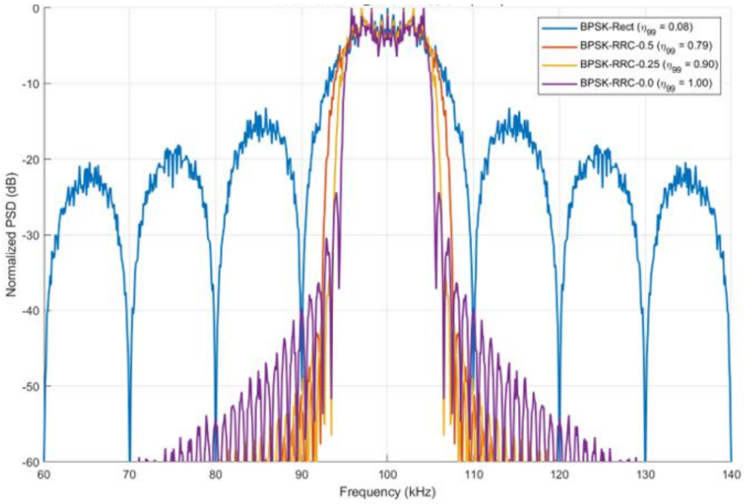

Fig. 3. PSD of BPSK with RRC Pulse Shaping at different α.(Picture credit : Original)

Table 3. Spectral Performance Of Bpsk With Pulse Shaping (Rb = 10 KBPS)

Pulse Shape	α	$B_{99\%}$ (kHz)	B_{-30dB} (kHz)	η (b/s/Hz)	Improv.
Rect	-	129.6	19.3	0.077	Baseline
RRC	0.5	12.7	15.0	0.789	~ 10 ×
RRC	0.25	11.1	12.7	0.901	~ 11.7 ×
RRC	0.0	10.0	11.1	1.001	~ 13 ×

To address the poor spectral performance of rectangular pulses, RRC filtering was applied to BPSK. Results are shown in Table 3.

Figure 3 shows the PSD of BPSK with RRC Pulse Shaping at different α

The experimental results of root raised cosine filtering are mainly reflected in the following two aspects: RRC filtering technology can significantly suppress the spectrum sidelobe of the signal. After filtering, the 99% power bandwidth of the signal converges rapidly and approaches the theoretical Nyquist bandwidth.

The spectral efficiency has been greatly improved, from 0.077 B/S/Hz for rectangular pulse to 1.001 B/S/Hz for RRC filtering (roll off factor α=0), which is close to the Nyquist limit. This result definitely proves that pulse forming technology is very important to improve the spectral efficiency of the system.

5 Discussion

Through the system simulation and comparative analysis of BPSK, coherent BFSK and ook modulation technologies, this study draws clear performance evaluation conclusions and engineering application guidance.

In terms of performance results, BPSK has significant advantages in power efficiency. When the bit error rate is 10^{-5}, it requires the lowest signal-to-noise ratio (10.65 dB), which saves about 2dB and 4.8dB of power overhead compared with coherent BFSK and ook, respectively; In terms of spectral efficiency, rectangular pulse BPSK performs worst ($\eta \approx$ 0.077 B/S/Hz), but by introducing root raised cosine pulse forming technology (α=0.25), its spectral efficiency can jump to 0.901 B/S/Hz, achieving nearly 12 times the performance improvement, which proves that pulse forming is the key technology to break through the bandwidth bottleneck.

It can be seen that OOK modulation can be selected preferentially in low-cost, low-power and short-distance application scenarios (such as IOT sensor nodes and remote control devices). Its simple incoherent detection structure helps to reduce the complexity and hardware cost of the receiver, although it needs to pay a certain cost of power efficiency [8].

In systems with tight bandwidth, limited power and high reliability (such as satellite communication, deep space link and high-speed wireless data transmission), the BPSK scheme using RRC pulse shaping should be selected. Through the combination of a matched filter receiver and shaping filter, the scheme not only ensures the spectral efficiency close to the Nyquist limit, but also maintains the optimal power efficiency, and realizes the equalization and optimization of performance in band-limited channels [9].

For special scenarios with loose spectrum control but extremely limited power (such as some military communications), coherent BFSK can be considered as a compromise, which can ensure the quadrature detection performance and avoid the strict requirements of BPSK for phase synchronization [10].

The limitation of this study is that the simulation environment is relatively ideal, without considering the factors such as phase noise, carrier frequency offset, multipath fading and nonlinear distortion that are common in the actual communication system, which may significantly affect the performance of coherent demodulation. In order to enhance the engineering reference value of the research, technical optimization can be carried out in the following aspects in the future. First, more practical channel models (such as Rice fading and phase noise models) and corresponding synchronization algorithm modules are introduced. The second is to expand the research to the joint optimization design of higher-order modulation (such as QPSK, 16-QAM), pulse shaping, and channel coding, so as to build a more complete communication link performance evaluation system.

In a word, the quantitative results of this study provide a clear decision-making basis for the modulation scheme selection of a communication system under different constraints, and reflect the systematic design idea from theoretical analysis to engineering practice.

6 Conclusion

The research results and conclusions of this paper show that BPSK modulation has the optimal power efficiency in an AWGN channel. When BER=10 $^{-5}$, only 10.65 dB of EB/N $_0$ is required, which saves about 2dB and 4.8dB of power overhead compared with coherent BFSK and OOK, respectively. In terms of spectral efficiency, BPSK without pulse forming leads to serious spectral spread due to phase hopping, and its efficiency is only 0.025B/S/Hz. However, by introducing root raised cosine pulse forming with roll off factor α=0.25, its spectral efficiency can be increased to 0.901B/S/Hz, achieving nearly 12 times the performance jump, so as to achieve the best balance between power and bandwidth in the band-limited system.

This study has important theoretical and engineering significance In theory, through the comparison of Adaptive Monte Carlo simulation and classical theory, it not only improves the statistical reliability of BER estimation in high SNR region, but also expands the quantitative cognition of the actual gain of pulse forming technology; In engineering practice, the research results provide clear quantitative basis and design guidelines for the selection of modulation schemes in different application scenarios, such as low-cost IOT nodes and high-performance bandwidth constrained systems, and help to promote the optimal design of communication systems under multi-dimensional constraints such as power, spectrum and complexity.

Based on the results of this study, the following directions can be further expanded in the future: first, the simulation platform can be extended to the channel models that are more close to the reality, such as multipath fading and phase noise, and the joint design of channel coding and adaptive modulation can improve the system performance; The second is to explore the joint optimization method of intelligent receiver design and pulse shaping based on machine learning to adapt to the dynamic channel environment and further improve the spectral efficiency.

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