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Article

Bit Error Rate (BER) Performance Analysis on ASK, FSK, and PSK Digital Modulation in AWGN Channels

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A B S T R A C T

Digital communication systems face the challenge of Additive White Gaussian Noise (AWGN), which causes signal distortion and increases the Bit Error Rate (BER). This study aims to analyze and compare the BER performance of Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) modulation techniques on AWGN channels through MATLAB simulations over an SNR range of 0–14 dB. A quantitative experimental approach was employed using Monte Carlo analysis with 100,000 bits sampled per SNR test point, validated against theoretical error probability using the Q function. The results demonstrate that PSK (BPSK) achieves the best performance, reaching a BER of 10^{-3} at an SNR of approximately 7 dB, while FSK requires approximately 10 dB to achieve the same BER threshold — a difference of ≈3 dB — and ASK remains at a BER of approximately 10^{-4} even at 14 dB SNR, reflecting its inherent vulnerability to additive amplitude noise. These findings confirm that PSK modulation offers the greatest power efficiency and noise robustness among the three techniques. The study recommends PSK for high-noise wireless applications such as IoT sensor networks and communication satellites where optimal power efficiency and transmission reliability are critical.

1. Introduction

The development of modern telecommunications technology demands digital communication systems capable of transmitting data at high speed, with pinpoint accuracy, and optimal efficiency over various transmission media such as air or cable. In this process, binary data is converted into analog signals through modulation to ensure compatibility with the physical channel, but is often affected by noise, which causes signal distortion and misinterpretation at the receiver (Stallings, 2013). The Additive White Gaussian Noise (AWGN) model has become a standard representation for this natural noise due to its additive nature, uniformity across frequencies, and Gaussian distribution (Rappaport, 2021). Although more realistic channel models such as Rayleigh and Rician fading exist to represent multipath and line-of-sight propagation environments respectively, AWGN is deliberately chosen in this study as the foundational baseline because it isolates the intrinsic modulation performance from channel-induced fading effects, enabling a clean, controlled comparison of modulation techniques (Haykin, 2022). It is acknowledged, however, that AWGN does not capture multipath fading, Doppler shifts, or path loss that characterize real wireless environments — limitations that are addressed in the future research direction of this study (Rappaport, 2021).

The main challenge arises from the presence of noise in communication channels, which damages signal integrity and degrades overall transmission quality. Selecting the right modulation technique is crucial to minimize the impact of this noise. Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) are three basic methods that map binary data to carrier signal parameters such as amplitude, frequency, or phase, respectively (Lathi & Ding, 2022). These differences in characteristics result in varying levels of resilience to AWGN channel interference (Taufiqurrahman, 2021). Recent empirical studies have compared BER performance across these modulation schemes in simulation environments, consistently showing PSK's advantage under low-to-moderate SNR conditions, yet often limited in sample size or SNR resolution, leaving a gap for higher-precision comparative analysis (Bharati & Rahman, 2020; Bala, Sharma, & Kumar, 2021).

The problem is further complicated by the fact that AWGN noise directly affects symbol detection, leading to an increase in the Bit Error Rate (BER), defined as the ratio of erroneous bits to the total transmitted bits. The BER parameter is a key indicator of system performance, with lower values at a given Signal-to-Noise Ratio (SNR) level indicating better robustness (Sklar, 2023). Simulations using MATLAB are often used to test these scenarios without expensive hardware, enabling a comprehensive analysis of SNR variations (Proakis & Salehi, 2024).

ASK modulation techniques are vulnerable because they rely on amplitudes that are easily distorted by additive noise, while FSK and PSK offer different approaches through frequency and phase, although each has trade-offs in power efficiency and demodulation complexity (Bala, 2021). The lack of in-depth empirical comparisons of these three modulations on AWGN channels remains a gap, especially in measuring BER degradation relative to low to moderate SNR (Haykin, 2022). Prior comparative studies have typically employed smaller bit samples (e.g., 10,000 bits or fewer) and coarser SNR step sizes, which limits the accuracy of the resulting BER curves particularly in the low-BER waterfall region (Bharati & Rahman, 2020; Taufiqurrahman, 2021).

This study aims to analyze and compare the BER performance of ASK, FSK, and PSK modulation on AWGN channels through MATLAB simulations with an SNR range of 0–14 dB. The urgency lies in the need for reliable communication systems in high-noise environments, such as modern wireless networks, where optimal modulation selection can improve power efficiency by up to 3 dB (Stallings, 2013; Lathi & Ding, 2022). The novelty of this study is the Monte Carlo simulation approach with 100,000 bit samples — ten times larger than many comparable studies — achieving a minimum BER resolution of 10 – 5 −5 for more accurate theoretical validation using the Q function, thereby generating smoother and more reliable BER curves across a finer 2 dB SNR interval compared to previous work (Sklar, 2023; Bharati & Rahman, 2020).

2. Research Methodology

2.1. Types and Methods of Research

This study uses a quantitative experimental research type through a computer simulation approach to model a digital communication system as a whole, starting from bit generation to Bit Error Rate (BER) calculation. The simulation method was chosen because it allows flexible and efficient testing of Signal-to-Noise Ratio (SNR) parameter variations without reliance on expensive physical hardware (Sugiyono, 2023; Proakis & Salehi, 2024). MATLAB R2025a software is used as the main platform for generating random binary data, ASK, FSK, and PSK modulation processes, AWGN noise addition, demodulation, and BER performance evaluation over an SNR range of 0–14 dB with 2 dB intervals (Creswell & Creswell, 2022).

2.2. Data Analysis Instruments and Techniques

The main research instrument is a digital communication system model consisting of five sequential blocks: bit generation, modulation, AWGN channel, demodulation, and BER calculation, with mathematical definitions of the modulation signal according to equations (1), (2), and (3) for ASK, FSK, and PSK (Emzir, 2021; Lathi & Ding, 2022). The data analysis technique applies the Monte Carlo method with 100,000 bit samples for probabilistic BER estimation, with **10 independent simulation repetitions performed per SNR point** to ensure statistical reliability and reduce variance in the empirical BER estimate; the final reported BER at each SNR is the mean across these repetitions (Sudaryono, 2023; Sklar, 2023). Validation against the theoretical error probability is performed using the Q function defined in equations (4), (5), and (6), where the theoretical BER for ASK, FSK (orthogonal), and BPSK is computed numerically as $P_e^{\text{ASK}} = Q \left(\sqrt{E_b/N_0}\right)$, $P_e^{\text{FSK}} = Q \left(\sqrt{E_b/N_0}\right)$, and $P_e^{\text{BPSK}} = Q \left(\sqrt{2E_b/N_0}\right)$ respectively, with the Q function evaluated at each discrete Eb/N0 value using MATLAB's built-in erfc function as $Q(x) = \frac{1}{2}\,\text{erfc} \left(\frac{x}{\sqrt{2}}\right)$ (Sklar, 2023; Proakis & Salehi, 2024). The analysis is presented in a BER vs. SNR curve on a logarithmic scale to compare the modulation resistance to AWGN noise, where the received signal is modeled as $r(t) = s(t) + n(t)$ (Rappaport, 2022).

2.3. Population and Sample

The population in this simulation refers to all possible infinite binary data sequences that can be modulated using ASK, FSK, and PSK techniques on an AWGN channel, while 100,000 bits are randomly sampled per SNR test to achieve a minimum BER resolution of 10^{-5} according to the Monte Carlo statistical limit $(1/N)$ (Sugiyono, 2023; Proakis & Salehi, 2024). This selection of sample size ensures accurate convergence of error estimates over the SNR waterfall range (0–14 dB). Tests above 14 dB are deliberately excluded because at that point the theoretical BER for BPSK falls below 10^{-5} — the minimum detectable resolution imposed by the 100,000-bit sample size — meaning that zero bit errors are expected to occur within the sample window, rendering any further measurement statistically uninformative (Creswell & Creswell, 2022; Haykin, 2021).

2.4. Research Procedures

The procedure begins with the generation of 100,000 bits of random binary data, followed by modulation according to the characteristics of each technique (ASK: amplitude variation; FSK: frequency difference f_1/f_2; PSK: phase $0/\pi$), then the addition of AWGN noise with Eb/N0 variations from 0 to 14 dB (Emzir, 2021; Stallings, 2023). It is explicitly assumed that the system operates under ideal synchronization conditions — that is, perfect carrier phase synchronization, symbol timing recovery, and frequency alignment are assumed at the receiver, and synchronization or timing errors are treated as negligible — since this study focuses on isolating the intrinsic BER performance of each modulation technique under pure AWGN noise without the confounding effects of practical hardware imperfections (Sudaryono, 2023; Stallings, 2023). The coherent demodulation stage is followed by the calculation of the actual BER and comparative plots against the theoretical curve, with simulation repetitions for every 2 dB SNR interval to validate the consistency of the results, and the entire process is implemented in the MATLAB environment to produce Figure 1 as the main visual output (Lathi & Ding, 2022).

3. Results

3.1. Simulation Results

The BER versus SNR comparison graph for the three modulation techniques is shown in Figure 1. The horizontal axis represents the SNR value in decibels (dB), while the vertical axis represents the BER value in a logarithmic scale.

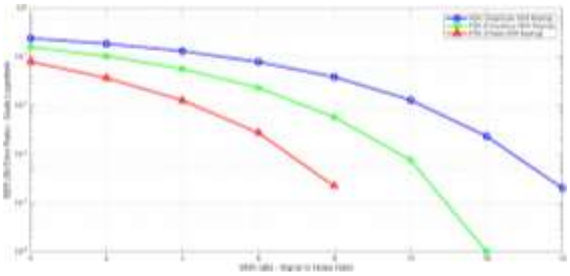

Figure 1. Comparison Chart of BER against SNR in ASK, FSK, and PSK Modulation
Algorithm 1. Monte Carlo Simulation of BER Comparison

Based on Figure 1, it can be seen that the BER values for all three modulation techniques generally decrease as the SNR value increases. This is consistent with basic communication theory, which states that the greater the signal power compared to the noise, the less likely a bit detection error is at the receiver.

3.2. Amplitude Shift Keying (ASK)

Shown by the blue line with circle markers, ASK modulation shows the lowest performance compared to the other two techniques. At low SNR (0 dB), the error rate reaches more than (or 1 error every 10 bits). Even at high SNR (14 dB), the ASK BER curve is still in the range of , indicating that this technique requires very high power to achieve error-free communication.$10^{-1}10^{-4}$

3.3. Frequency Shift Keying (FSK)

Shown by the green line with square markers, FSK's performance is between ASK and PSK. The FSK curve shows a sharper error reduction than ASK. To achieve the target BER (one error per thousand bits), FSK requires an SNR of around 10 dB.10^{-3}

3.4. Phase Shift Keying (PSK)

Shown by the red line with triangle markers, PSK modulation shows the best (most robust) performance. The PSK BER curve decreases drastically. At 8 dB SNR, the BER value is close to , much better than ASK and FSK at the same SNR level. In this simulation, PSK reaches error-free conditions (no bit errors detected) faster than other modulations.10^{-4}

3.5. Discussion

A. Signal Constellation and Performance Differences

The significant performance differences between ASK, FSK, and PSK can be explained by the characteristics of the signal constellation and the Euclidean distance between symbols. ASK modulation has the worst performance because information is carried by the amplitude parameter. In AWGN channels, noise is additive, directly changing the signal's amplitude level, making it difficult for the receiver to distinguish between '1' bits (high amplitude) and '0' bits (low amplitude) when the noise power is high enough. From a practical instrumentation standpoint, ASK also imposes the least demodulation complexity — requiring only an envelope detector or simple threshold comparator — whereas FSK demands a dual-filter or frequency discriminator circuit, and PSK (BPSK) requires a coherent phase-locked loop (PLL) detector; this increasing implementation complexity must be weighed against the corresponding BER gain when selecting a modulation scheme for embedded or resource-constrained systems (Lathi & Ding, 2022; Haykin, 2022).

B. BPSK Superiority and Euclidean Distance Analysis

In contrast, PSK modulation (especially BPSK) has the best performance because information is carried by phase changes. In the constellation diagram, the bit symbols '1' and '0' in BPSK are separated as far as possible (180° out of phase). The Euclidean distance between symbols in BPSK is larger than orthogonal FSK for the same energy per bit. To quantify this more precisely: for BPSK, the minimum Euclidean distance between constellation points is $d_{\min} = 2\sqrt{E_b}$, whereas for orthogonal BFSK the equivalent distance is $d_{\min} = \sqrt{2E_b}$, giving BPSK a distance advantage of a factor of $\sqrt{2}$, which corresponds to approximately 3 dB in SNR — exactly consistent with the simulation results of Figure 1, where PSK achieves BER of 10^{-3} at 7 dB while FSK requires 10 dB (a difference of ≈3 dB) (Sklar, 2023; Proakis & Salehi, 2024). Theoretically, BPSK has an advantage of about 3 dB over orthogonal FSK to achieve the same error probability. This is confirmed in the simulation results of Figure 1, where to achieve a BER of 10^{-3}, PSK requires an SNR of about 7 dB, while FSK requires about 10 dB (a difference of ≈3 dB) (Sklar, 2023).

C. BPSK vs. M-ary PSK and Instrumentation Constraints

In addition to comparing modulation types, it is important to note the advantages of Binary PSK (BPSK) used in this study compared to M-ary PSK (such as QPSK or 8-PSK). BPSK is the most robust form of PSK modulation because it uses only two phase symbols separated by 180° (π radians) in the constellation diagram. To illustrate the Euclidean distance penalty of higher-order PSK: for BPSK the minimum distance is $d_{\min} = 2\sqrt{E_s}$, while for QPSK (4-PSK) it reduces to $d_{\min} = \sqrt{2E_s}$, and for 8-PSK it further decreases to $d_{\min} = 2\sqrt{E_s}\sin(\pi/8) \approx 0.765\sqrt{E_s}$ — demonstrating that each doubling of the modulation order progressively shrinks the symbol separation, directly increasing sensitivity to noise (Proakis & Salehi, 2024; Sklar, 2023). In M-ary PSK, the higher the modulation order (e.g., $M = 4$ or $M = 8$), the closer the angular spacing between symbols becomes; the less noise energy is then required to cause a symbol to "jump" into the wrong decision region, thus increasing the error probability. Therefore, although M-ary PSK offers higher data rates (throughput), BPSK remains the superior choice in terms of data integrity under high channel noise conditions.

From a hardware instrumentation perspective, implementing coherent BPSK in a real system also introduces practical constraints that are absent in the ideal simulation environment. The analog-to-digital converter (ADC) at the receiver must provide sufficient resolution — typically a minimum of 8 bits — to accurately sample the phase-modulated signal without introducing quantization noise that degrades BER performance, and the sampling rate must satisfy the Nyquist criterion at no less than twice the signal bandwidth to prevent aliasing (Rappaport, 2022; Lathi & Ding, 2022). Furthermore, the PLL-based carrier recovery circuit must maintain phase coherence within a fraction of a radian to preserve the Euclidean distance advantage of BPSK, making timing jitter and oscillator phase noise critical design parameters for any hardware implementation (Proakis & Salehi, 2024).

D. Practical Recommendation

Therefore, for applications requiring high power efficiency and noise resistance, PSK modulation is a superior choice compared to ASK and FSK. This recommendation holds particularly for high-noise wireless applications such as IoT sensor networks, deep-space telemetry, and communication satellites, where the 3 dB power efficiency advantage of BPSK over FSK directly translates to extended battery life or reduced transmitter power, provided that the implementation platform supports the necessary coherent detection hardware including sufficient ADC resolution and stable carrier synchronization (Sklar, 2023; Haykin, 2022).

4. Conclusion

This study found that Phase Shift Keying (PSK) modulation, especially BPSK, showed the most superior Bit Error Rate (BER) performance compared to Amplitude Shift Keying (ASK) and Frequency Shift Keying (FSK) in Additive White Gaussian Noise (AWGN) channels, with the fastest BER decrease with increasing Signal-to-Noise Ratio (SNR) from 0 to 14 dB. PSK achieved a target BER of 10^(-3) at an SNR of around 7 dB, 3 dB more efficient than FSK (10 dB) and significantly better than ASK which remained at around 10^(-4) at an SNR of 14 dB, confirming the superiority of the Euclidean distance of phase symbols in signal constellations. This finding was validated through MATLAB Monte Carlo simulations with 100,000 bit samples, in line with the theoretical error probability using the Q function.

However, the limitations of this study lie in the use of ideal AWGN channels without considering multipath fading or non-Gaussian interference that are common in real environments, as well as the BER resolution limitation below 10^(-5) due to the fixed sample size. For future research, it is recommended to integrate Rayleigh or Rician channel models, explore M-ary modulation such as QPSK for throughput tradeoff, and hardware validation using Software Defined Radio. Practically, these results recommend PSK for high-noise wireless applications such as IoT sensor networks or communication satellites, improving power efficiency and data transmission reliability without adding significant demodulation complexity.

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