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BER Analysis of PAM Communications over AWGN Channels

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Abstract

This paper presents a detailed investigation into the performance of a Pulse Amplitude Modulation (PAM) communication system operating over an Additive White Gaussian Noise (AWGN) channel, utilizing comprehensive MATLAB simulations for validation. The core of the analysis focuses on evaluating Bit Error Rate (BER) trends under varying Signal-to-Noise Ratio (SNR) conditions. The obtained results clearly demonstrate PAM's inherent sensitivity to channel noise, particularly at low SNRs where high error rates are observed. Conversely, the analysis confirms significantly improved reliability and lower BER as the SNR increases. These simulation outcomes are thoroughly consistent with well-established theoretical expectations regarding PAM system behavior over noisy channels, thereby affirming the robustness of the implemented simulation model and methodology.

Keywords

Pulse Amplitude Modulation; AWGN; Bit Error Rate; SNR; MATLAB Simulation.

1. Introduction

In digital communications, efficiently transmitting data over physical media, such as wireless or fiber communications, is a fundamental challenge [1-3]. This process involves overcoming various forms of signal degradation and ensuring reliable information delivery across potentially noisy and bandwidth-limited channels. Pulse Amplitude Modulation (PAM) is a key modulation technique where information is encoded into the amplitude of transmitted pulses [4]. Each distinct amplitude level corresponds to a unique digital symbol (e.g., bits), allowing multiple bits to be transmitted per symbol depending on the number of levels used. Although PAM is conceptually straightforward and bandwidth-efficient, it is highly susceptible to noise, including Additive White Gaussian Noise (AWGN) [5] and Inter-Symbol Interference (ISI) [6, 7]. Noise corrupts the received pulse amplitudes, which complicates symbol detection and increases the bit error rate (BER) [8]. Therefore, understanding and managing noise impact is critical for PAM communication system design. An in-depth analysis of noise characteristics and their interaction with modulation schemes helps optimize system parameters and improve overall reliability.

This work uses MATLAB to conduct detailed simulation on a communication system, focusing on analyzing the impact of various models, including PAM modulation model and AWGN channel mode. MATLAB provides a versatile and powerful environment for signal processing and allows researchers to test various modulation and noise configurations efficiently. By adjusting the signal-to-noise ratio (SNR), we observe changes in BER, enabling quantitative evaluation of noise effects on system performance. This approach allows for a visual and numerical understanding of how different SNR values influence communication quality. Results show that PAM is especially vulnerable to AWGN at low to moderate SNR levels. However, with proper selection of modulation order and coding, PAM can maintain reliable performance. Through this work, a deeper understanding of the interaction between modulation methods and channel noise is achieved. Mastering such concepts lays a solid foundation for exploring more complex communication systems,

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such as those involving adaptive modulation, MIMO architectures, or channel equalization techniques that are prevalent in modern digital communication networks [8, 9].

The rest of this paper is organized as follows. Section 2 introduces the principle of PAM model AWGN channel model. Section 3 presents the simulation design and results. Section 5 concludes this work.

2. Models

2.1 PAM Modulation Model

Pulse Amplitude Modulation (PAM), proposed by A. Rivers in 1937, can be categorized into 2-PAM, 4-PAM, 8-PAM and so on based on the number of discrete amplitude levels [10]. The number of levels determines how many bits can be encoded per symbol, with higher-order PAM allowing more data to be transmitted per pulse at the cost of increased susceptibility to noise. PAM operates by converting analog signals into digital signals via periodic sampling, where each sample's amplitude is quantized into a finite set of discrete levels. These levels represent the analog signal's instantaneous amplitude at each sampling point, preserving the essential shape of the original signal within a digital framework. In this way, PAM provides a straightforward yet powerful approach to representing analog waveforms digitally.

PAM is often used in simple digital control systems for digital processing and transmission of analog control signals. The PAM signal can be expressed as:

$$s(t) = \sum_{n} a_n G(t - nT_s) \tag{1}$$

where a_n is the amplitude of the n-th symbol selected from M levels (e.g., 2, 4, or 8). $G(t)$ is the pulse shaping function and T_s is the symbol period. Amplitude levels for PAM follow:

$$a_k = -(M-1)A + 2kA, \quad k = 0,1,2 \dots, M-1 \tag{2}$$

An example of amplitude and bit mapping is shown in Table 1.

Table 1. An example of amplitude and bit mapping

Type	Amplitude levels	Bit mapping
2-PAM	±A	0→-A, 1→+A
4-PAM	±A, ±3A	00→-3A, 11→+3A
8-PAM	±A, ±3A, ±5A, ±7A	000→-7A, 111→+7A

The primary difference among 2-PAM, 4-PAM, and 8-PAM lies in transmission efficiency. While 2-PAM carries 1 bit per symbol, 4-PAM carries 2 bits, and 8-PAM carries 3 bits per symbol, calculated as:

$$k = \log_2 M \tag{3}$$

where k is bits per symbol and M is the modulation order (2, 4, or 8). The signal-to-noise ratio (SNR) is defined as:

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{4}$$

2.2 AWGN Channel Model

In communication engineering, a fundamental communication model consists of three elements: transmitter, channel, and receiver, with noise acting as an interference. This basic model forms the conceptual foundation for analyzing and designing both simple and complex communication systems. The source generates information, such as voice, images, or digital signals, initiating the communication process by converting data into transmittable signals. This step involves signal encoding, modulation, and pulse shaping to prepare the data for transmission over physical media.

The channel is the medium through which signals propagate, which can be wired or wireless. Common examples include copper cables, fiber-optic lines, and radio-frequency wireless links. Each type of channel has unique properties and constraints, such as attenuation, dispersion, or susceptibility to interference. During transmission, noise infiltrates the channel, commonly modelled as AWGN. AWGN is characterized as additive noise with Gaussian distribution and a flat power spectral density (white noise), degrading signal quality and causing errors. This model effectively captures the random thermal noise present in most physical communication systems and is widely used in both theoretical and practical performance evaluation. Its simplicity and analytical tractability make it a standard benchmark for evaluating modulation schemes and coding strategies. Fig. 1 shows a diagram of a AWGN channel model.

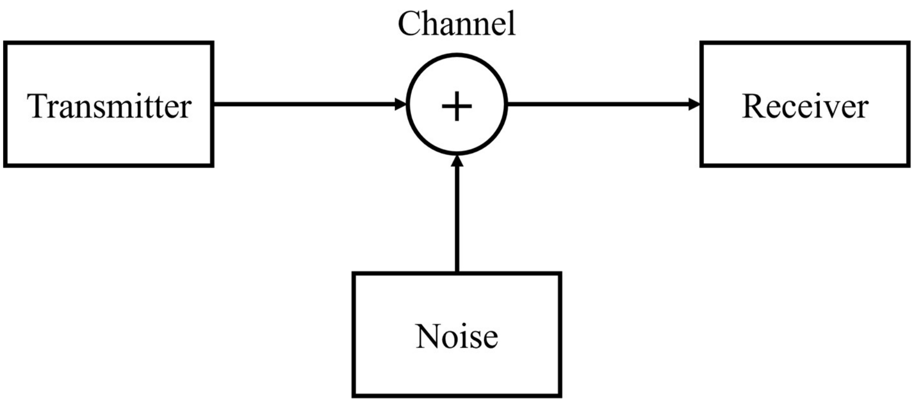

Figure 1. AWGN channel diagram

The receiver recovers the transmitted information, converting electrical signals back into usable forms, such as sound or images. This process often involves demodulation, decoding, and filtering to reverse the effects introduced during transmission and to extract the original data with high fidelity. Understanding these interactions is essential for optimizing communication system design, channel utilization, and noise mitigation to ensure accurate data transmission.

3. Simulation Results

This work simulates a PAM communication system using MATLAB. The number of transmitted symbols per modulation order was set to 10^7 to ensure statistically significant results. For example, when the 4-PAM modulation was used, the total number of transmitted bits is 2 x 10^7, since each symbol carries 2 bits of information. A random binary bit stream was generated by the MATLAB, mimicking real-world digital input data. This bit stream was then grouped and mapped to PAM symbols based on the modulation order, using discrete amplitude levels as defined in Table 1.

AWGN was added to the transmitted signals at the receiver side to emulate channel noise, allowing the simulation to realistically approximate practical communication scenarios. The noise power was dynamically adjusted based on the SNR value. Demodulation employed minimum-distance decoding by comparing each received sample to all PAM levels and selecting the nearest. This decision rule assumes that the most likely transmitted symbol is the one with the smallest Euclidean distance from the received noisy sample. Detected symbols were then converted back to binary bits and the bit error rate (BER) was computed by comparing transmitted and detected bits.

Simulations spanned SNR values from 0 dB to 20 dB in 2 dB increments, covering both low- and high-noise environments. The BER versus SNR curve under different PAM modulation orders using MATLAB is shown in Fig. 2. Results reveal an exponentially decreasing BER trend as SNR increases. In the low SNR range (0–6 dB), BER remains high due to strong noise influence. As SNR improves, noise power becomes less dominant, leading to more accurate symbol detection. For 2-PAM, once SNR surpasses 12 dB, BER sharply decreases below 10^{-4}, demonstrating the system's reliability under moderate and high SNR conditions. This indicates that even simple modulation schemes like 2-PAM can achieve high performance in relatively clean channels. Conversely, higher-order PAM schemes still experience noticeable error rates at the same SNR due to their denser amplitude spacing. This highlights the tradeoff between data rate and noise robustness in digital modulation design.

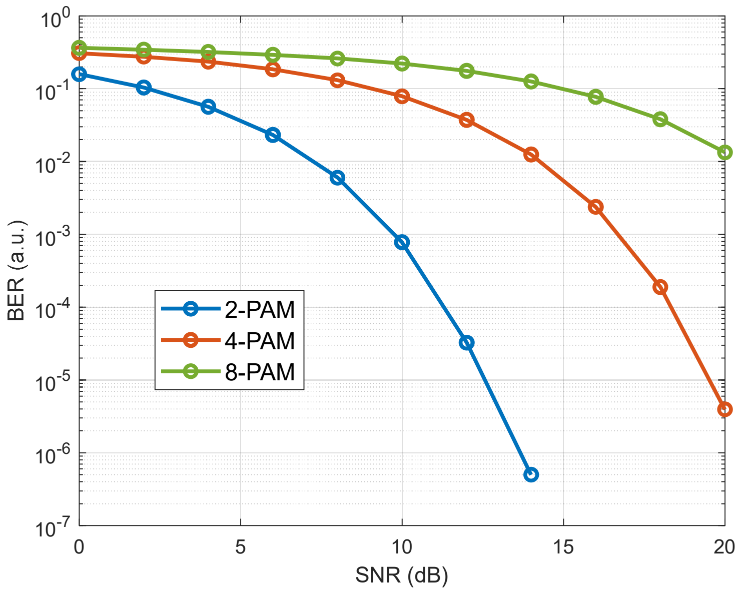

Figure 2. BER versus SNR under different PAM modulation orders

4. Conclusion

This paper analyzed a PAM communication system operating under AWGN channel conditions using MATLAB-based simulations. After introducing the fundamental principles of PAM modulation and AWGN noise modeling, we evaluated system performance through BER analysis across varying SNR levels. The simulation was carefully designed to emulate realistic transmission scenarios, with dynamic noise generation and robust bit-to-symbol mapping procedures. The results confirmed that PAM exhibits strong sensitivity to noise at low SNRs, where BER remains high due to overlapping amplitude levels and signal distortion. However, the performance improves significantly as SNR increases. These findings not only validate the accuracy of the simulation model but also highlight its applicability for guiding the design and optimization of more advanced digital communication systems. The insights gained from the BER vs. SNR trends can inform modulation order selection, system power allocation, and error control strategies in practical implementations. In this way, the study lays a solid foundation for future research into more robust and efficient communication systems.

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