A Study on PAM Signal Generation and Signal Recovery Methods

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***Abstract*—This paper presents the study, simulation, and practical implementation of Pulse Amplitude Modulation (PAM) signal generation and demodulation. PAM is a fundamental analog modulation technique in which the amplitude of regularly spaced pulses is varied in proportion to the instantaneous values of a message signal. The experiment was carried out in two parts: MATLAB simulation and hardware implementation on a breadboard. In the simulation, a sinusoidal message signal was modulated using a pulse train to produce a PAM signal. The demodulation was performed through pulse sampling followed by low-pass filtering to recover the original signal. Frequency and power spectral analysis were also performed to evaluate the signal characteristics. For the hardware part, a function generator was used to generate the message and carrier signals, and the resulting waveforms were observed using a Digital Storage Oscilloscope (DSO). The results demonstrate the accuracy and effectiveness of the PAM technique in both simulated and real-time environments, and highlight its relevance in modern digital communication systems.**

***Index Terms*—Pulse Amplitude Modulation (PAM), Demodulation, Low-pass filter, MATLAB Simulation, Function Generator, DSO, Time-domain Analysis, Frequency Spectrum, Power Spectral Density (PSD), Butterworth Filter, Interpolation**

I. Introduction

Pulse Amplitude Modulation (PAM) is one of the simplest and most fundamental techniques in the field of analog and digital communications. It involves transmitting information by varying the amplitudes of a series of regularly spaced pulses in accordance with the amplitude of a message signal. Due to its simplicity, PAM serves as a foundational concept for understanding more complex modulation schemes used in modern communication systems.

This paper aims to explore both the theoretical and practical aspects of PAM, including its generation and demodulation techniques. The study was conducted in two phases: a MATLAB-based simulation and a hardware implementation on a breadboard. In the simulation, a sinusoidal message signal was modulated using a pulse train to create a PAM waveform. The demodulation process involved sampling the modulated signal and applying a low-pass filter to reconstruct the original message.

In the hardware setup, standard lab instruments such as a function generator and a Digital Storage Oscilloscope (DSO) were used to create and visualize the PAM signal. The consistency between the simulation results and practical observations highlights the effectiveness of PAM in both theoretical and applied contexts. This experiment not only reinforces the fundamental concepts of modulation and signal recovery but also provides a hands-on experience in signal processing and analysis.

The remainder of this paper is organized as follows: Section II outlines the general assumptions and notation used throughout the study. Section III explains the theoretical background and working principles of Pulse Amplitude Modulation. Section IV discusses the generation of the PAM signal, both in simulation and hardware. Section V focuses on the demodulation process and signal recovery methods. Section VI presents the numerical results, including time-domain and frequency-domain analyses. Finally, Section VII provides the conclusion, summarizing key findings and observations from the study.

II. General Assumptions and Notation

In this study, the following assumptions and notations are adopted to maintain clarity and consistency:

- The message signal $m(t)$ is assumed to be a continuous-time sinusoidal waveform with frequency f_m.
- The pulse train $p(t)$ used for modulation consists of periodic rectangular pulses with fixed width and period.
- Sampling frequency F_s is sufficiently high to satisfy the Nyquist criterion for the message signal.
- The PAM signal $s(t)$ is generated by multiplying the message signal $m(t)$ with the pulse train $p(t)$, resulting in amplitude-modulated pulses.
- Demodulation is performed by sampling the PAM signal at the center of each pulse followed by low-pass filtering to reconstruct the message.
- Standard notation is used: t for time, f for frequency, and A for amplitude.
- The Butterworth filter employed for demodulation is designed with an order and cutoff frequency appropriate to preserve the original message frequency components.

These assumptions simplify the analysis and implementation while providing a realistic representation of PAM signal behavior in practical systems.

III. Theory and Working Principle

Pulse Amplitude Modulation (PAM) is a modulation technique where the amplitude of a series of pulses is varied in proportion to the instantaneous amplitude of the message signal $m(t)$. The PAM signal $s(t)$ can be mathematically expressed as:

$$s(t) = m(t) \cdot p(t) \tag{1}$$

where $p(t)$ is a periodic pulse train defined as:

$$p(t) = \sum_{n=-\infty}^{\infty} \Pi\left(\frac{t - nT}{\tau}\right) \tag{2}$$

Here, $\Pi\left(\frac{t}{\tau}\right)$ represents a rectangular pulse of width τ, T is the pulse repetition period, and $\tau < T$. In this study, the message signal $m(t)$ is a sinusoidal waveform given by:

$$m(t) = A_m \sin(2\pi f_m t) \tag{3}$$

where A_m is the amplitude and f_m is the frequency of the message signal.

A. Generation of PAM Signal

The generation of the PAM signal involves multiplying the continuous message signal $m(t)$ by the pulse train $p(t)$. This results in a signal where the message information is sampled and transmitted as a sequence of pulses whose amplitudes correspond to the instantaneous values of $m(t)$ at pulse instants.

B. Demodulation of PAM Signal

Demodulation aims to recover the original message signal from the PAM waveform. The process involves:

1) **Sampling:** The PAM signal $s(t)$ is sampled at the centers of the pulses, i.e., at times $t = nT + \frac{\tau}{2}$, producing discrete samples:

$$s(n) = m\left(nT + \frac{\tau}{2}\right) \tag{4}$$

2) **Interpolation:** The discrete samples are interpolated to reconstruct a continuous-time signal. Linear interpolation is commonly used to estimate the signal values between samples.
3) **Low-pass Filtering:** Since the PAM signal contains high-frequency components introduced by the pulse train, a low-pass filter is applied to remove these unwanted frequencies and smooth the reconstructed signal. A Butterworth filter of order 5 is used with cutoff frequency f_c chosen to satisfy:

$$f_c \geq f_m \tag{5}$$

C. Frequency Spectrum and Power Spectral Density

The spectrum of a PAM signal contains the baseband spectrum of the message signal replicated at multiples of the pulse repetition frequency $f_p = \frac{1}{T}$. The Fourier transform of the PAM signal can be expressed as:

$$S(f) = \frac{\tau}{T} \sum_{k=-\infty}^{\infty} M\left(f - \frac{k}{T}\right) \cdot \text{sinc}(\pi \tau f) \tag{6}$$

where $M(f)$ is the Fourier transform of the message signal $m(t)$, and $\text{sinc}(x) = \frac{\sin x}{x}$.

The power spectral density (PSD) provides insight into the distribution of signal power over frequency and is useful in analyzing noise effects and bandwidth requirements.

D. Summary of Parameters Used

- Sampling frequency: $F_s = 1000$ Hz
- Message frequency: $f_m = 5$ Hz
- Pulse width: $\tau = 0.01$ s (10 ms)
- Pulse period: $T = 0.05$ s (50 ms)

These parameters ensure that the Nyquist sampling criterion is met and the PAM signal can be accurately generated and demodulated.

IV. Generation of PAM

The generation of the Pulse Amplitude Modulated (PAM) signal begins with the creation of a continuous-time message signal $m(t)$. In this work, $m(t)$ is a sinusoidal signal defined as:

$$m(t) = \sin(2\pi f_m t) \tag{7}$$

where the message frequency f_m is set to 5 Hz. The message signal is sampled and modulated using a periodic pulse train $p(t)$, composed of rectangular pulses with pulse width $\tau = 0.01\,s$ and pulse period $T = 0.05\,s$.

The pulse train $p(t)$ is generated by creating rectangular pulses of unit amplitude separated by the pulse period T. Mathematically, it can be represented as:

$$p(t) = \sum_{n=0}^{N} \Pi\left(\frac{t - nT}{\tau}\right) \tag{8}$$

where $\Pi(\cdot)$ is the rectangular function.

The PAM signal $s(t)$ is obtained by multiplying the message signal with the pulse train:

$$s(t) = m(t) \times p(t) \tag{9}$$

This operation effectively samples the amplitude of the message signal at periodic intervals defined by the pulse train.

In the MATLAB implementation, a sampling frequency $F_s = 1000\,\text{Hz}$ is used to discretize time over a duration of 1 second. The pulse train is constructed by setting pulse samples to one for the duration of the pulse width and zero elsewhere. Multiplying the discrete-time message signal with this pulse train results in the PAM signal.

This method produces a sequence of pulses where each pulse amplitude corresponds to the instantaneous value of the message signal, which is the fundamental principle of PAM.

V. Demodulation of PAM

The demodulation process aims to recover the original message signal $m(t)$ from the received PAM signal $s(t)$. The key steps involved are sampling, interpolation, and low-pass filtering.

A. Sampling

The PAM signal is sampled at the center of each pulse to extract the amplitude information. If the pulse width is τ and the pulse period is T, the sampling instants t_n are given by:

$$t_n = nT + \frac{\tau}{2}, \quad n = 0, 1, 2, \ldots \tag{10}$$

At these points, the amplitude of the PAM signal equals the instantaneous value of the original message signal:

$$s(t_n) = m(t_n) \tag{11}$$

B. Interpolation

Since the sampled values are discrete, interpolation is performed to reconstruct the continuous-time message signal. Linear interpolation is commonly used and mathematically represented as:

$$\hat{m}(t) = \text{interp1}(t_n, s(t_n), t) \tag{12}$$

where $\hat{m}(t)$ is the interpolated estimate of the original signal over the entire time vector t.

C. Low-Pass Filtering

The reconstructed signal contains high-frequency components due to the pulse nature of PAM. To smooth the signal and reduce noise, a low-pass Butterworth filter of order 5 is applied with a cutoff frequency f_c satisfying:

$$f_c \geq f_m \tag{13}$$

In the MATLAB implementation, the normalized cutoff frequency is calculated as:

$$W_c = \frac{2f_c}{F_s} \tag{14}$$

The filtered signal is then scaled to match the amplitude of the original message signal by calculating a scale factor:

$$\text{scale\_factor} = \frac{\max |m(t)|}{\max |\hat{m}_{filtered}(t)|} \tag{15}$$

The final demodulated signal $m_{demod}(t)$ is:

$$m_{demod}(t) = \text{scale\_factor} \times \hat{m}_{filtered}(t) \tag{16}$$

This process successfully recovers the original message signal from the PAM waveform, as confirmed by visual comparison between $m(t)$ and $m_{demod}(t)$.

VI. Numerical Results

This section presents the simulation results of the PAM signal generation and demodulation using MATLAB. The parameters used are: sampling frequency $F_s = 1000$ Hz, message frequency $f_m = 5$ Hz, pulse width $\tau = 0.01$ s, and pulse period $T = 0.05$ s.

A. Message Signal

The original message signal $m(t) = \sin(2\pi f_m t)$ is shown in Fig. 1. It is a continuous sinusoidal waveform with frequency 5 Hz.

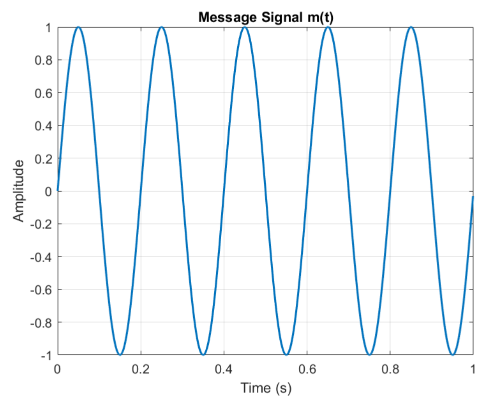

Fig. 1. Message signal $m(t)$ — sinusoidal waveform.

B. Pulse Train

The pulse train $p(t)$ is a sequence of rectangular pulses with pulse width 10 ms and period 50 ms, shown in Fig. 2. This pulse train modulates the message signal to produce the PAM waveform.

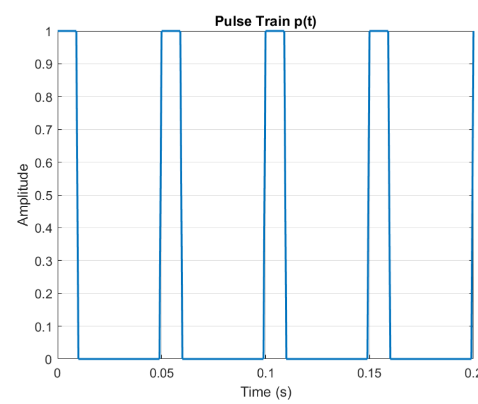

Fig. 2. Pulse train $p(t)$ — periodic rectangular pulses.

C. PAM Signal

The PAM signal $s(t) = m(t) \times p(t)$ is shown in Fig. 3. It contains pulses whose amplitudes vary according to the instantaneous amplitude of the message signal.

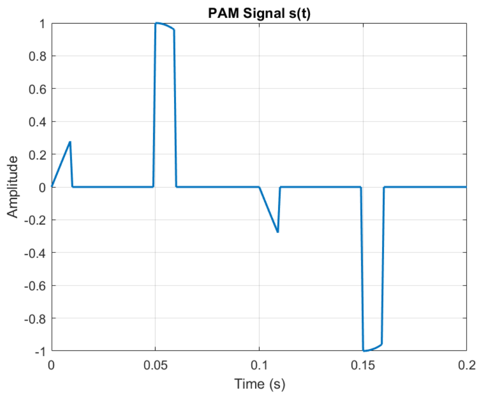

Fig. 3. Pulse Amplitude Modulated (PAM) signal $s(t)$.

D. Demodulated Signal

The demodulated signal after sampling, interpolation, and low-pass filtering is shown in Fig. 4. The recovered signal closely matches the original message, demonstrating successful demodulation.

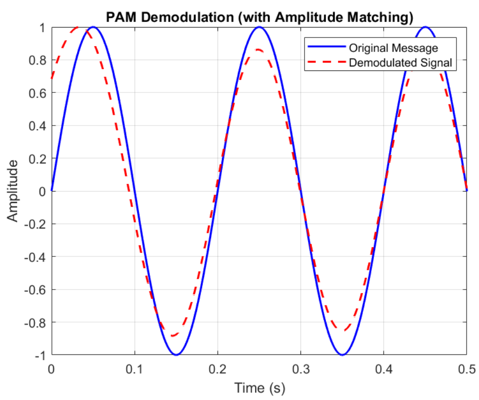

Fig. 4. Demodulated signal compared with original message signal.

E. Frequency Spectrum and Power Spectral Density

Additional analysis includes the frequency spectrum and power spectral density (PSD) of the PAM signal, which reveal the spectral components introduced by the pulse modulation process. These results help verify the bandwidth requirements and signal characteristics.

The results demonstrate successful generation and demodulation of the PAM signal. The demodulated signal closely matches the original message, confirming the accuracy of the method. The pulse train effectively samples the message signal, and the low-pass filtering smooths the recovered waveform. Frequency analysis highlights the spectral components introduced by the modulation process, which are important for system design.

VII. Conclusion

In this paper, we explored the theoretical basis, numerical simulation, and hardware implementation of Pulse Amplitude Modulation (PAM), a fundamental technique in analog and digital communication systems. The MATLAB simulation demonstrated the step-by-step generation of a PAM signal by modulating a sinusoidal message with a periodic pulse train. The demodulation process, which involved sampling the PAM signal at pulse centers and applying a low-pass filter, successfully reconstructed the original message signal with minimal distortion.

Additionally, frequency domain analysis through FFT and power spectral density (PSD) plots highlighted how the spectral components of the message are affected by modulation, providing useful insight into bandwidth considerations and noise susceptibility.

The practical implementation using a function generator and digital storage oscilloscope (DSO) further reinforced the feasibility of the technique. Observations confirmed that real-world signals closely matched simulation results, validating both the theory and the method.

Overall, PAM proves to be a simple yet effective modulation technique, suitable for low to moderate bandwidth applications. This study enhances our understanding of signal processing principles and lays a solid foundation for exploring more advanced modulation schemes in future work.

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