Waveforming en modulación digital

Leonel Ricardo Araque 2204224
Leandro José Garzón 2194232

Universidad Industrial de Santander

Github: https://github.com/leo09p/COMMII_A1_G8/tree/Practica_6

Abstract

This laboratory explores the practical implementation of digital pulse shaping using Raised Cosine (RC) and Root Raised Cosine (RRC) filters within GNU Radio. The purpose is to understand how these filters influence the behavior of digitally modulated signals, particularly in terms of bandwidth occupation, symbol integrity, and mitigation of intersymbol interference (ISI). Through several controlled experiments, different pulse-shaping configurations and modulation schemes were analyzed, both in ideal scenarios and in the presence of channel noise. The obtained results confirm that appropriate waveform shaping significantly enhances spectral efficiency and reduces ISI, contributing to more reliable digital communication systems.

Keywords: Pulse shaping, Raised Cosine filter, ISI, spectral efficiency, GNU Radio, digital modulation

I. INTRODUCTION

In digital communication systems, the waveform used to transmit symbols plays a critical role in determining signal quality and bandwidth efficiency. If the transmitted pulses overlap excessively in time, the receiver experiences *intersymbol interference* (ISI), which degrades performance and increases error probability.

Pulse-shaping filters, such as the Raised Cosine (RC) and its derivative Root Raised Cosine (RRC), are widely used to control the time–frequency characteristics of the signal. These filters meet the Nyquist criterion for zero ISI under ideal conditions and allow the designer to tune the trade-off between spectral compactness and signal smoothness through the roll-off parameter β.

Using GNU Radio as a simulation environment, this laboratory investigates how different pulse-shaping choices affect the transmitted signal's temporal waveform, frequency spectrum, eye diagram, and constellation.

II. GOALS

To analyze pulse-shaping techniques using Raised Cosine and Root Raised Cosine filters in a digital communication system..

- Implement RC and RRC pulse-shaping filters in GNU Radio.
- Evaluate how the roll-off parameter β influences bandwidth and ISI.
- Compare the performance under different modulation formats.
- Assess the behavior of the system in noisy channel conditions, including 16-QAM.

III. METHODOLOGY

1. A dedicated directory and GitHub repository were created to manage the laboratory files.
2. The block diagram provided in the laboratory guide was replicated in GNU Radio, including the constellation modulator and interpolation filtering blocks.
3. Experiments were first performed using a rectangular (non-shaped) pulse, and then repeated with RC and RRC filters.
4. For each configuration, the following visualizations were recorded:
   - Time-domain waveform
   - Power spectral density (PSD)
   - Eye diagram
   - Signal constellation
5. Noise was later introduced through an AWGN channel, and the modulation was changed to 16-QAM to analyze performance under more demanding conditions.
6. The theoretical bandwidth for each pulse-shaping case was compared against the measured spectrum in GNU Radio.

IV. THEORETICAL FRAMEWORK

In digital communication systems, pulse shaping is used to control how each transmitted symbol occupies time and frequency. Without proper shaping, the transmitted pulses spread and overlap, producing intersymbol interference (ISI). This effect makes it difficult for the receiver to correctly determine the transmitted data.

The **Raised Cosine** (RC) filter is one of the most common solutions to reduce ISI while keeping the occupied bandwidth under control. Its key parameter is the roll-off factor β, which determines how much additional bandwidth is allowed around the main lobe.

- When $\beta = 0$, the signal uses the minimum bandwidth but has very sharp transitions.
- When β increases, the pulse becomes smoother, making the system more tolerant to distortion at the cost of more bandwidth.

The **Root Raised Cosine** (RRC) filter is often used when the transmitter and receiver each apply half of the shaping. A single RRC filter does not remove ISI completely, but when

combined with another RRC at the receiver, both filters together behave like a full RC filter.
In this laboratory context, comparing rectangular pulses, RC filters, and RRC filters allows us to observe how each option affects the spectrum, the eye diagram, and the shape of the constellation. This makes it easier to understand why pulse shaping is essential, especially when using higher-order modulations such as 16-QAM, which are more sensitive to distortion and noise.

V. RESULTS

A. Case 1: Rectangular Pulse, No Filtering, No Noise

A basic rectangular pulse shape was used without any additional filtering. The 8-PSK modulated waveform displayed clean constellation points, and the eye diagram showed a wide opening under ideal conditions. Since no channel distortion or noise was present, symbol separation remained clear.

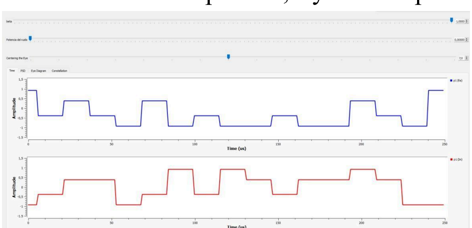

Fig. 1: Time-domain signal obtained for Case 1 using 8-PSK modulation.

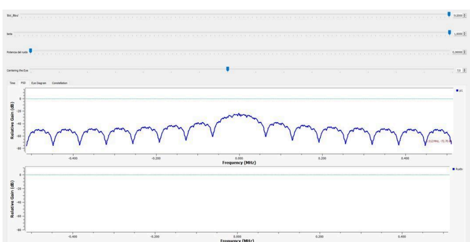

Fig. 2: Frequency-domain representation (PSD) for Case 1 with 8-PSK modulation.

Fig. 1 remains well-defined, and the spectrum in **Fig. 2** displays the expected wide bandwidth of a rectangular pulse.

The eye diagram in **Fig. 3** shows a fully open shape, confirming the absence of intersymbol interference. Likewise, the constellation in **Fig. 4** presents tightly grouped symbol clusters

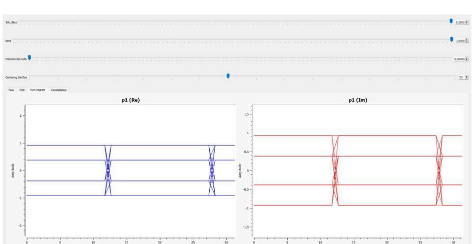

Fig. 3: Eye diagram corresponding to Case 1 for 8-PSK.

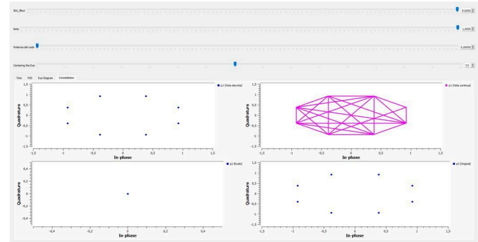

Fig. 4: Constellation diagram obtained in Case 1 for 8-PSK..

B. Case 2: Rectangular Pulse with Low-Pass Filter

When passing the rectangular pulse through a low-pass filter with bandwidth equal to the symbol rate, the waveform becomes noticeably distorted. As shown in **Fig. 5**, the temporal spreading of the signal introduces clear ISI.
This effect is confirmed in the eye diagram of **Fig. 6**, where the eye opening becomes partially closed. The impact is also visible in the constellation (**Fig. 7**), where the symbol points appear less concentrated than in Case 1.

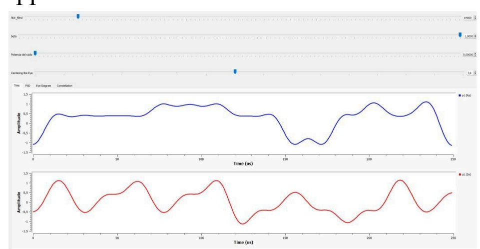

Fig. 5: Time-domain waveform in Case 2 showing ISI distortion.

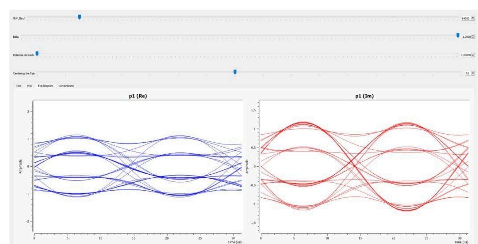

Fig. 6: Eye diagram for Case 2, highlighting intersymbol interference.

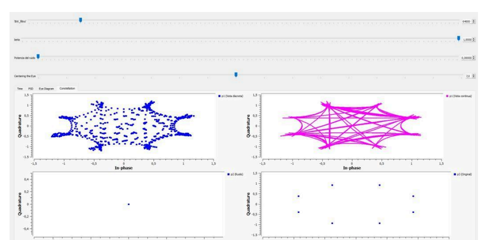

Fig. 7: Constellation diagram for Case 2 under ISI conditions.

C. Case 3: Raised Cosine Filter, β = 1

Applying a Raised Cosine filter with roll-off β = 1 results in a smoother pulse shape and a wider occupied bandwidth. The

PSD in **Fig. 8** matches the expected theoretical bandwidth expansion due to the high roll-off factor.

The eye diagram in **Fig. 9** opens cleanly, confirming that the RC filter completely removes ISI under ideal conditions..

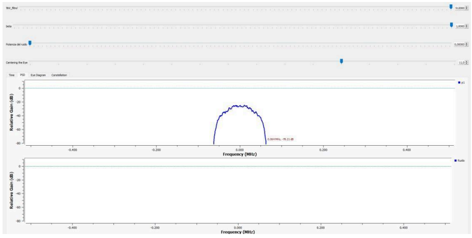

Fig. 8: Power spectral density for Case 3 using a Raised Cosine filter (β = 1).

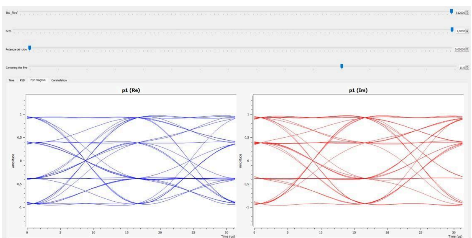

Fig. 9: Eye diagram for Case 3 with β = 1 pulse shaping.

.

D. Case 4: Raised Cosine Filter, β = 0

With a roll-off of β = 0, the RC filter provides the minimum possible bandwidth while still satisfying the Nyquist condition. The time-domain signal in **Fig. 10** remains smooth, and the spectrum in **Fig. 11** shows the narrowest bandwidth among all RC configurations.

The eye diagram in **Fig. 12** remains widely open, indicating that despite its minimal bandwidth, the filter avoids ISI.

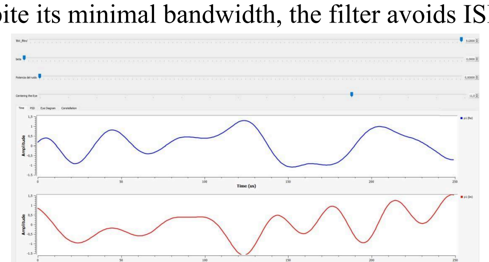

Fig. 10: Time-domain waveform for Case 4 with Raised Cosine filtering (β = 0)..

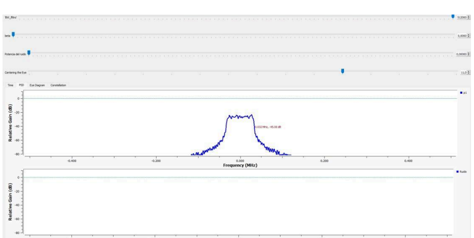

Fig. 11: PSD obtained in Case 4 using β = 0.

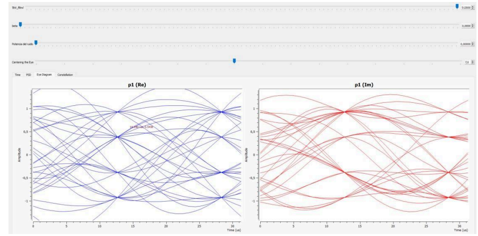

Fig. 12: Eye diagram corresponding to Case 4 (β = 0).

E. Case 5: Raised Cosine Filter, β = 0.5

This configuration represents a midpoint between Cases 3 and 4. The waveform in **Fig. 13** shows smooth symbol transitions, and the spectrum in **Fig. 14** reflects moderate bandwidth usage.

As seen in **Fig. 15**, the eye diagram remains open and stable, confirming proper pulse shaping and absence of ISI.

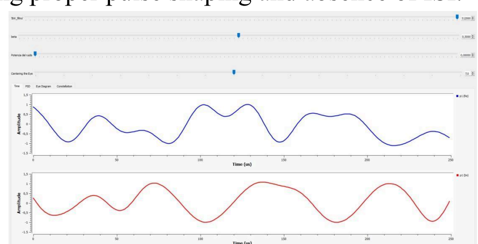

Fig. 13: Time-domain signal for Case 5 with Raised Cosine filtering (β = 0.5).

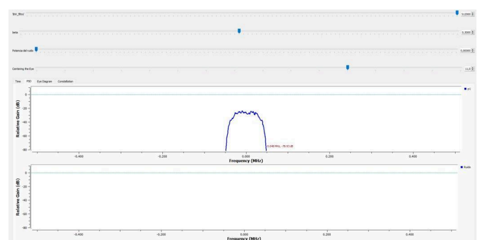

Fig. 14: PSD associated with Case 5 (β = 0.5).

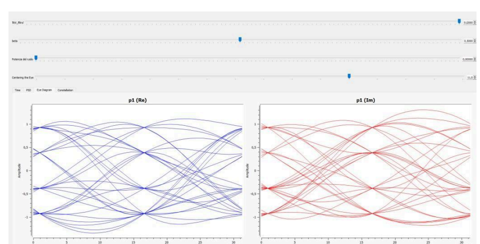

Fig. 15: Eye diagram for Case 5 using β = 0.5.

F. Case 6: Root Raised Cosine Filter, β = 0.5

In this scenario, only a transmitter-side RRC filter is used. Because an RRC filter alone does not fully satisfy the Nyquist criterion, a small amount of ISI remains. This is visible in the eye diagram of **Fig. 16**, which does not open as widely as in the full RC cases.

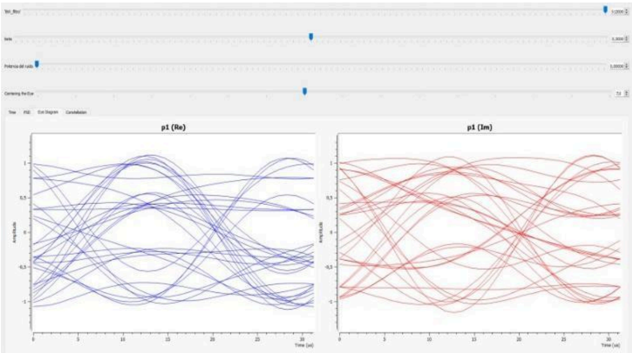

Fig. 16: Eye diagram for Case 6 using a Root Raised Cosine filter (β = 0.5).

G. 16-QAM with AWGN Noise

In this final experiment, the modulation scheme is changed to **16-QAM**, and additive white Gaussian noise (AWGN) is introduced into the channel. Since 16-QAM conveys information using both amplitude and phase levels, it becomes more sensitive to distortion than the previous PSK cases.

When noise is added, the constellation points tend to spread around their ideal positions, making symbol detection more difficult. The eye pattern also shows a partial closure, indicating that the noise interferes with the distinction between adjacent symbols. Although the spectral shape remains similar, the noise increases the overall energy floor.

This case highlights that higher-order modulation schemes require cleaner pulse shaping and higher SNR to maintain acceptable performance. Proper filtering becomes more important to avoid excessive symbol overlap, especially in channels affected by noise.

H. General Comparison of All Pulse-Shaping Cases

This section summarizes the main differences observed across all pulse-shaping configurations analyzed in the laboratory. By comparing the eye diagrams, spectra, and overall signal behavior in each case, it becomes clear how the choice of filter affects bandwidth usage and intersymbol interference.

- **Rectangular Pulse (Cases 1 and 2):** The rectangular pulse occupies the widest bandwidth and shows no time-domain smoothing. When no filtering is applied (Case 1), the signal appears clean only because there is no distortion or noise. Once a basic low-pass filter is added (Case 2), significant ISI appears, demonstrating that rectangular pulses are not suitable for practical systems where bandwidth is limited.
- **Raised Cosine, β = 1 (Case 3):** This filter provides the smoothest pulse transitions. It eliminates ISI in ideal conditions, but it also requires the largest bandwidth among all RC configurations. The eye diagram remains widely open, indicating excellent symbol separation.
- **Raised Cosine, β = 0 (Case 4):** This configuration uses the smallest possible bandwidth allowed by the Nyquist criterion. Despite the narrow spectrum, the eye diagram stays clean and fully open, confirming that β = 0 still prevents ISI. However, the abrupt spectral transition may make the system more sensitive to imperfect channel conditions.
- **Raised Cosine, β = 0.5 (Case 5):** This case represents a compromise between the smoothness of β = 1 and the bandwidth efficiency of β = 0. The signal maintains good temporal behavior, and the spectrum remains controlled, providing a balanced option between performance and bandwidth usage.
- **Root Raised Cosine (Case 6):** Using only a transmitter-side RRC filter reduces pulse overlap but does not completely eliminate ISI, as expected. The eye diagram shows a partial closure compared to the RC cases. In practical systems, a matched RRC filter at the receiver completes the shaping and recovers the full Raised Cosine response.

Overall, the comparison shows that full Raised Cosine filtering provides the best ISI suppression, while Root Raised Cosine is effective only when used at both transmitter and receiver. Rectangular pulses are the least efficien

VI. CONCLUSIONS

The results demonstrate that pulse shaping plays a fundamental role in controlling intersymbol interference and bandwidth usage. Raised Cosine filters consistently provided clean eye diagrams and stable constellations, confirming their effectiveness in meeting the Nyquist criterion.

The comparison of different roll-off factors showed that β influences both spectral compactness and temporal behavior. While β = 0 minimizes bandwidth, intermediate values such as β = 0.5 offer a practical compromise between performance and efficiency.

The experiments with 16-QAM under noise highlight the increased sensitivity of higher-order modulation schemes. Proper pulse shaping becomes essential to preserve symbol clarity, especially when the channel introduces distortion or reduces the signal-to-noise ratio.

.

REFERENCES

[1] **H. Ortega and O. Reyes**, *Comunicaciones Digitales basadas en Radio Definida por Software*.

[2] **OpenAI**, “ChatGPT: Language Model for Conversational AI.” Available: https://openai.com/chatgpt