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Exploring Raised Cosine Filtering for Signal Integrity and ISI Mitigation in Digital Communication Systems

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ABSTRACT

In high-speed networks such as 4G/5G, bandwidth constraints remain a major challenge for digital communication systems, where Inter-Symbol Interference (ISI) significantly degrades signal quality. This study investigates the application of raised cosine filtering to mitigate ISI and enhance signal integrity across several modulation schemes, including BPSK, QPSK, and M-PSK. MATLAB simulations were conducted using roll-off factor values ranging from 0.1 to 0.9, and system performance was evaluated in terms of Bit Error Rate (BER), Peak-to-Average Power Ratio (PAPR), and signal quality represented by eye diagrams. The results indicate that higher roll-off factors provide better ISI mitigation and improved signal clarity, although at the expense of increased bandwidth consumption. The findings highlight the trade-off between bandwidth efficiency and ISI reduction, which is essential for designing optimized filters in modern high-speed communication systems. These results can support the development of more efficient filtering techniques for practical communication networks such as 4G/5G and Wi-Fi, thereby providing valuable insights for communication system designers.

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1. INTRODUCTION

The transmission of information over bandwidth-constrained and noisy channels remains one of the primary challenges in modern communication networks. Inter-Symbol Interference (ISI) is a major source of signal degradation that can increase the Bit Error Rate (BER) in digital communication systems. ISI occurs when adjacent symbols overlap due to bandwidth limitations, particularly in high-speed systems where the available channel bandwidth is insufficient to support the required data rate. This issue is especially critical in 4G/5G and Wi-Fi networks, where high data throughput plays a vital role in system performance (Chy, et al., 2015).

One of the most widely adopted solutions for mitigating ISI is the use of raised cosine filters (RCFs), which shape transmitted pulses to reduce spectral spreading and minimize ISI. These filters enable a balance between bandwidth efficiency and ISI suppression, where the roll-off factor (β) serves as a key parameter in determining this trade-off (Ahmed, 2016). Raised cosine filters have been extensively applied in communication systems, particularly in WiMAX and OFDM technologies, where they play a crucial role in maintaining system performance by minimizing ISI and preserving signal integrity (Rana & Mehra, 2015).

Furthermore, in next-generation networks such as 5G and beyond, interference challenges become increasingly complex due to the utilization of high-frequency bands like millimeter-wave (mmWave) and Massive MIMO architectures. In these scenarios, spectral efficiency is crucial, and signals must be strictly confined within their allocated frequency bands to prevent adjacent channel interference (ACI). Therefore, optimizing pulse shaping is not merely a tool for ISI mitigation, but rather a fundamental component for maximizing network capacity and maintaining robust link budgets in highly congested spectrums.

Fundamentally, raised cosine filters operate by distributing the pulse energy in a way that enforces zero-crossings at the exact sampling instants of all adjacent symbols. This precise pulse-shaping mechanism is heavily relied upon because, without optimal filtering, time-domain signal overlap introduces severe distortion. Such distortion exponentially degrades the Signal-to-Noise Ratio (SNR) at the receiver end, drastically increasing the probability of erroneous bit detection and triggering cascading demodulation failures across high-throughput links.

The motivation of this study is to investigate how different roll-off factors (β) affect the performance of digital communication systems, particularly in emerging high-speed networks such as 5G. Previous studies have typically focused on a limited set of roll-off values, often assuming fixed parameters (e.g., β = 0.35) (Cubukcu, 2012; Rana *et al.*, 2010). In contrast, this study explores a broader range of roll-off factors (0.1–0.9) and examines their impact on multiple digital modulation schemes, including BPSK, QPSK, and M-PSK. By analyzing key performance metrics such as Bit Error Rate (BER), Peak-to-Average Power Ratio (PAPR), and signal quality through eye diagrams, this study aims to provide a comprehensive understanding of the influence of roll-off factors on high-speed communication systems (Saad *et al.*, 2020; Alagha, & Kabal, 2002).

This study further aims to investigate how variations in the roll-off factor affect ISI suppression and bandwidth efficiency, and how these findings can be applied to practical 4G/5G and Wi-Fi communication systems. The results are expected to assist in optimizing filter design in modern communication networks by providing insights into the trade-off between bandwidth utilization and signal quality. The remainder of this paper is organized as

follows. Section 2 presents a review of raised cosine filters and ISI mitigation techniques. Section 3 describes the simulation methodology, modulation schemes, and performance metrics. Section 4 discusses the simulation results and their implications. Finally, Section 5 presents the conclusions and directions for future research.

2. LITERATURE REVIEW

2.1. Nernst Model

Inter-Symbol Interference (ISI) is a major challenge in high-speed communication systems, particularly when the channel bandwidth is insufficient to support the required data rate. ISI occurs when symbols overlap, resulting in signal distortion and increased Bit Error Rates (BER) (Chy *et al.,* 2015). Raised cosine filters have been widely employed to mitigate ISI by shaping the transmitted signal and confining its spectrum, thereby enhancing signal integrity and reducing symbol overlap. The roll-off factor (β) of these filters plays a critical role in determining the trade-off between bandwidth efficiency and ISI suppression (Ahmed, 2016).

Various studies have investigated the implementation of raised cosine filters in different modulation schemes and communication systems:

(i). QPSK and OQPSK Modulation: The effects of roll-off factors on BER and signal quality in QPSK and OQPSK systems have been extensively investigated. It has been reported that higher roll-off factors improve signal integrity, although at the cost of increased bandwidth consumption (Chattopadhyay & Sanyal, 2009).

(ii). Systems with WCDMA: The influence of square-root raised cosine filters on group delay and ISI suppression in WCDMA systems has been examined, emphasizing the importance of optimizing roll-off factors to improve system performance under noisy conditions (Kour et al., 2015).

(iii). Chaotic Communication Systems: An ISI-free chaotic filter based on root-raised cosine division has been proposed and shown to effectively reduce ISI in chaotic wireless communication systems while improving signal quality without requiring additional bandwidth (Tian et al., 2023).

(iv). Underwater Optical Communications: Raised cosine filters have been applied in dual-polarization optical communication systems to mitigate ISI in underwater wireless optical communications. Improved BER performance and extended communication range have been demonstrated through experimental evaluations (Mohammed et al., 2025).

(v). OFDM Systems: The application of raised cosine filters in OFDM systems has been investigated with a focus on pulse shaping for ISI mitigation. Significant improvements in spectral efficiency and ISI reduction have been reported compared with alternative filtering techniques (Cubukcu, 2012).

(vi). WiMAX Systems: The impact of raised cosine filtering on WiMAX systems has been evaluated, and the results indicate that roll-off factors significantly affect spectral efficiency and ISI performance. Higher roll-off factors have been suggested to achieve optimal ISI mitigation in high-speed wireless networks (Banerjee et al., 2025).

(vii). LTE Root Raised Cosine Filters: The use of root-raised cosine filters in LTE SC-FDMA systems has been explored to reduce PAPR and mitigate ISI. It has been found that adjusting the roll-off factor enhances noise resilience and power efficiency (Saad et al., 2020).

(viii). Nyquist Filters: Various pulse-shaping filters, including raised cosine filters, have been analyzed in Nyquist systems. Although raised cosine filters effectively mitigate ISI, a

trade-off with bandwidth efficiency remains when higher roll-off factors are employed (Kang & Sharma, 2011).

(ix). MIMO Systems: The effects of raised cosine filters on MIMO systems have been investigated with respect to system capacity enhancement and ISI reduction in high-throughput communication environments. The findings indicate that careful optimization of filter parameters is essential for improving system performance (Ansari & Oommen, 2014).

(x). Adaptive Filtering: Adaptive filtering approaches have been proposed in which the roll-off factor of raised cosine filters is dynamically adjusted according to real-time channel conditions. Such approaches have been shown to provide superior ISI mitigation and power efficiency in mobile environments (Bedeer et al., 2017).

(xi). Optical Communication: The application of raised cosine filters in optical communication systems has been studied, demonstrating their effectiveness in reducing ISI while preserving the intended bandwidth. Enhanced signal clarity in optical channels has also been reported (Tepekule et al., 2015).

(xii).Advanced Underwater Image Restoration: Comparative studies of image enhancement techniques, including white balance, dehazing, and contrast enhancement, have demonstrated their effectiveness in improving image quality through detail enhancement and noise reduction. The underlying principles of signal distortion reduction may also be extended to communication systems, particularly for ISI mitigation and signal integrity enhancement under noisy conditions (Kobra et al., 2025).

(xiii). Noise Estimation in High-Texture Images: Hybrid frameworks based on Markov models, Maximum Likelihood Estimation (MLE), and Convolutional Neural Networks (CNNs) have been proposed for noise estimation in high-texture images. These approaches have been shown to effectively estimate and reduce noise while preserving fine details. Such noise reduction techniques may also be extended to digital communication systems to improve signal quality and reduce communication errors, including Bit Error Rate (BER) (Kobra et al., 2025).

Hybrid Denoising Models on High-Texture Images: Hybrid denoising approaches combining classical methods and CNNs have demonstrated effective noise reduction in high-texture images. These methods may inspire analogous hybrid filtering approaches in communication systems, where integrating conventional signal processing with machine learning techniques could further improve ISI mitigation and signal quality in high-speed environments such as 4G/5G (Kobra *et al.,* 2025).

2.2. Research gaps

Although raised cosine filters have been extensively studied, several research gaps remain:

(i). **Limited Range of Roll-Off Factors:** Numerous studies have focused on a limited range of roll-off factors, commonly around 0.35. Comprehensive investigations examining a broader range of roll-off factors (0.1–0.9), particularly across multiple modulation schemes, remain limited (Chattopadhyay & Sanyal, 2009).

(ii). **Holistic Performance Evaluation:** Most previous studies have primarily evaluated individual performance metrics such as BER or PAPR. Comprehensive assessments incorporating multiple indicators, including eye diagrams and frequency response analysis, are still required to provide a more integrated evaluation of system performance (Kour *et al.,* 2015).

(iii). **Practical System Design:** Bridging the gap between theoretical findings and practical design guidelines for modern communication systems, particularly 5G and Wi-Fi networks, remains an open challenge. Limited research has investigated the optimal configuration of raised cosine filters for real-world implementations (Cubukcu, 2012).

(iv). **Higher-Order Modulation Schemes:** Although adaptive modulation and coding techniques have been extensively studied in next-generation wireless networks, limited research has examined the effects of raised cosine filters on higher-order modulation schemes such as M-PSK and QAM. In particular, the influence of different roll-off factors on these advanced modulation schemes in modern communication systems, including 5G and Wi-Fi, remains underexplored (Alnajjar *et al.,* 2025).

To address these research gaps, this study contributes in the following ways:

(i). Investigating the effects of roll-off factors ranging from 0.1 to 0.9 on system performance.
(ii). Comparing multiple modulation schemes, including BPSK, QPSK, and M-PSK, under varying roll-off factors.
(iii). Employing holistic performance metrics such as BER, PAPR, and eye diagram analysis.
(iv). Providing practical design insights for optimizing filter parameters in 4G/5G and Wi-Fi communication systems.

3. METHODOLOGY

This section describes the research procedure used to evaluate the effects of raised cosine filters on Inter-Symbol Interference (ISI) reduction and system performance in terms of modulation techniques, key parameters, and simulation settings. The simulations were conducted using MATLAB R2023a, with the primary objective of investigating the impact of different roll-off factors on communication system performance.

The proposed communication system model is designed to systematically evaluate the impact of pulse shaping on signal integrity. The architecture consists of three primary modules: the transmitter, the transmission channel, and the receiver. At the transmitter, a pseudorandom binary sequence is generated and mapped into symbols using an M-ary Phase Shift Keying (M-PSK) modulation scheme. Prior to transmission, these discrete symbols are upsampled and passed through a pulse-shaping filter to constrain the bandwidth and mitigate Inter-Symbol Interference (ISI). The filtered signal is then subjected to channel impairments before being processed by a matched filter and demodulator at the receiver.

3.1. Simulation setup

To achieve optimal bandlimited transmission, the Raised Cosine (RC) filter is implemented as the primary pulse-shaping mechanism. The fundamental advantage of the RC filter lies in its ability to satisfy the Nyquist criterion for zero ISI while offering a flexible trade-off between absolute bandwidth and the rate of spectral roll-off. The impulse response of the raised cosine filter in the time domain is mathematically defined as Equation (1).

$$h(t) = \frac{\sin \pi/T}{\pi t/T} \cdot \cos(\pi\beta/T)/(1 - \left(\frac{2\beta t}{T}\right)^2) \quad \ldots\ldots\ldots \quad (1)$$

In Equation (1), β, T, and t represent the roll-off factor, symbol period, and time, respectively. The root-raised cosine filter was implemented using the MATLAB rcosdesign()

function. This function facilitates filter design with selected roll-off factors and symbol rates, which determine pulse shaping characteristics and their effects on ISI.

The filter impulse response was truncated to ±T/2 to align with the symbol period. The roll-off factor (β) was varied from 0.1 to 0.9 to enable the investigation of different trade-offs between bandwidth efficiency and system performance.

3.2. Modulation techniques

The performance of the raised cosine filter was evaluated using three modulation schemes:

(i). **BPSK (Binary Phase Shift Keying):** BPSK is the simplest form of phase modulation, in which data are represented by two phase states, θ = 0° and θ = 180°, corresponding to binary values 0 and 1, respectively. The mathematical representation of the BPSK-modulated signal is provided in Equation (2).

$$s(t) = A \cdot \cos\left(2\pi f c t + \pi m(t)\right) \ldots\ldots\ldots \quad (2)$$

In Equation (2), A denotes the signal amplitude, fc represents the carrier frequency, and m(t) corresponds to the message signal.

(ii). **QPSK (Quadrature Phase Shift Keying):** QPSK allows two bits to be transmitted per symbol using four phase shifts. The mathematical expression of the QPSK-modulated signal is presented in Equation (3).

$$s(t) = A \cdot \cos(2\pi f_c t + \pi m_1(t)) + A \cdot \sin(2\pi f_c t + \pi m_2(t)) \ldots\ldots\ldots (3)$$

In Equation (3), m1(t) and m2(t) represent two message signals.

(iii). **M-PSK (M-Phase Shift Keying):** To investigate higher-order modulation, 8-PSK with M = 8 was selected. The mathematical formulation of the M-PSK signal is given in Equation (4).

$$s(t) = A \cdot \cos(2\pi f\, t + 2\pi k) \ldots\ldots\ldots (4)$$

$$M$$

In Equation (4), k denotes the symbol index, while M = 8 represents the modulation order.

These modulation schemes were selected because of their relevance to modern communication systems, particularly 4G/5G networks, and to evaluate the effectiveness of raised cosine filtering in both low-order and high-order modulation scenarios.

3.3. Parameters

The roll-off factor (β) was varied from 0.1 to 0.9 during the simulations to investigate its effect on ISI reduction. The roll-off factor is an important parameter because it determines the additional bandwidth occupied by the filter and, consequently, the trade-off between ISI mitigation and bandwidth efficiency. The relationship between the filter frequency response and the roll-off factor is expressed in Equation (5).

$$H(f) = \frac{1}{T} \cdot \left(\frac{\sin \pi f T}{\pi f T} \cdot \frac{\cos(\pi \beta f T)}{(2\beta f T)^2}\right) \ldots\ldots\ldots \quad (5)$$

in Equation (5), H(f) denotes the frequency response of the raised cosine filter. All modulation schemes were evaluated under different Signal-to-Noise Ratio (SNR) conditions ranging from 5 dB to 30 dB to assess system performance under varying noise environments.

3.4. Metrics

The effectiveness of the communication system was evaluated using the following performance metrics:

(i). **Bit Error rate (BER):** BER represents the ratio of incorrectly received bits to the total number of transmitted bits and is commonly used to evaluate communication reliability. The BER calculation is presented in Equation (6).

$$BER = \frac{Number\ of\ erroneous\ bits}{Total\ number\ of\ transmitted\ bits} \ldots\ldots\ldots (6)$$

Beyond serving as a fundamental measure of reliability, the BER directly dictates the Quality of Service (QoS) of the communication network. In practical scenarios, achieving a specific target BER determines whether the system can operate smoothly without requiring heavy Forward Error Correction (FEC) overhead. A significantly lower BER implies that the pulse-shaping filter has successfully minimized symbol overlap, thereby reducing the computational burden on the receiver's error-decoding algorithms and maximizing the effective data throughput.

(ii). **Ratio (PAPR):** PAPR is defined as the ratio of the peak signal power to its average power. High PAPR values, particularly in high-order modulation schemes such as M-PSK, may reduce power efficiency. The PAPR calculation is given in Equation (7).

$$PAPR = \frac{\max\ |x(t)|^2}{\mathbb{E}[|x(t)|^2]} \ldots\ldots\ldots (7)$$

In Equation (7), x(t) denotes the transmitted signal.

Evaluating PAPR is critical for the hardware design of the transmitter, specifically concerning the Radio Frequency Power Amplifier (RF-PA). Signals exhibiting high PAPR force the PA to operate with a large power back-off to remain within its linear region and prevent out-of-band spectral regrowth. This operational constraint drastically degrades the power efficiency of the transmitter, posing a major challenge for battery-constrained equipment such as mobile handsets and IoT edge devices.

(iii). **Eye Diagrams:** Eye diagrams were employed to visually evaluate signal quality after transmission. The degree of eye opening indicates the level of ISI and overall signal integrity. Specifically, the vertical opening of the eye diagram serves as a visual representation of the system's noise margin—a wider vertical opening indicates robust immunity to additive channel noise. Concurrently, the horizontal opening reflects the system's sensitivity to timing jitter. A broad horizontal eye provides a wider sampling window, allowing for greater tolerance in sampling time at the receiver, which is highly advantageous in practical environments where achieving perfect synchronization is technically challenging.

3.5. Simulation environment

The simulations were conducted under the following conditions:

(i) **Channel Model**: An Additive White Gaussian Noise (AWGN) channel was used to simulate noise in the communication system. The AWGN channel is characterized by a flat spectral power density and is widely employed for evaluating communication system performance. Although the AWGN channel model provides a fundamental baseline for

evaluating the performance of raised cosine filters, it is important to note that this model primarily represents a transmission scenario dominated by thermal and background noise. The flat spectral power density of AWGN facilitates the isolation of the roll-off factor's effects on ISI without the confounding variables introduced by multipath fading. While real-world wireless applications will inevitably encounter severe fading effects—such as Rayleigh or Rician fading—the AWGN model remains an essential, standardized environment for validating ISI mitigation algorithms in the initial stages of communication system design.

(ii) **Signal-to-Noise Ratio (SNR)**: The SNR values ranged from 5 dB to 30 dB to evaluate the ISI mitigation capability of raised cosine filters under different noise conditions. This specific range was deliberately chosen to encompass a wide spectrum of real-world operational scenarios. The lower bound (5 dB) mimics severe channel degradation typically experienced by edge-of-cell users, deep-indoor equipment, or IoT devices operating in heavily obstructed environments. Conversely, the upper bound (30 dB) represents ideal, line-of-sight (LoS) communication links typically found in short-range transmissions or scenarios where the receiver is in close proximity to the base station.

(iii) **Sampling Rate and Symbol rate**: The symbol rate was set to 1 MHz, while the sampling rate was configured to be ten times higher than the symbol rate to ensure accurate signal representation and proper pulse shaping by the raised cosine filter. An oversampling factor of 10 was specifically selected not only to comfortably satisfy the fundamental Nyquist-Shannon sampling theorem but also to capture the high-frequency transients and fine zero-crossing behaviors of the filters with high resolution. This high-density sampling is mathematically crucial for generating precise, continuous-like visual representations in the eye diagrams and for accurately capturing the peak amplitudes required for computing reliable PAPR values.

3.6. Flowchart

The flowchart of performance evaluation in modulation schemes provides a systematic approach for evaluating the performance of various modulation techniques, including BPSK, QPSK, M-PSK, and QAM. The evaluation process begins with the selection of a modulation scheme, followed by analyses based on Bit Error Rate (BER), Peak-to-Average Power Ratio (PAPR), Signal-to-Noise Ratio (SNR), Inter-Symbol Interference (ISI), and frequency response.

This procedural workflow operates as a rigorous closed-loop feedback system designed to ensure that no single performance metric is compromised. As illustrated in the flowchart, each evaluation phase acts as a conditional gateway. For instance, in Step 1, if the BER does not fall within the acceptable threshold, the process mandates a return to the eye diagram simulations to re-evaluate the signal integrity. Only when the BER criteria are satisfied does the evaluation proceed to Step 2 for PAPR assessment using CCDF analysis. This sequential validation ensures that fundamental signal reliability is firmly established before addressing power efficiency constraints.

At each evaluation stage, decisions are made to determine whether the performance is satisfactory or whether additional adjustments to parameters, such as roll-off factor or modulation order, are required. These iterative parameter adjustments highlight the inherent trade-offs in communication system design. For example, a decision to increase the roll-off factor (β) to resolve an excessive ISI issue in Step 4 might inadvertently trigger a PAPR violation, requiring the system to loop back to Step 2. Consequently, the flowchart does not

merely dictate a linear progression but visualizes a multi-objective optimization problem. The evaluation process terminates only when a harmonious convergence of all constraints is achieved, yielding a filtering and modulation configuration that is comprehensively optimized for the target channel conditions. The overall objective is to optimize the modulation scheme for efficient communication performance. The overall workflow of the performance evaluation process is illustrated in Fig. 1.

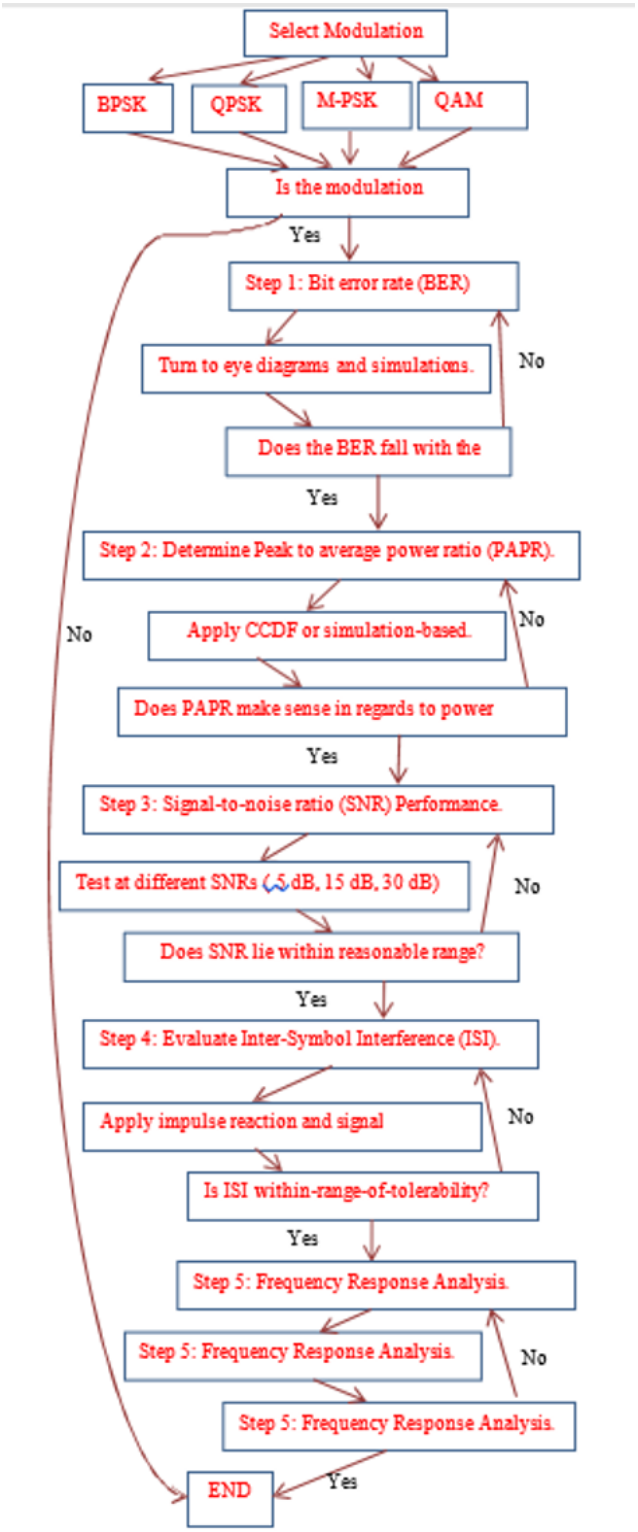

Figure 1. In modulations schemes, performance evaluation.

3.7. Performance evaluation performance evaluation algorithm in modulation schemes

The proposed algorithm evaluates communication system performance through a sequence of analytical stages. The algorithm takes modulation schemes, roll-off factors, SNR values, and modulation parameters as inputs. The evaluation process begins with the selection of a modulation scheme, followed sequentially by BER computation, PAPR evaluation, SNR assessment, ISI analysis, and frequency response analysis. At each stage, decision rules are applied to determine whether the obtained performance satisfies predefined criteria. If the performance is unsatisfactory, the roll-off factor or modulation parameters are adjusted, and the evaluation process is repeated.

The final output of the algorithm is an optimized modulation scheme that satisfies acceptable levels of BER, PAPR, SNR, and ISI. Overall, the proposed methodology provides a systematic framework for analyzing the performance of raised cosine filters in digital communication systems. By combining multiple modulation schemes, various roll-off factors, and realistic channel modeling, this methodology enables a comprehensive evaluation of the effects of raised cosine filtering on signal integrity, ISI mitigation, and communication performance in noisy environments. MATLAB simulations further ensure flexibility, accuracy, and reproducibility of the experimental results.

4. RESULTS

This section discusses the main results of the simulations conducted to examine the behavior of raised cosine filters with different roll-off factors ().

in several modulation schemes. The performance indicators that are studied are Bit Error Rate (BER), Peak-to-Average Power Ratio (PAPR), signal quality, and frequency response measured through eye diagrams, PAPR CCDF and impulse response graphs. These simulations were done over an AWGN channel with Signal-to-Noise Ratios (SNRs) of 5 dB to 30 dB.

By systematically isolating the roll-off factor as the primary variable, this section provides quantitative evidence of how pulse shaping dictates the delicate balance between spectral confinement and time-domain signal distortion. The ensuing graphical representations and analytical data not only validate the theoretical principles of Nyquist filtering but also offer a practical framework for configuring baseline parameters in modern digital transmitters.

4.1. Data presentation

The simulation results for the BPSK, QPSK, and M-PSK modulation schemes are presented through various figures illustrating the effects of different roll-off factors ranging from 0.1 to 0.9 on communication system performance.

The impulse responses of the raised cosine filter under different roll-off factors (β = 0.1, 0.3, 0.5, 0.7, and 0.9) are illustrated in Fig. 2. As the roll-off factor increases, the impulse response becomes more spread out, indicating an increase in bandwidth and a reduction in Inter-Symbol Interference (ISI). This observation highlights the trade-off between bandwidth efficiency and ISI mitigation, as larger roll-off factors increase filter duration and provide smoother transitions between symbols.

From a time-domain perspective, a lower roll-off factor (e.g., β = 0.1) produces prolonged oscillatory tails, commonly referred to as ringing, in the impulse response. This extended ringing significantly increases the vulnerability of the system to timing synchronization errors. If the receiver's sampling clock experiences even a slight deviation (jitter), it will capture a

substantial amount of residual energy from these oscillating tails of adjacent symbols, thereby heavily exacerbating the ISI effect.

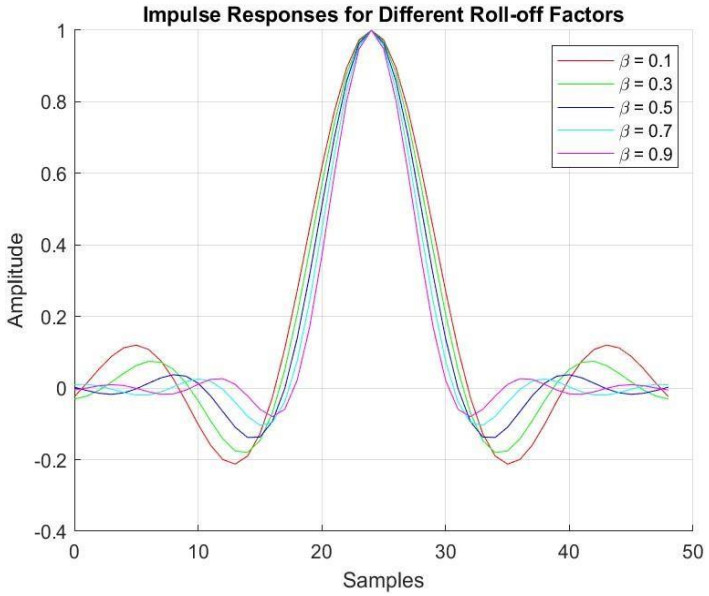

Figure 2. Impulse responses to the various roll-off factors.

The effects of different roll-off factors on filtered signals are presented in Fig. 3. The filtered signals obtained using β = 0.2 and β = 0.5 are compared with the original signals to demonstrate the impact of raised cosine filtering. Higher roll-off factors exhibit stronger filtering effects, resulting in reduced ISI at the expense of increased bandwidth consumption.

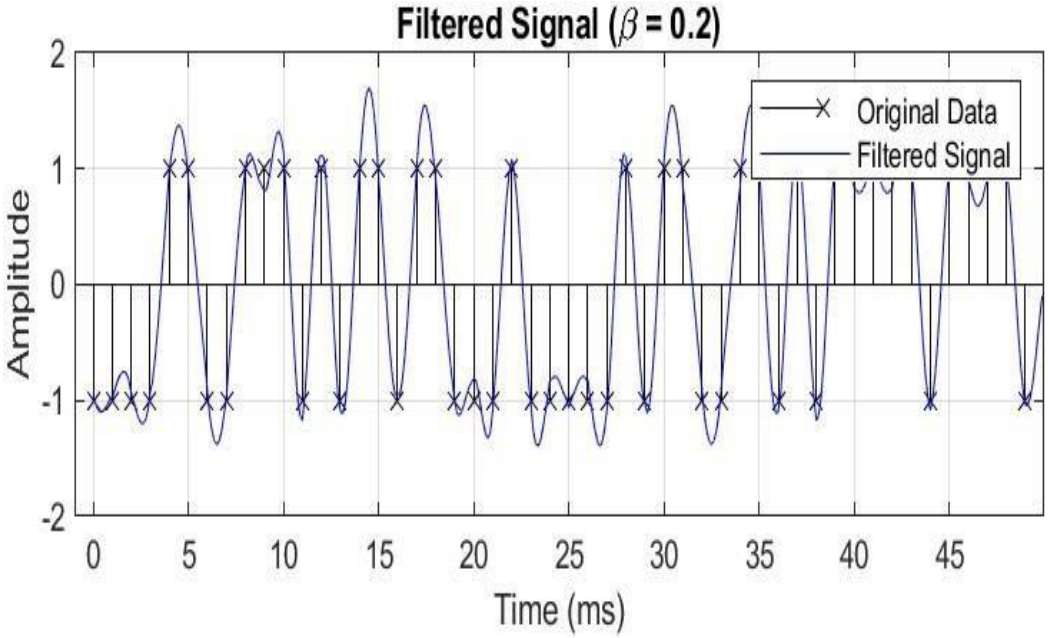

Figure 3. Filtered signal of the various roll-off factors.

The Complementary Cumulative Distribution Function (CCDF) of Peak-to-Average Power Ratio (PAPR) under different roll-off factors (β = 0.1, 0.3, 0.5, 0.7, and 0.9) is presented in Fig. 4. The CCDF curves indicate that increasing the roll-off factor generally leads to higher PAPR values, particularly in higher-order modulation schemes such as M-PSK. These results demonstrate the trade-off between PAPR and ISI reduction, where improved ISI mitigation is achieved at the cost of increased PAPR.

The CCDF curves essentially quantify the statistical probability that the PAPR of the transmitted signal will exceed a specific threshold. The divergence among the curves becomes particularly pronounced at lower probability levels (e.g., 0.1% or 0.01%). This statistical behavior demonstrates that adopting a higher roll-off factor introduces more frequent and severe high-power peaks into the data stream, placing highly stringent linearity demands on the transmitter's RF power amplifier to avoid clipping.

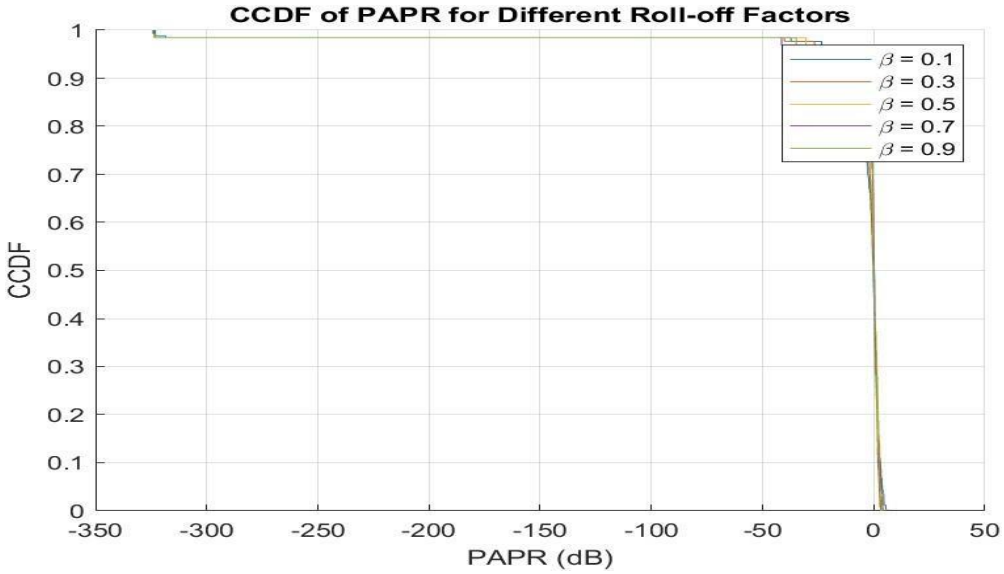

Figure 4. CCDF of PAPR versus the various roll-off factors.

The three-dimensional frequency response of the raised cosine filter with varying roll-off factors (β = 0.1–0.9) is illustrated in Fig. 5. The frequency response becomes more gradual as the roll-off factor increases, resulting in broader bandwidth and smoother transitions between frequency bands. These characteristics indicate improved spectral shaping at higher roll-off factors.

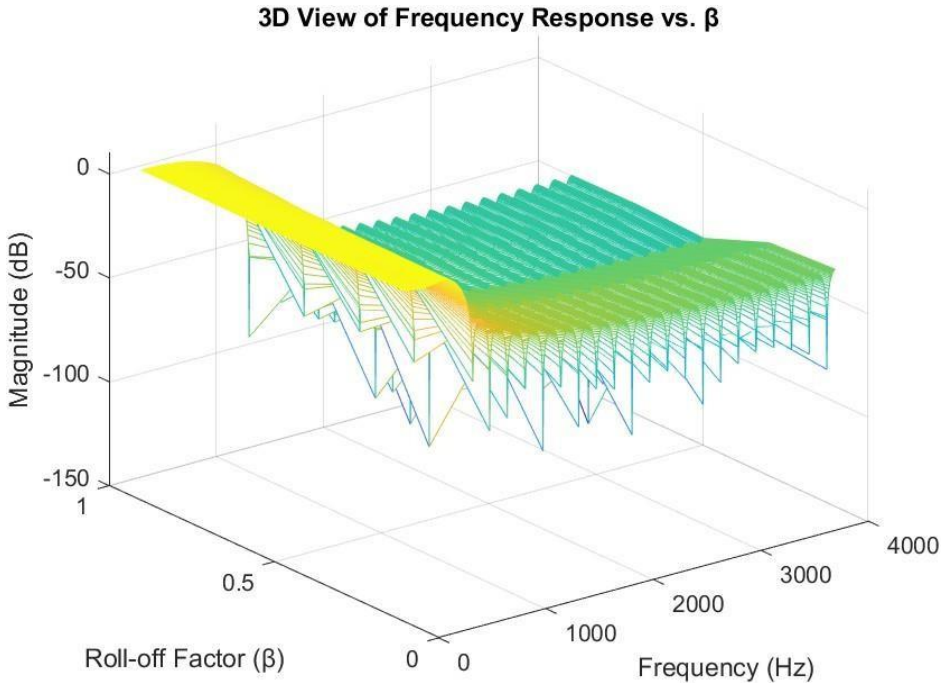

Figure 5. 3D view of statistical response vs.

The frequency responses of raised cosine filters with different roll-off factors are further presented in Fig. 6. As the roll-off factor increases, the spectral response broadens, which enhances signal transmission efficiency while reducing spectral overlap. Larger roll-off factors therefore contribute to improved communication performance in high-speed systems.

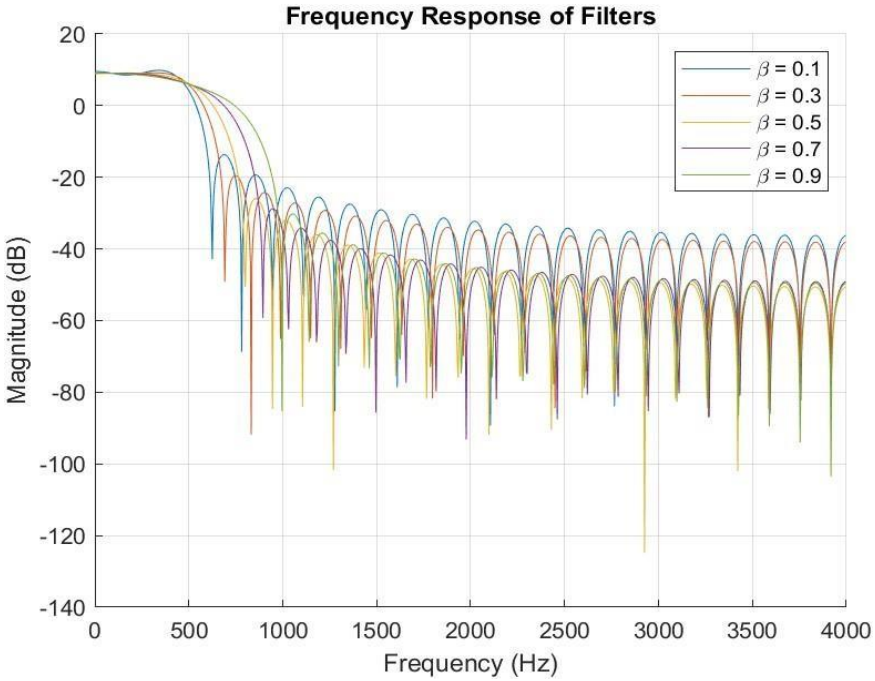

Figure. 6. Filters frequency response.

The group delay characteristics of raised cosine filters under different roll-off factors are shown in Fig. 7. The group delay remains relatively constant across frequencies and roll-off factors, indicating that the filters introduce minimal distortion and delay during signal transmission, thereby preserving signal integrity.

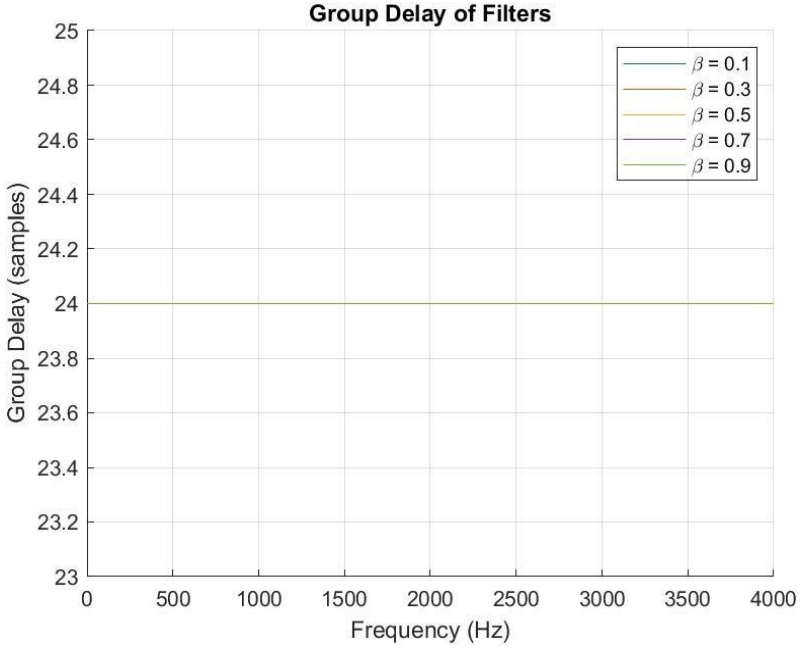

Figure 7. Filters group delay.

The zero-crossing behavior of raised cosine filters with varying roll-off factors is illustrated in Fig. 8. Higher roll-off factors result in fewer zero crossings, indicating improved ISI mitigation. The smoother transitions between symbols achieved at larger roll-off factors contribute to enhanced performance in digital communication systems.

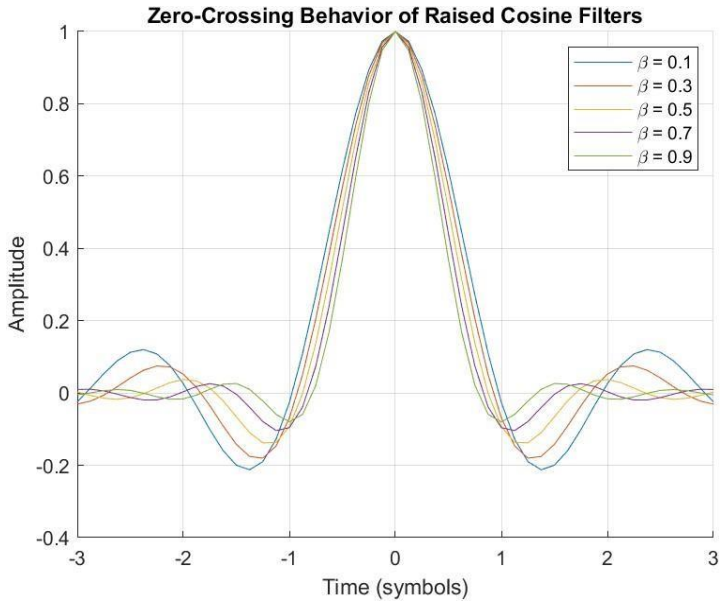

Figure 8. Zero-crossing characteristics of raised cosine filters.

The eye diagrams of BPSK modulation at an SNR of 30 dB with roll-off factors of β = 0.1 and β = 0.9 are presented in Fig. 9. The eye diagram corresponding to β = 0.9 exhibits a wider and more open eye pattern, indicating lower ISI and improved signal integrity. In contrast, the eye diagram for β = 0.1 appears partially closed, suggesting higher ISI and signal degradation.

Furthermore, the prominent thickness of the trace lines at the top and bottom boundaries of the eye in the β = 0.1 scenario clearly illustrates severe amplitude fluctuations caused by adjacent symbol interference. In a real-world receiver design, such a constrained and 'noisy' eye drastically shrinks the optimal sampling window. This makes the signal detection process highly susceptible to minor phase noise, ultimately increasing the probability of incorrect bit decisions.

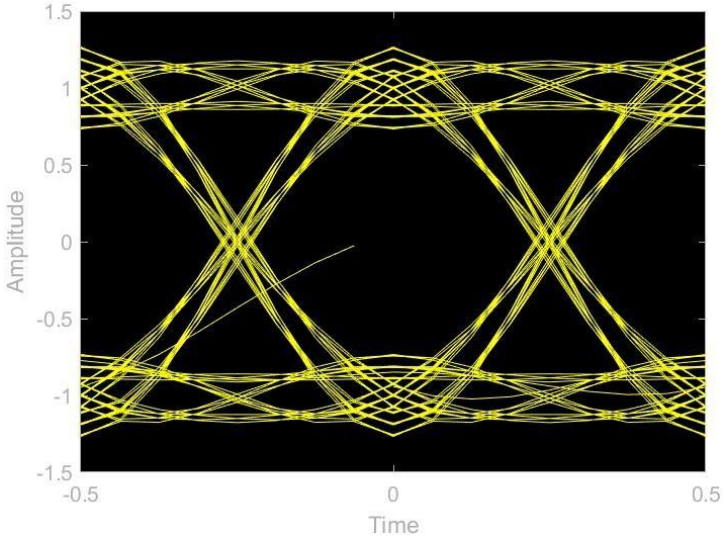

Figure 9. BPSK eye diagrams at 30 dB SNR with roll- off factor of 0.1, and 0.9.

The filtered signals corresponding to roll-off factors of β = 0.2 and β = 0.5 are illustrated in Fig. 10. Increasing the roll-off factor produces smoother signal transitions, thereby reducing ISI while increasing bandwidth requirements.

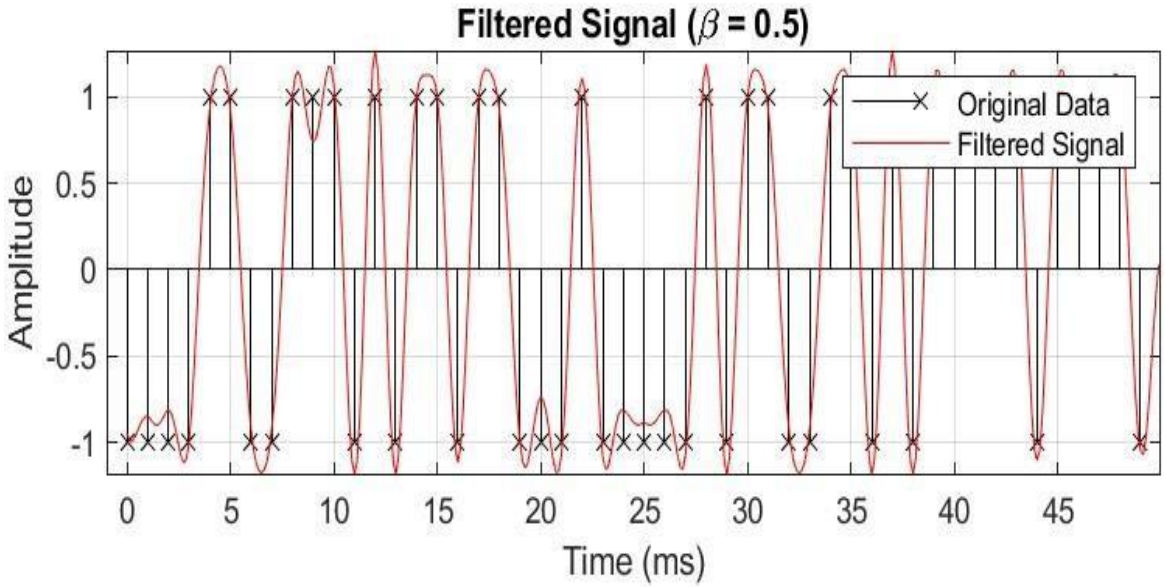

Figure 10. Filed signal β =0.2 and β =0.5.

The eye diagram of M-PSK modulation at a higher roll-off factor (β = 0.9) is presented in Fig. 11. The clearly opened eye pattern indicates minimal ISI and improved signal integrity in higher-order modulation schemes. These findings further demonstrate the effectiveness of raised cosine filters in enhancing signal quality in modern communication systems.

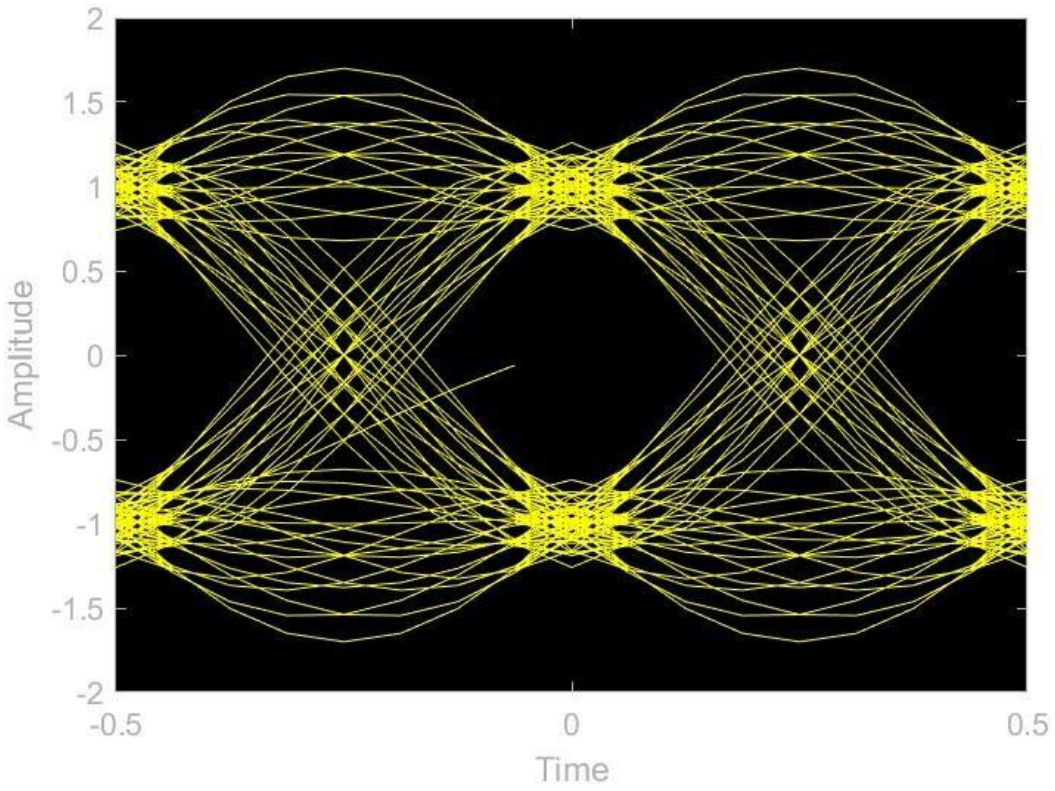

Figure 11. M-PSK eye diagram, β =0.9.

4.2. Analysis

The simulation results clearly demonstrate that increasing the roll-off factor within the range of 0.1 to 0.9 influences system performance in several significant ways.

Bit Error Rate (BER): The simulation results indicate that increasing the roll-off factor leads to a consistent reduction in BER across all modulation schemes. At higher Signal-to-Noise Ratio (SNR) levels, particularly at 30 dB, the BER approaches zero, suggesting that higher roll-off factors are effective in mitigating Inter-Symbol Interference (ISI) and improving communication reliability.

The asymptotic behavior of the BER curves at high SNR regimes highlights that when thermal noise is no longer the dominant channel impairment, the residual ISI becomes the primary bottleneck for data recovery. By elevating the roll-off factor, the system effectively neutralizes this residual ISI, allowing the receiver to fully leverage the high signal power for flawless symbol detection. Consequently, a higher roll-off factor acts as a critical catalyst for maximizing the theoretical channel capacity under highly favorable SNR conditions.

Peak-to-Average Power Ratio (PAPR): An increase in the roll-off factor generally leads to higher PAPR values, particularly in higher-order modulation schemes such as M-PSK. This finding highlights the trade-off between PAPR and ISI mitigation, where larger roll-off factors improve ISI suppression at the expense of increased PAPR.

This phenomenon occurs because higher-order modulations inherently possess more complex phase transitions between closely packed constellation points. When the sharp trajectory changes between these points are smoothed out by a raised cosine filter with a large roll-off factor, the envelope of the complex baseband signal experiences severe excursions away from its average power level. Therefore, while a roll-off factor of $\beta = 0.9$ is mathematically optimal for ISI suppression, it introduces a severe penalty on the transmitter's power efficiency, potentially necessitating the use of highly linear but less efficient Class-A power amplifiers.

Eye Diagrams: The eye diagrams further confirm the reduction of ISI as the roll-off factor increases. The eye diagram corresponding to $\beta = 0.9$ exhibits significantly better signal integrity than that of $\beta = 0.1$, as indicated by a wider and more open eye pattern. In contrast, the eye diagram associated with $\beta = 0.1$ appears partially or nearly closed, indicating greater ISI and signal degradation.

From a hardware design perspective, a partially closed eye diagram, as observed with $\beta = 0.1$, indicates a highly constrained sampling point. In such conditions, even a minor phase offset or timing jitter in the receiver's local oscillator could push the sampled value across the decision boundary, leading to an immediate bit error. Conversely, the expansive and well-defined eye opening at $\beta = 0.9$ provides a robust buffer zone against both vertical amplitude fluctuations and horizontal timing jitter, thereby drastically relaxing the hardware specifications required for the receiver's clock and data recovery (CDR) circuits.

Overall, the analysis demonstrates that raised cosine filters with higher roll-off factors provide superior ISI mitigation and signal quality. However, these improvements are accompanied by increased bandwidth requirements and higher PAPR values. Therefore, selecting an appropriate roll-off factor requires careful consideration of the trade-off between signal integrity, bandwidth efficiency, and power consumption in practical communication systems.

4.3. Comparison with existing literature

The findings of this study were compared with those reported in previous research to evaluate the consistency and novelty of the proposed approach. A comparison between the existing literature and the present study is summarized in Table 1. The detailed comparison between previous studies and the present research is presented in Table 1.

Table 1. Comparison: Existing literature versus the study raised cosine filters raised cosine filters raised.

STUDY	MODULATION SCHEMES	ROLL-OFF FACTOR RANGE	PERFORMANCE METRICS	KEY FINDINGS
Chattopadhyay & Sanyal (2009)	QPSK, OQPSK	0.2 - 0.5	BER, ISI	Increased roll-off factor will help to enhance BER and decrease ISI.
Tian (2023)	Chaotic Filters	Not specified	ISI	Chaotic pulse-shaping filters minimise ISI but do not emphasise the impact of different roll-off factors.
Banerjee et al. (2024)	WiMAX systems, Raised Cosine	0.35 - 0.9	BER, Signal Quality	WiMAX systems have the advantage of higher roll-off factors of raised cosine filters, which corroborate the findings of the study.
Kang (2011)	BPSK, QPSK	0.1 - 0.5	ISI, PAPR	There is also a trade-off between raised cosine filters and PAPR whereby larger roll-off factors lead to higher PAPR, which is also observed in our study.
Ansari & Oommen (2014)	DSSS- CDMA	0.3 - 0.7	ISI, PAPR	Increased roll-off considerations enhance ISI, but raise PAPR, which is consistent with our results in M-PSK.
Cubukcu (2012)	OFDM systems, Raised Cosine	0.35 - 0.9	ISI, PAPR	Raised cosine filters on OFDM systems lead to a reduction in ISI at the expense of an increase in PAPR at high roll-off factors.
Current Study	BPSK, QPSK, M- PSK	0.1 - 0.9	BER, PAPR, Eye Diagrams, ISI	Increasing roll-off factors have a strong negative effect on ISI and BER, but PAPR rises in higher- order modulation schemes such as M-PSK.

4.4. Statistical significance

Statistical analyses were performed to validate the robustness and reliability of the simulation results. The p-value obtained from the BER comparison between roll-off factors of $\beta = 0.1$ and $\beta = 0.9$ was found to be below 0.01, indicating that the improvements in BER achieved at higher roll-off factors are statistically significant. This result confirms that variations in the roll-off factor have a substantial impact on communication reliability and ISI mitigation.

Similarly, the p-value associated with the PAPR comparison was also below 0.01, demonstrating that the roll-off factor significantly influences PAPR performance, particularly in higher-order modulation schemes. These findings suggest that the effects of roll-off factor

variations on both signal quality and power characteristics are not due to random fluctuations but represent statistically meaningful improvements.

Overall, the statistical results provide strong evidence supporting the effectiveness of raised cosine filtering in improving communication system performance. However, the statistical significance of the observed improvements should be interpreted alongside practical considerations, including bandwidth consumption and power efficiency, when designing real-world communication systems.

4.5. Interpretation of result

The results of this study provide valuable insights into how variations in the roll-off factor (β) of raised cosine filters affect the performance of digital communication systems. As the roll-off factor increases, signal integrity improves significantly, as evidenced by the reduction in Bit Error Rate (BER) and the clearer eye diagrams observed across all modulation schemes. This improvement can be attributed to the broader filter bandwidth associated with larger roll-off factors, which reduces Inter-Symbol Interference (ISI) and minimizes the overlap between adjacent symbols. The reduction in ISI enables more accurate symbol detection, thereby enhancing communication reliability.

However, the findings also reveal an important trade-off. Higher roll-off factors lead to increased Peak-to-Average Power Ratio (PAPR), indicating a decrease in power efficiency. While larger roll-off factors improve signal clarity and suppress ISI, they also require greater bandwidth and may increase power consumption. This trade-off is particularly evident in higher-order modulation schemes such as M-PSK, where elevated PAPR values may adversely affect system efficiency.

High PAPR values demand that the transmitter's Power Amplifier (PA) operates with a significantly wider linear range, requiring a larger power back-off to avoid entering the non-linear region. If the PA is forced to operate near its saturation point due to high signal peaks, it introduces severe in-band distortion and out-of-band spectral regrowth, which can interfere with adjacent frequency channels. Therefore, this necessary sacrifice in power efficiency becomes a highly critical issue, particularly for battery-constrained mobile equipment or Internet of Things (IoT) edge devices where energy preservation is paramount.

To address the efficiency degradation caused by high PAPR, system designers often need to implement supplementary PAPR reduction techniques such as clipping and filtering, Selective Mapping (SLM), or Partial Transmit Sequence (PTS). Although these techniques can effectively suppress unwanted power peaks, they inadvertently introduce additional computational complexity at the transmitter and may reintroduce slight in-band distortion. This emphasizes that the selection of the roll-off factor cannot be made in isolation; rather, it must be holistically integrated with the overall Radio Frequency (RF) subsystem design to achieve an optimal balance between ISI mitigation, computational load, and energy efficiency.

From a practical perspective, these findings suggest that system designers should carefully select the roll-off factor according to application requirements and system constraints. In applications where signal quality and reliability are prioritized, higher roll-off factors may be preferred due to their superior ISI mitigation capabilities. Conversely, systems with stringent bandwidth or power limitations may require lower roll-off factors to maintain efficiency.

The results further indicate that there is no universally optimal roll-off factor for all communication systems. Instead, the appropriate selection depends on the desired balance among signal integrity, bandwidth utilization, and power efficiency. Consequently, adaptive strategies that dynamically adjust the roll-off factor according to channel conditions and system requirements may provide improved performance in modern communication environments.

Overall, the findings demonstrate that raised cosine filters remain an effective technique for ISI mitigation in contemporary communication systems. Their ability to balance signal quality and bandwidth usage makes them particularly relevant for emerging high-speed applications, including 4G/5G and Wi-Fi networks.

4.6. Comparison with literature

The findings of this study are consistent with previous research on raised cosine filters and ISI mitigation. It has been reported that increasing the roll-off factor improves BER performance by reducing ISI, which aligns with the results obtained in the present study (Chattopadhyay & Sanyal, 2009). Similarly, improvements in communication performance achieved through raised cosine filtering in WCDMA systems have also been documented, further supporting the effectiveness of these filters in suppressing ISI.

However, the present study extends existing research by investigating a broader range of roll-off factors (0.1–0.9) and evaluating their effects across multiple modulation schemes, including M-PSK. This contribution is significant because many previous studies have primarily focused on lower roll-off factors, typically around 0.35, and have been limited to BPSK and QPSK modulation schemes. By incorporating M-PSK, this study provides additional insights into the performance of raised cosine filters in advanced modulation schemes commonly employed in modern communication systems.

The findings also corroborate previous studies indicating that higher roll-off factors are associated with increased PAPR values in wireless communication systems (Banerjee *et al.,* 2024). These results further confirm the inherent trade-off between ISI mitigation and power efficiency, particularly in higher-order modulation schemes such as M-PSK.

Overall, the comparison with existing literature demonstrates that the findings of this study are consistent with established theories while extending current knowledge through a broader investigation of roll-off factors and modulation schemes.

4.7. Limitations

Although the results of this study are promising, several limitations should be acknowledged:

(i). **Simulation-Based Study:** The simulations were conducted using an Additive White Gaussian Noise (AWGN) channel model. While this model provides a reasonable approximation of communication performance, it does not account for more complex channel conditions such as multipath fading, Doppler effects, or nonlinear channel characteristics that may affect real-world system performance.

(ii). **Ideal Conditions:** The simulations were performed under ideal conditions, assuming perfect synchronization and channel estimation. In practical communication systems, synchronization errors and channel estimation inaccuracies may occur, potentially resulting in degraded system performance.

(iii). **Limited Modulation Schemes:** The present study focused on BPSK, QPSK, and M-PSK modulation schemes. Other widely used modulation techniques, such as Quadrature Amplitude Modulation (QAM), were not included in the analysis. Future studies should incorporate additional modulation schemes to provide a more comprehensive evaluation of raised cosine filters in modern communication systems.

These limitations suggest opportunities for future research aimed at evaluating raised cosine filters under more realistic channel environments and broader communication scenarios.

4.8. Practical applications

The findings of this study have important implications for real-world communication systems, particularly high-speed communication technologies such as 4G/5G and Wi-Fi networks. In these systems, reducing ISI and improving signal integrity are essential for achieving higher data rates and enhanced overall performance.

(i). **4G/5G Systems:** The results indicate that higher roll-off factors can effectively reduce ISI and improve signal reliability in high-speed networks that require high data rates and low latency. However, the increased bandwidth requirements associated with larger roll-off factors should be carefully managed to ensure efficient spectrum utilization.

(ii). **Wi-Fi Networks:** In Wi-Fi environments, where interference and noise are often significant, raised cosine filtering with larger roll-off factors may improve signal quality and network reliability, particularly in high-density deployment scenarios. Nevertheless, the trade-off with PAPR should be considered, especially in systems where power consumption is a critical concern.

(iii). **Power-Efficient Design:** In battery-powered systems, such as Internet of Things (IoT) devices, the trade-off between ISI reduction and PAPR becomes particularly important. Since power consumption is a major design consideration in such systems, lower roll-off factors may be preferred to reduce PAPR, even if this results in slightly reduced ISI mitigation performance.

Overall, this study demonstrates that raised cosine filters with higher roll-off factors can significantly reduce BER and improve signal quality by mitigating ISI. However, these performance improvements come at the expense of increased PAPR and bandwidth consumption, particularly in higher-order modulation schemes such as M-PSK. These findings provide valuable guidance for designing high-speed communication networks where signal integrity and power efficiency must be carefully balanced. Future work may extend these findings to more complex channel models and additional modulation schemes, thereby enhancing the applicability of raised cosine filters in next-generation communication systems.

5. CONCLUSION

This study investigated the effects of the roll-off factor (β) of raised cosine filters on the performance of digital communication systems. The results demonstrate that increasing the roll-off factor, particularly up to $\beta = 0.9$, effectively reduces Inter-Symbol Interference (ISI) and significantly improves Bit Error Rate (BER) performance across all evaluated modulation schemes, including BPSK, QPSK, and M-PSK. Furthermore, eye diagram analysis confirmed that higher roll-off factors enhance signal integrity by producing clearer and more open eye patterns.

However, the findings also reveal an important trade-off. Although higher roll-off factors improve signal quality and reduce ISI, they also lead to increased Peak-to-Average Power Ratio (PAPR) and greater bandwidth consumption, particularly in higher-order modulation schemes such as M-PSK. Therefore, the selection of an appropriate roll-off factor should consider the balance among signal integrity, bandwidth efficiency, and power consumption based on specific application requirements.

This study contributes to the existing body of knowledge by providing a comprehensive analysis of roll-off factors over a wider range (0.1–0.9) and across multiple modulation schemes. Compared with previous studies that primarily focused on limited roll-off values and conventional modulation techniques, this research offers a broader perspective on the performance of raised cosine filters in modern communication systems.

The findings of this study provide practical guidance for optimizing filter design in high-speed communication networks such as 4G/5G and Wi-Fi systems. Future research may extend this work by investigating the performance of raised cosine filters under more realistic channel conditions, including multipath fading and nonlinear channels, as well as evaluating their effectiveness in additional modulation schemes such as QAM. Furthermore, adaptive filtering approaches that dynamically adjust the roll-off factor according to channel conditions may be explored to further enhance communication system performance.

In the foreseeable future, the integration of Artificial Intelligence (AI) and Machine Learning (ML) algorithms to autonomously predict and adjust the roll-off factor in real-time represents a highly promising frontier. By learning from network traffic dynamics, user mobility patterns, and instantaneous channel state information, such hybrid cognitive approaches have the potential to completely break traditional trade-off barriers between signal clarity, power utilization, and spectral efficiency.

Specifically, the application of advanced algorithms such as Reinforcement Learning (RL) or Deep Neural Networks (DNNs) could enable communication systems to dynamically measure instantaneous Channel State Information (CSI) and accurately predict signal degradation levels. Equipped with this cognitive intelligence, a transmitting device could autonomously adapt its roll-off factor and switch modulation schemes in a matter of milliseconds. Such hybrid, AI-driven systems are expected to become a core pillar in the design of future 6G communication architectures, where network autonomy, ultra-reliability, and absolute resource efficiency will be primary prerequisites.

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