Department of Electronic & Telecommunication Engineering

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EN2074 Communication Systems Engineering

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Lab Assignment – Eye diagrams and Equalization

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Abstract...

In the world of digital communication, sending modulated signals effectively depends on using special filters that shape the signals just right. These filters need to be tough enough to handle noise and timing differences. This study compares two popular filters: the sinc filter and the raised cosine filter. We use a tool called an "eye diagram" to see how well 2-Level Pulse Amplitude Modulation (2-PAM) works in tough conditions, like when signals bounce around and mix up with each other (called inter-symbol interference or ISI), and when there's extra random noise. Our main goal is to carefully check how many errors happen when using 2-PAM and see if using a Zero Forcing equalizer helps fix any distortions caused by ISI.

1.Introduction

Communication systems serve as conduits for the generation, conversion, transmission, and reception of messages between two or more entities. Focusing our attention on baseband digital communication systems, this report delves into their intricate workings.

Below, we present a comprehensive model depicting the core elements of a baseband communication system.

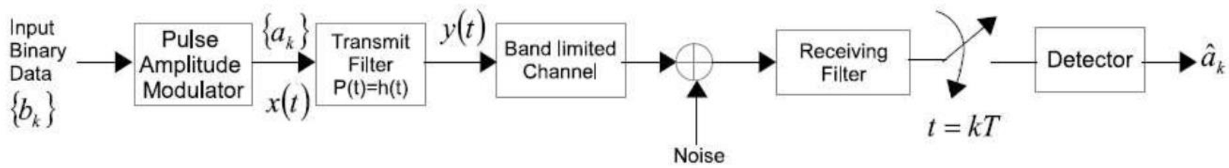


Figure1. 1 - Baseband Communication System Model

Input Binary Data (b_k): At the onset, digital communication begins with binary data, denoted as (b_k). These binary symbols typically represent the information to be transmitted, such as text, audio, or video data.

Pulse Amplitude Modulator: To prepare the binary data for transmission, it undergoes modulation using a Pulse Amplitude Modulator. This modulation process converts the discrete binary symbols into continuous modulated symbols (a_k), adjusting their amplitudes based on the binary input.

Transmit Filter (P(t)): Before transmission, the modulated symbols pass through a transmit filter represented by (P(t)). This filter shapes the signals to meet specific requirements, such as controlling bandwidth, reducing intersymbol interference, and improving signal-to-noise ratio. Common types of transmit filters include raised cosine and sinc filters.

Band Limited Channel: The filtered signals (x(t)) are then transmitted through a communication channel. This channel may be physical (such as a wired or wireless medium) or simulated (in the case of computer simulations). The channel's bandwidth is often limited, meaning it can only pass signals within a certain frequency range.

Noise: During transmission, the signal is susceptible to various sources of noise, including thermal noise, interference from other signals, and environmental factors. This noise can distort the transmitted signal, leading to errors in reception.

Receiving Filter: Upon reaching the receiver, the received signal (y(t)) undergoes further processing through a receiving filter. Like the transmit filter, this filter helps mitigate the effects of noise and shape the signal to facilitate accurate detection.

Detector: The processed signal is finally fed into a detector, which analyzes the received symbols (a_k) and decodes them back into binary data (b_k). The detector's primary task is to distinguish between different symbol levels and identify the correct sequence of symbols, despite any distortions introduced during transmission.

The channel introduces various types of errors, including:

Additive White Gaussian Noise (AWGN): This noise, typically present in communication channels, disrupts the transmitted symbols by adding random disturbances to the pulses. As a result, the received symbols may deviate from their intended positions, leading to errors in bit detection.

Inter-Symbol Interference (ISI): Communication channels are characterized by limited bandwidth

B). Any pulse with a bandwidth exceeding B experiences spectral distortion, causing it to spread in the time domain. This spreading leads to interference with neighboring pulses, known as Inter-Symbol Interference (ISI).

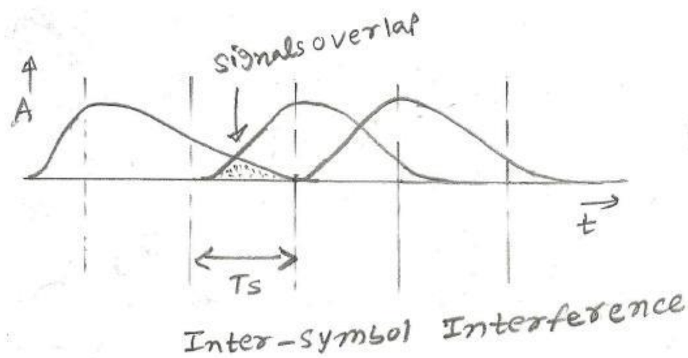


Figure 1.2 Intersymbol interference.

Synchronization Errors: Timing discrepancies between transmitted and received bits can lead to synchronization errors, where bits are incorrectly interpreted due to misalignment in timing.

Communication engineers strive to design systems that mitigate the impact of these errors. One valuable tool for assessing system robustness is the 'Eye Diagram,' which provides insights into the performance of the communication system under various error conditions.

Pulse Shaping Filters in Digital Communication Systems

In digital communication systems, the initial signal is composed of impulses which are then transformed into Binary Phase Shift Keying (BPSK) symbols. These impulses cannot be directly transmitted due to practical limitations, thus necessitating their conversion into appropriate signals via **a pulse-shaping filter**.

The resulting transmitted signal, $y(t)$, can be expressed as the summation of weighted pulses over a certain duration, represented by:

$$y(t) = \sum_{k=-M}^{M} \alpha k \times P(t - kT)$$

Where:

- αk represents the BPSK symbols.
- T denotes the pulse duration.

It's crucial to note that the communication channel has a limited bandwidth. Therefore, the bandwidth of the transmitting signal must be equal to or smaller than that of the channel. Additionally, the bandwidth of the pulse-shaping filter should be taken into consideration when selecting the appropriate filter.

In this report we are using following pulse shaping filters:

1. **Sinc Pulse**

The Sinc pulse is represented by the function $p(t)$, defined as:

$$p(t) = \begin{cases} 1 & t = 0 \\ \dfrac{\sin(\pi R_b t)}{\pi R_b t} & t \neq 0 \end{cases}$$

The Sinc pulse is not time limited. Its decay is proportional to $1/t$, resulting in large side lobes of the pulse. This characteristic leads to time jitters in the transmitted signal.

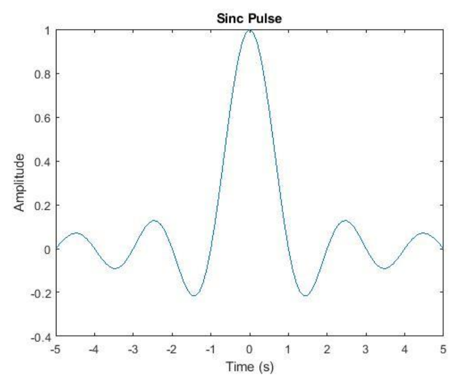


Figure 1.3- sinc pulse.

2. **Raised Cosine Pulse with γ =0.5**

The raised cosine pulse, denoted by p(t), is given by:

$$p(t) = \begin{cases} R_b & t = 0 \\ \dfrac{R_b \operatorname{sinc}(\pi R_b t) \cos(\pi \gamma R_b t)}{1-(2\gamma R_b t)^2} & t \neq 0 \end{cases}$$

The decay is $1/t^3$, resulting in small side lobes, making it robust to synchronization errors.

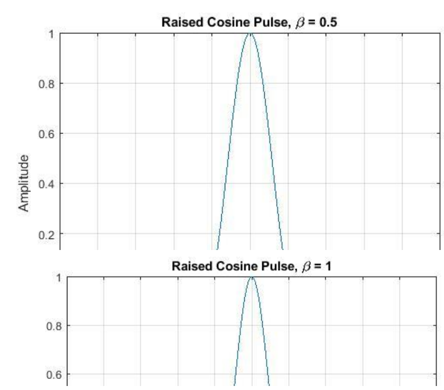


Figure 1.2 - Raised Cosine Pulse with γ =0.5

3. **Raised Cosine Pulse with γ =1**

For the raised cosine pulse with γ =1, the decay is higher compared to γ =0.5. Consequently, the side lobes are even smaller, enhancing the robustness of the pulse to synchronization errors.

Figure 1.3 - Raised Cosine Pulse with γ =1

Eye Diagrams

In the realm of communication engineering, particularly in the design and analysis of digital communication systems, "Eye Diagrams" serve as a crucial tool for visualizing and assessing the quality of transmitted signals. An eye diagram provides valuable insights into the behavior of signals as they traverse through the communication channel, allowing engineers to evaluate the system's performance and identify potential issues.

At its core, an eye diagram is a graphical representation of a waveform, typically obtained by superimposing multiple signal transitions over a period of time. The resulting plot resembles the shape of an "eye," hence the name. This unique visual depiction offers a holistic view of signal characteristics, including amplitude, timing, and noise.

Analysis of Eye Diagram Parameters:

1. Slope of the Eye:

- Indicates sensitivity to sampling time, reflecting immunity to synchronization errors.

- Higher slope implies increased susceptibility to synchronization errors, making timing information retrieval challenging.

2. Optimum Sampling Instant:

- Identifies the ideal sampling point for extracting information, located at the maximum eye opening.

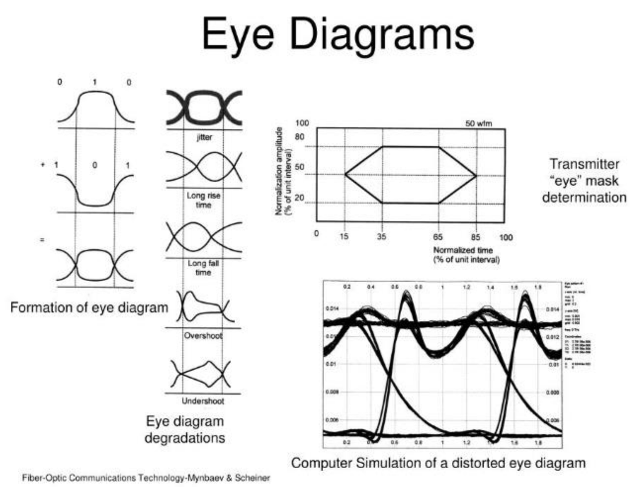


Figure 1.4 - eye diagram.

3. Eye Height: - Represents noise margin, calculated as the ratio of amplitude to twice the standard deviation.

- Greater eye height signifies improved resistance to Additive White Gaussian Noise (AWGN) introduced by the channel.

- Also signifies Signal-to-Noise Ratio (SNR) at the optimal sampling point.

4. Eye Width:

- Indicates the region with the highest SNR and represents the bit/symbol period (\(T \)).

- Narrower eye diagrams correspond to higher data transmission rates.

- Wider eyes reduce the likelihood of sampling errors.

5. Time Variation of Level-Crossing (Zero-Crossing):

- Reflects timing jitter resulting from mismatches in pulse rise and fall times.

- Narrow level-crossing ambiguity width enhances robustness against Inter-Symbol Interference (ISI), crucial for high-speed data transmission.

6. Peak Distortion:

- Measures the change in pulse peak amplitude due to AWGN during transmission.

- Lower values indicate greater robustness against AWGN-induced distortion.

Zero-Forcing Equalization

Zero-Forcing Equalization is a linear equalization technique commonly employed in communication systems **to mitigate the effects of channel distortion**. It works by applying the inverse of the channel's frequency response to the received signal, aiming to counteract the distortion introduced by the channel. By doing so, it attempts to minimize intersymbol interference (ISI) and restore the transmitted signal to its original form.

The concept behind Zero-Forcing Equalization is straightforward: given the channel's frequency response $H(f)$, the equalizer's frequency response $G(f)$is constructed as the reciprocal of the channel's response:

$$G(f) = \frac{1}{\mathrm{H(f)}}$$

Ideally, the combination of the channel and the equalizer should result in a flat frequency response and linear phase, ensuring minimal distortion of the transmitted signal.

However, Zero-Forcing Equalization has limitations and may not be suitable for all scenarios:

1. **Infinite Impulse Response Requirement**: While the channel impulse response is typically finite, the equalizer's impulse response often needs to be infinitely long to achieve ideal equalization. This can be impractical to implement in real-world systems.

2. **Noise Amplification**: In situations where the received signal is weak or noise levels are significant, the gain of the zero-forcing filter can become excessively large. As a consequence, any noise present after the channel gets amplified significantly, deteriorating the overall signal-to-noise ratio.

3. **Inversion Challenges**: Some channels may have zeros in their frequency response that cannot be inverted effectively. In such cases, Zero-Forcing Equalization may fail to fully compensate for the channel distortion.

While Zero-Forcing Equalization offers a straightforward approach to equalizing channel distortion, its effectiveness depends on the specific characteristics of the channel and the noise environment. In practice, it may be necessary to explore alternative equalization techniques or combine Zero-Forcing Equalization with other methods to achieve optimal performance in communication systems.

2. Assignment

Task 1

1.Generate an impulse train representing BPSK symbols

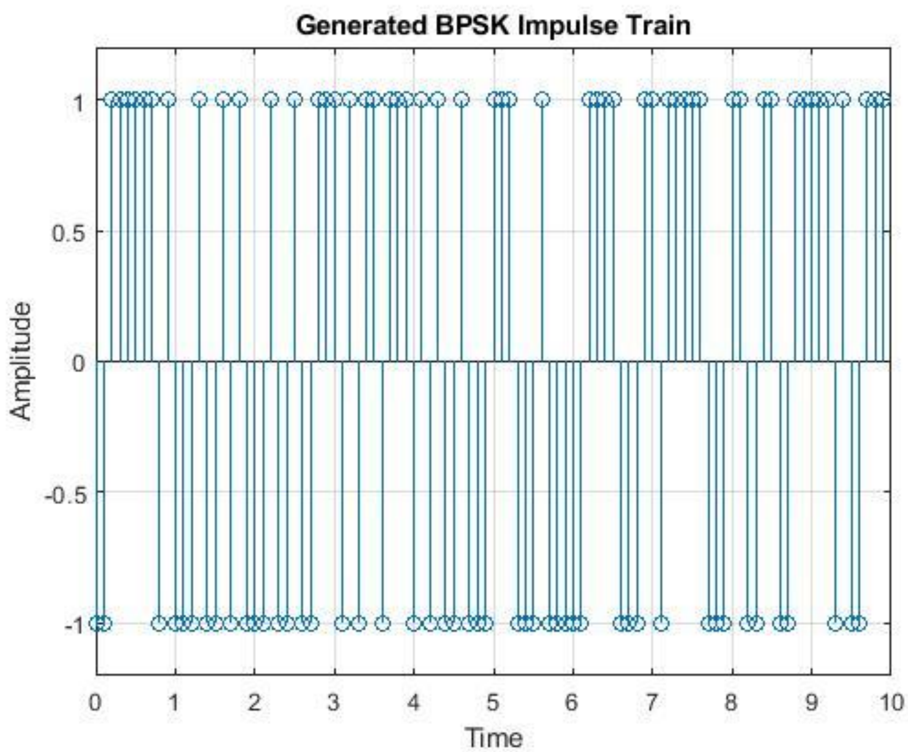


Figure 2.1 Generated BPSK impulse train

2.transmit signal by convolving the impulse train with a pulse.

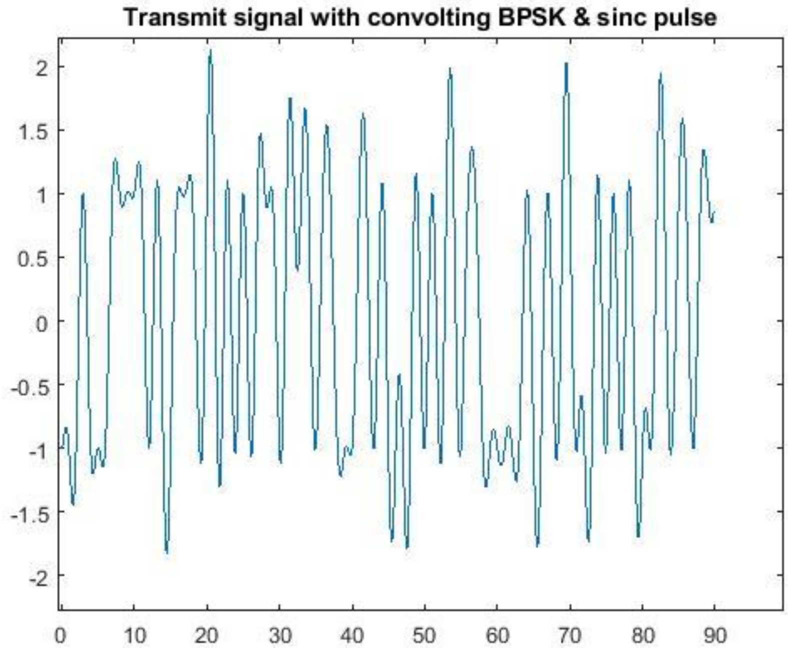


Figure 2.2 transmit signal with sinc pulse

3.Generate the eye diagram of the transmit signal

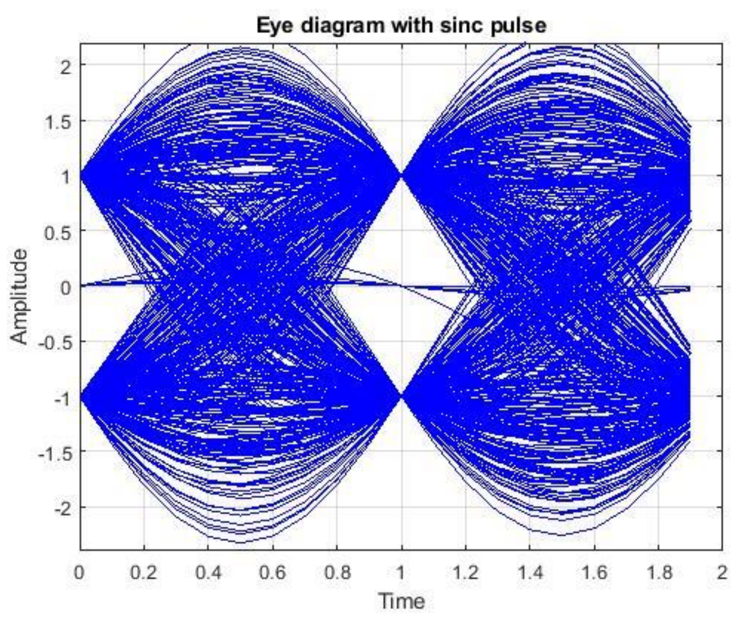


Figure 2.3 eye diagram with sinc pulse

4.Repeat 1-3 for raised cosine pulse shaping filters with roll-off factor 0.5 and 1 *roll-off factor 0.5.*

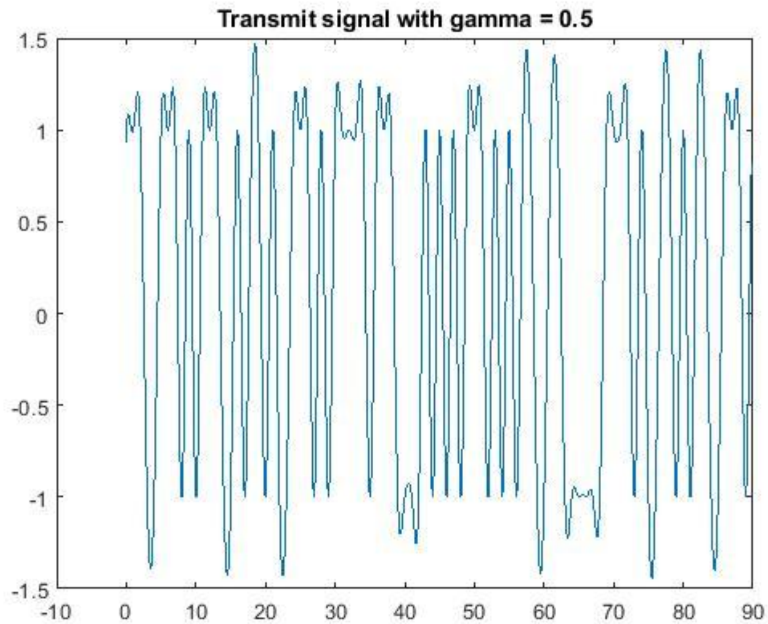


Figure 2.4 transmit signal with raise cosine pulse rof = 0.5

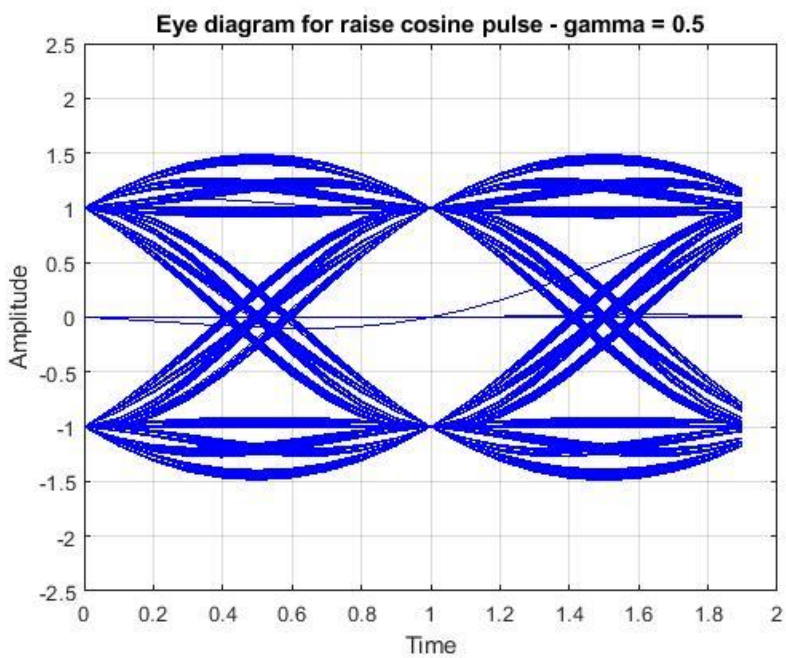


Figure 2.5 eye diagram for raise cosine pulse rof = 0.5

roll-off factor 1

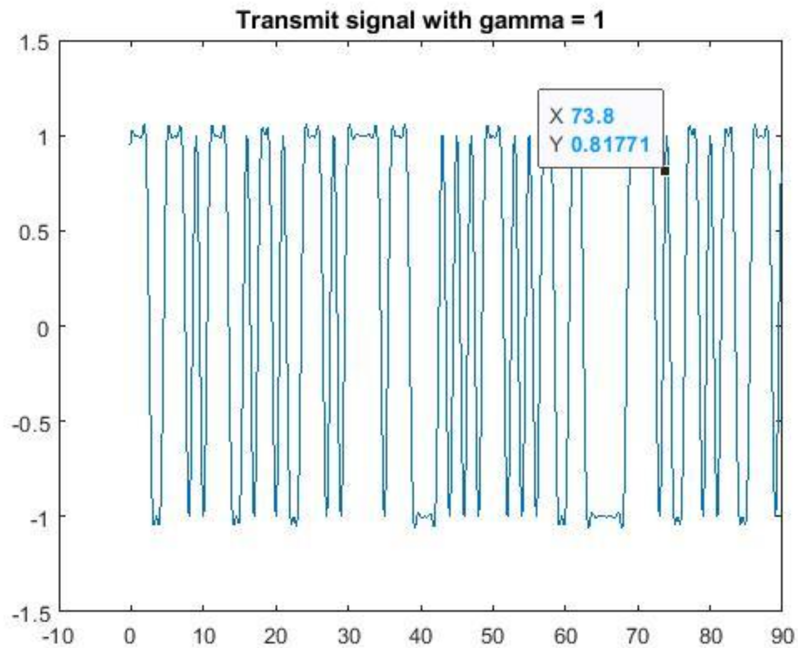


Figure 2.6 transmit signal with raise cosine pulse rof = 1

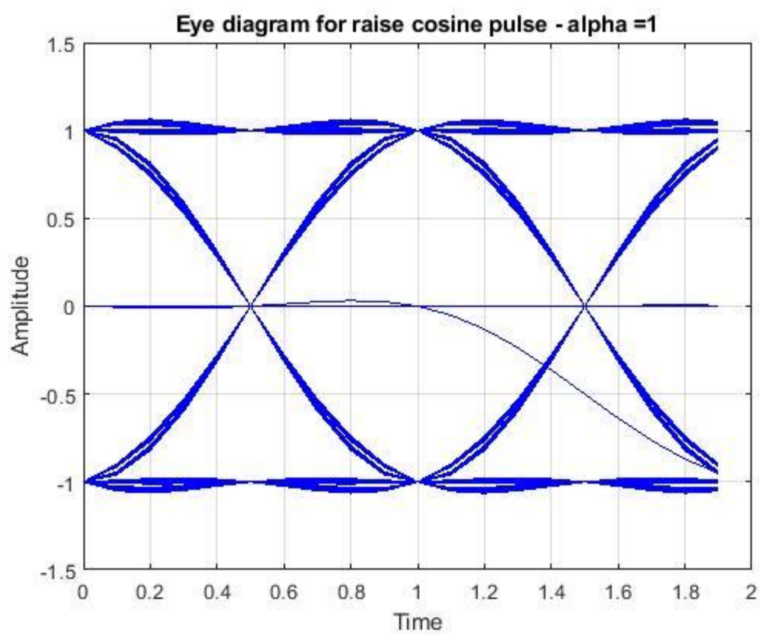


Figure 2.7 eye diagram for raise cosine pulse rof = 1

5.Compare the robustness of the system with respect to noise, sampling tine and synchronization errors.

Characteristic of the Eye diagram	**Information**	**Sinc Pulse**	**Raised Cosine Pulse (Roll-off = 0.5)**	**Raised Cosine Pulse (Roll-off = 1)**
Eye Height	Noise margin or the signal's immunity to noise. A larger eye height indicates better noise immunity	The signal amplitudes are spred, which makes it more susceptible to noise. Even small noise levels can cause interference and contribute to intersymbol interference (ISI).	Eye height is reduced but better compared to that of a sinc filter, while the sampling error probability has decreased.	The eye height is reduced, to happen the ISI it want to higher noise levels.
Eye Width	The duration of time during which the received signal is error-free and is often associated with the intersymbol interference (ISI). A wider eye width suggests a longer error-free sampling region, which is desirable for accurate signal recovery.	There is less margin for error-free sampling. This makes the system less robust against sampling errors and increases the likelihood of errors due to ISI.	The eye width is wider than that of the sinc pulse but narrower than that of the roll-off = 1 raised cosine pulse, providing a medium range of sampling without any error.	It is the widest among the three filters, providing a larger region for sampling the data with better Signal-to-Noise Ratio (SNR).
Slope of the eye	The rate of change of the eye opening's edges. It is indicative of the timing accuracy or synchronization of the received signal. A steeper slope suggests a higher likelihood of synchronization errors.	There is a high probability of timing errors. This could be due to rapid changes in the signal, making it difficult to accurately sample at the correct times.	The slope varies within a range and consists of the lowest slope among the three types, making it most robust to synchronization errors.	It is the widest among the three filters, providing a larger region for sampling the data with better Signal-to-Noise Ratio (SNR).

Thickness of the edge	the variation in timing at the points where the signal crosses zero amplitude. It provides insight into timing jitter, which refers to the deviation in the timing of signal transitions.	The significant jitter at zero-crossings indicates a high variability in the timing of signal transitions. This can lead to timing uncertainty and further exacerbate timing errors.	Range and jitter are better than those of a sinc filter but worse than those of a raised cosine filter with a high gamma..	Both the range and jitter are best in this filter, indicating superior stability and timing accuracy compared to the other filters.
Thickness at the peak	The deviation of the signal at its maximum amplitude.	The presence of peak deviation suggests that there are fluctuations in the signal at its highest points, which can further complicate sampling and contribute to errors.	There is very low peak deviation.	There is very low peak deviation.

The height of the eye directly reflects its noise immunity, with greater height indicating better immunity against noise interference. This immunity decreases progressively from the raised cosine filter with gamma 1 to gamma 0.5 and then to the sinc filter. Similarly, the sampling error probability increases in the same order, from the raised cosine filter with gamma 1 to gamma 0.5 and then to the sinc filter. On the other hand, the levels of synchronization errors decrease from the sinc filter to the raised cosine filter with gamma 1 and further to the raised cosine filter with gamma 0.5. These observations underscore the trade-offs between noise immunity, sampling error probability, and synchronization errors across different filter types. Therefore, the choice of filter must be carefully considered based on the specific requirements and constraints of the communication system.

Task 2

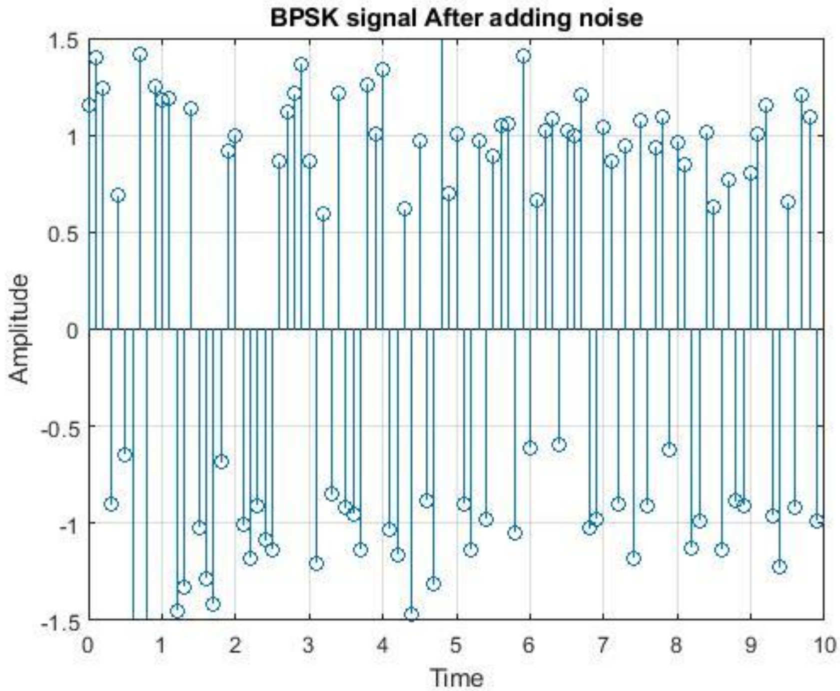


Figure 2.8 BPSK signal after adding noise.

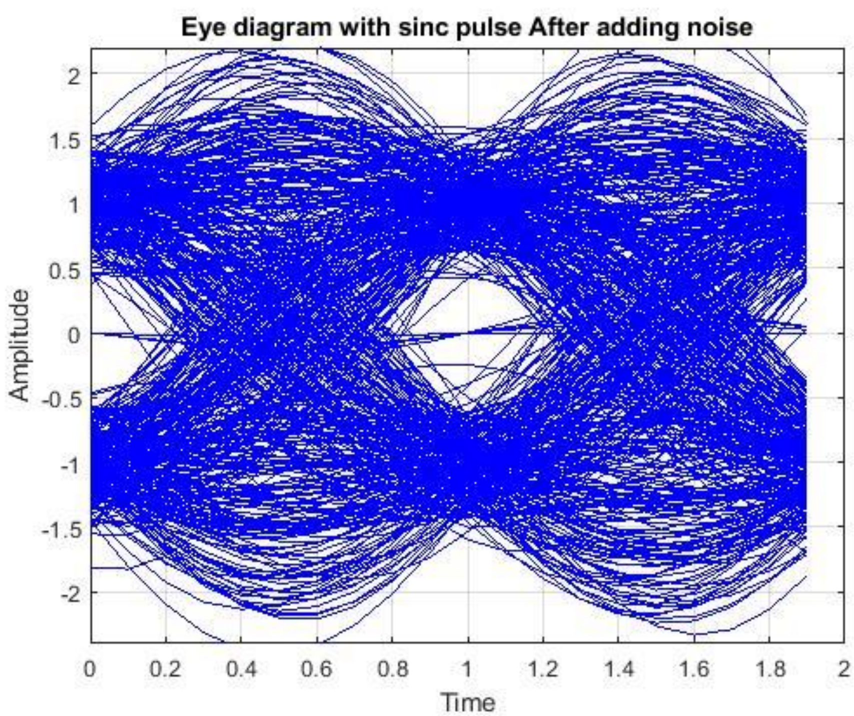


Figure 2.9 After adding noise eye diagram with sinc pulse

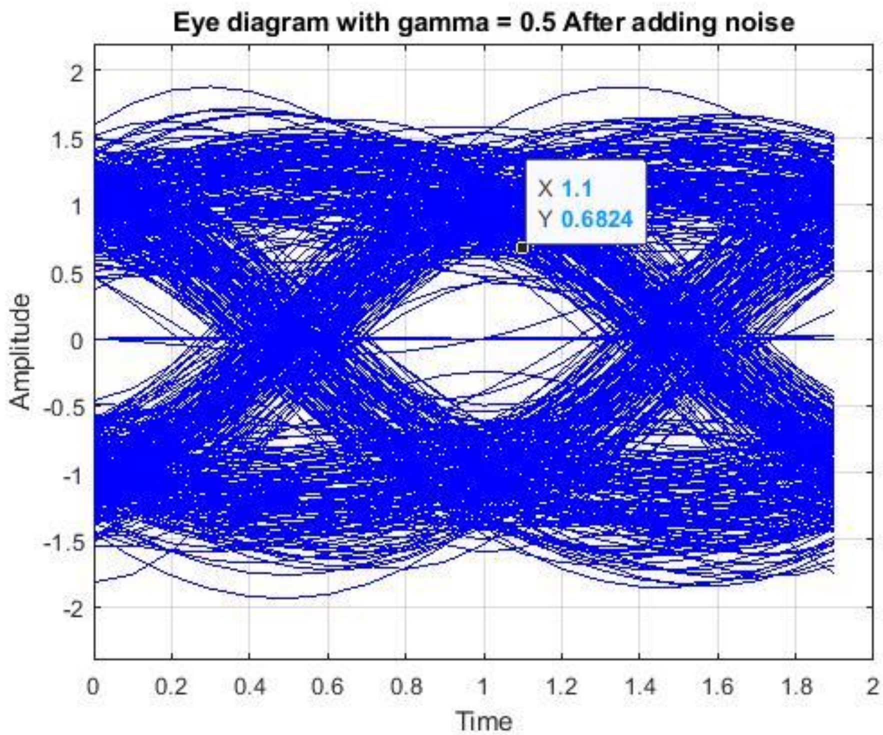


Figure 2.10 After adding noise eye diagram with rof = 0.5

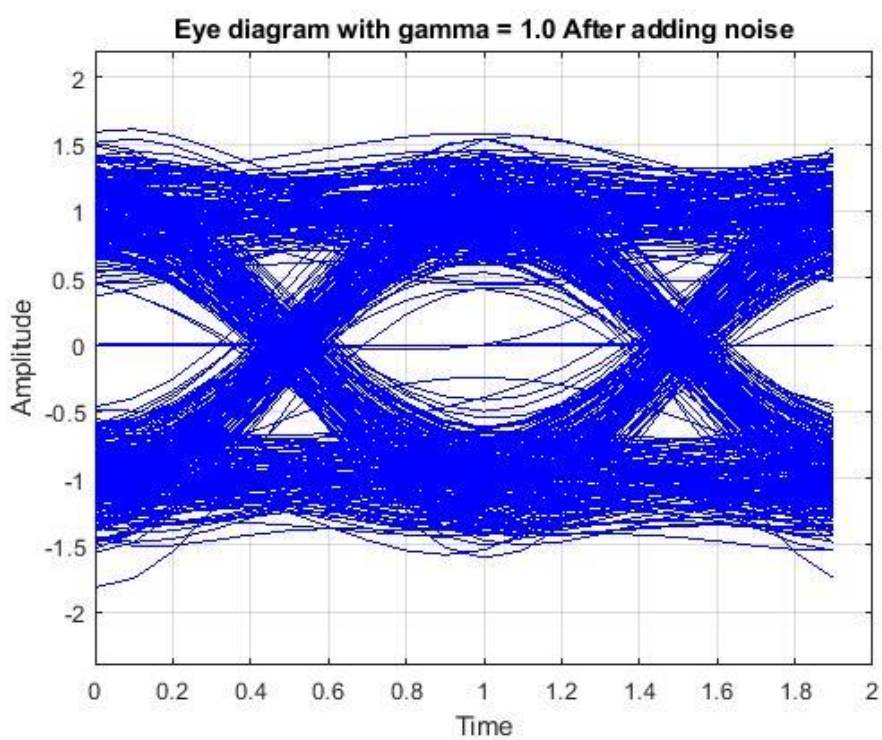


Figure 2.11 After adding noise eye diagram with rof = 1

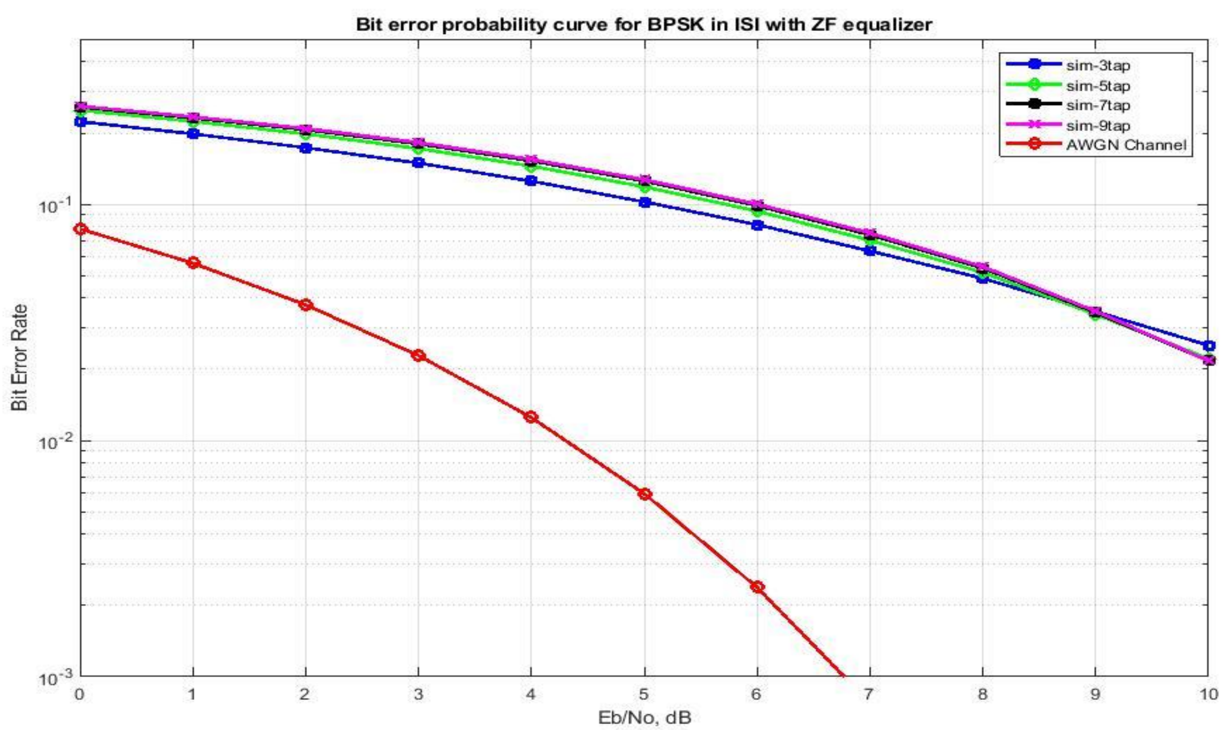
5.Compare the robustness of the system with respect to noise, sampling tine and synchronization errors.

Characteristic of the Eye diagram	Information	Sinc Pulse	Raised Cosine Pulse (Roll-off = 0.5)	Raised Cosine Pulse (Roll-off = 1)
Eye Height	Noise margin or the signal's immunity to noise. A larger eye height indicates better noise immunity	The eye height has diminished further compared to when there was no noise present. This indicates a low Signal-to-Noise Ratio (SNR) at the sampling, resulting in a high occurrence of bit errors during sampling. The diminished height suggests a reduced margin for error-free signal detection, leading to increased vulnerability to noise interference and higher bit error rates.	The possibility of sampling errors has increased compared to the noise-free scenario, it is still better than the sinc pulse. This suggests a compromise between noise immunity and sampling errors compared to the sinc pulse.	This pulse shape exhibits better robustness to sampling errors compared to the other two under noisy conditions. The higher height, even in the presence of noise, indicates a relatively better margin for error-free signal detection and lower susceptibility to noise interference, resulting in a lower occurrence of bit errors during sampling.
Eye Width	The duration of time during which the received signal is error-free and is often associated with the intersymbol interference (ISI). A wider eye width suggests a longer error-free sampling region, which is desirable for accurate signal recovery.	The width has further reduced under the presence of noise. Almost all the region of the eye diagram is unsuitable for error-free sampling, indicating low robustness to sampling errors. The diminished width suggests limited opportunities for accurate signal detection, leading to increased susceptibility to errors during sampling.	he width has reduced due to the presence of noise, but there is still a considerable region available for error-free sampling. While it is more robust to sampling errors compared to the sinc pulse, it is not as robust as the raised cosine pulse with a roll-off factor of 1.0. Despite the reduction in width, there are still viable opportunities for reliable signal detection, albeit with a higher likelihood of	The width has reduced, but it still maintains an adequate width for error-free sampling. This pulse shape exhibits high robustness to sampling errors compared to the other two pulses. Despite the presence of noise, there are ample opportunities for accurate signal detection, with a lower likelihood of errors during

			errors compared to the noise-free scenario.	sampling compared to the others
Slope of the eye	The rate of change of the eye opening's edges. It is indicative of the timing accuracy or synchronization of the received signal. A steeper slope suggests a higher likelihood of synchronization errors.	It has a very high slope, indicating a rapid transition between signal states. This high slope increases the possibility of synchronization errors occurring due to the difficulty in accurately aligning sampling times with signal transitions.	It exhibits an average slope, falling between the very high slope of the sinc pulse and the low slope of the raised cosine pulse with a roll-off factor of 1. This moderate slope results in an average chance of synchronization errors, as the signal transitions are neither extremely rapid nor very gradual.	This type of pulse has a low slope, suggesting a slower transition between signal states. Consequently, there is a low possibility of synchronization error occurrence because the signal transitions are less abrupt and easier to synchronize with sampling times.
Thickness of the edge	the variation in timing at the points where the signal crosses zero amplitude. It provides insight into timing jitter, which refers to the deviation in the timing of signal transitions.	The jitter has further increased, indicating a higher variability in the timing of signal transitions. This pulse shape exhibits the lowest robustness to jitter or timing offsets, suggesting a higher susceptibility to timing errors and synchronization issues. The increased jitter amplifies the difficulty of accurately aligning sampling times with signal transitions, leading to a higher likelihood of errors in signal detection.	The jitter has increased compared to the noise-free scenario. However, the pulse shape demonstrates average robustness to jitter, indicating a moderate susceptibility to timing errors and synchronization issues. While there is an increased variability in the timing of signal transitions, the pulse shape offers a reasonable degree of stability in signal detection, mitigating the impact of timing offsets to some extent.	While there was no jitter present initially, some jitter is now visible. Despite this, it remains the lowest among the three pulse shapes, indicating better robustness to jitter. This pulse shape demonstrates improved stability in signal detection, with a lower susceptibility to timing errors and synchronization issues compared to the sinc and raised cosine pulses with a roll-off factor of 0.5.

Thickness at the peak	The deviation of the signal at its maximum amplitude.	The peak deviation is higher than in the noise-free case. Among the three cases, the sinc pulse has the highest peak deviation. This indicates significant fluctuations in the signal strength at its highest points, which can complicate accurate signal detection and contribute to errors in sampling.	Similar to the sinc pulse, the peak deviation is higher than in the noise-free case. However, compared to the other two cases, this pulse shape exhibits average peak deviation. There are noticeable fluctuations in signal strength at its highest points, albeit to a lesser extent than with the sinc pulse.	the peak deviation is higher than in the noise-free case. However, compared to the other two cases, this pulse shape has the lowest peak deviation. Although there are still fluctuations in signal strength at its highest points, they are comparatively less pronounced than others.

Task 3



11. Explain the discrepancy between the AWGN channel BER and the ZF equalized multipath channel:
    - In an AWGN channel, the noise is the only factor affecting the received signal. The BER performance in an AWGN channel can be accurately predicted by theoretical models, such as the Q-function.
    - However, in a multipath channel, in addition to noise, there are also distortions caused by the multipath propagation. These distortions can cause intersymbol interference (ISI), where symbols from adjacent time intervals interfere with each other, leading to errors in symbol detection.
    - The Zero-Forcing (ZF) equalizer aims to mitigate the effects of ISI by inversely filtering the received signal based on the known channel response. However, ZF equalization assumes perfect knowledge of the channel response, which may not be achievable in practice due to channel variations or estimation errors.
    - As a result, the ZF equalizer may not fully eliminate the effects of multipath distortion, leading to residual errors that contribute to a higher BER compared to an ideal AWGN channel.
12. Comment on the BER performance if binary orthogonal signaling was used instead of BPSK:
    - Binary orthogonal signaling schemes, such as OOK (On-Off Keying) or Walsh codes, have orthogonal properties that can help mitigate the effects of ISI in multipath channels.
    - Unlike BPSK, where symbols are represented by amplitude levels, binary orthogonal signaling uses orthogonal waveforms that are less susceptible to interference between symbols.
    - Therefore, if binary orthogonal signaling were used instead of BPSK, the BER performance in a multipath channel with ZF equalization may improve due to the reduced interference between symbols.
    - However, binary orthogonal signaling may also have drawbacks, such as lower spectral efficiency or higher complexity in modulation and demodulation, which need to be considered when comparing performance in practical scenarios.

Conclusion

Our study of pulse shaping filters, particularly sinc and raised cosine filters, highlighted their role in shaping communication system performance. Through the analysis of eye diagrams, we observed the trade-offs between noise immunity, sampling accuracy, and synchronization robustness. The raised cosine filter, especially with a roll-off factor of 1, emerged as a promising choice, exhibiting superior performance in maintaining signal integrity under challenging conditions. However, further exploration into advanced equalization techniques and modulation schemes remains crucial for optimizing system performance in real-world scenarios.

Appendix

Each task was completed using MATLAB R2022a.

Task1

```matlab
% Defining the system Parameters
BitCount = 10^3; % Number of Bits Transmitted
SamplingFrequency = 10; % Sampling frequency in Hz
SNR_dB = 10;
NoisePower = 1./(10.^(0.1*SNR_dB)); % Noise Power (Eb = 1 in BPSK)
time = -SamplingFrequency:1/SamplingFrequency:SamplingFrequency; % Time Array

%% Generating the BPSK Signal
% Mapping 0 -> -1 and 1 -> 1 (0 phase and 180 phase)
BPSK_Sig = 2*(rand(1,BitCount)>0.5)-1;
t = 0:1/SamplingFrequency:99/SamplingFrequency;
stem(t, BPSK_Sig(1:100)); xlabel('Time'); ylabel('Amplitude');
title('BPSK Impulse Train');
axis([0 10 -1.2 1.2]); grid on;

%% Upsampling the transmit sequence without noise
BPSK_Upsampled = [BPSK_Sig;zeros(SamplingFrequency-1,length(BPSK_Sig))]; % Upsampling the BPSK to match the sampling frequency
BPSK_U = BPSK_Upsampled(:).';
figure;
stem(t, BPSK_U(1:100)); xlabel('Time'); ylabel('Amplitude');
title('Upsampled BPSK Impulse Train');
axis([0 10 -1.2 1.2]); grid on;

%% sinc pulse shaping filter
Sinc_Num = sin(pi*time); % Numerator of the sinc function
Sinc_Den = (pi*time); % Denominator of the sinc function
Sinc_DenZero = find(abs(Sinc_Den) < 10^-10); % Finding the t=0 position
Sinc_Filt = Sinc_Num./Sinc_Den;
Sinc_Filt(Sinc_DenZero) = 1; % Defining the t=0 value
figure;
plot(time, Sinc_Filt);
title('Sinc Pulse shape');
xlabel('Time'); ylabel('Amplitude');
axis([-SamplingFrequency SamplingFrequency -0.5 1.2]); grid on

Conv_sinc_pulse = conv(BPSK_U, Sinc_Filt);
Conv_sinc_pulse = Conv_sinc_pulse(1:10000);
Conv_sinc_pulse_reshape = reshape(Conv_sinc_pulse, SamplingFrequency*2, BitCount*SamplingFrequency/20).';

transmit_signal_sinc = Conv_sinc_pulse(1,100:999);
tt=(-0.1:0.1:89.8);
plot(tt,transmit_signal_sinc);
title('Transmit signal with sinc pulse');

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figure;
plot(0:1/SamplingFrequency:1.99, real(Conv_sinc_pulse_reshape).', 'b');
title('Eye diagram with sinc pulse');
xlabel('Time'); ylabel('Amplitude');
axis([0 2 -2.4 2.2]);
grid on

%% Raised cosine pulse shaping filter (gamma = 0.5)
roll_off = 0.5;
cos_Num = cos(roll_off*pi*time);
cos_Den = (1 - (2 * roll_off * time).^2);
cos_DenZero = abs(cos_Den)<10^-10;
RaisedCosine = cos_Num./cos_Den;
RaisedCosine(cos_DenZero) = pi/4;
RC_gamma5 = Sinc_Filt.*RaisedCosine; % Getting the complete raised cosine pulse
figure;
plot(time, RC_gamma5);
title('Raised Cosine Pulse shape gamma = 0.5');
xlabel('Time'); ylabel('Amplitude');
axis([-SamplingFrequency SamplingFrequency -0.5 1.2]); grid on

Conv_RC_gamma5 = conv(BPSK_U,RC_gamma5);
Conv_RC_gamma5 = Conv_RC_gamma5(1:10000);
Conv_RC_gamma5_reshape = reshape(Conv_RC_gamma5,SamplingFrequency*2,BitCount*SamplingFrequency/20).';

transmit_signal_RC_gamma5 = Conv_RC_gamma5(1,100:999);
tt=(-0.1:0.1:89.8);
plot(tt,transmit_signal_RC_gamma5);
title('Transmit signal with gamma = 0.5');

figure;
plot(0:1/SamplingFrequency:1.99, Conv_RC_gamma5_reshape.','b');
title('Eye diagram with gamma = 0.5');
xlabel('Time'); ylabel('Amplitude');
axis([0 2 -2.5 2.5]);
grid on

%% Raised cosine pulse shaping filter (gamma = 1)
roll_off = 1;
cos_Num = cos(roll_off * pi * time);
cos_Den = (1-(2 * roll_off * time).^2);
cos_DenZero = find(abs(cos_Den)<10^-20);
RaisedCosine = cos_Num./cos_Den;
RaisedCosine(cos_DenZero) = pi/4;
```

```
RC_gamma1 = Sinc_Filt.*RaisedCosine; % Getting the complete raised cosine pulse
figure;
plot(time, RC_gamma1);
title('Raised Cosine Pulse shape gamma = 1');
xlabel('Time'); ylabel('Amplitude');
axis([-SamplingFrequency SamplingFrequency -0.5 1.2]); grid on

Conv_RC_gamma1 = conv(BPSK_U,RC_gamma1);
Conv_RC_gamma1 = Conv_RC_gamma1(1:10000);
Conv_RC_gamma1_reshape = reshape(Conv_RC_gamma1,SamplingFrequency*2,BitCount*SamplingFrequency/20).';

transmit_signal_RC_gamma1 = Conv_RC_gamma1(1,100:999);
tt=(-0.1:0.1:89.8);
plot(tt,transmit_signal_RC_gamma1);
title('Transmit signal with gamma = 1');

figure;
plot(0:1/SamplingFrequency:1.99, Conv_RC_gamma1_reshape.','b');
title('Eye diagram with gamma = 1');
xlabel('Time'); ylabel('Amplitude');
axis([0 2 -1.5 1.5 ]);
grid on
```

Task 2

```
%% Noise Array Generation based on SNR = 10dB
Noise1D = normrnd (0 , sqrt(NoisePower/2), [1, BitCount]);
AWGN_TX = BPSK_Sig + Noise1D;
figure;
stem(t, AWGN_TX(1:100)); xlabel('Time'); ylabel('Amplitude');
title('BPSK signal After adding noise');
axis([0 10 -1.5 1.5]); grid on;


%% upsampling the transmit sequence with Noise
AWGNTx_Upsample = [AWGN_TX;zeros(SamplingFrequency-1,length(BPSK_Sig))];
AWGNTx_U = AWGNTx_Upsample(:);
figure;
stem(t, AWGNTx_U(1:100)); xlabel('Time'); ylabel('Amplitude');
title('Upsampled BPSK After adding noise');
axis([0 10 -1.5 1.5]); grid on;

%% sinc with noise
Conv_sinc_noise = conv(AWGNTx_U,Sinc_Filt);
Conv_sinc_noise = Conv_sinc_noise(1:10000);
Conv_sinc_noise_reshape = reshape(Conv_sinc_noise, SamplingFrequency*2, BitCount*SamplingFrequency/20).';
figure;
plot(0:1/SamplingFrequency:1.99, Conv_sinc_noise_reshape.', 'b');
title('Eye diagram with sinc pulse After adding noise');
xlabel('Time'); ylabel('Amplitude');
axis([0 2 -2.4 2.2]);
grid on

%% raised cosine with noise (gamma = 0.5)
Conv_RC5_noise = conv(AWGNTx_U,RC_gamma5);
Conv_RC5_noise = Conv_RC5_noise(1:10000);
Conv_RC5_noise_reshape = reshape(Conv_RC5_noise,SamplingFrequency*2,BitCount*SamplingFrequency/20).';
figure;
plot(0:1/SamplingFrequency:1.99, Conv_RC5_noise_reshape.', 'b');
title('Eye diagram with gamma = 0.5 After adding noise');
xlabel('Time'); ylabel('Amplitude');
axis([0 2 -2.4 2.2]);
grid on

%% raised cosine with noise (gamma = 1)
Conv_R1_noise = conv(AWGNTx_U,RC_gamma1);
Conv_R1_noise = Conv_R1_noise(1:10000);
Conv_R1_noise_reshape = reshape(Conv_R1_noise,SamplingFrequency*2,BitCount*SamplingFrequency/20).';
figure;
```

```
%% raised cosine with noise (gamma = 1)
Conv_R1_noise = conv(AWGNTx_U,RC_gamma1);
Conv_R1_noise = Conv_R1_noise(1:10000);
Conv_R1_noise_reshape = reshape(Conv_R1_noise,SamplingFrequency*2,BitCount*SamplingFrequency/20).';
figure;
plot(0:1/SamplingFrequency:1.99, Conv_R1_noise_reshape.', 'b');
title('Eye diagram with gamma = 1.0 After adding noise');
xlabel('Time'); ylabel('Amplitude');
axis([0 2 -2.4 2.2]);
grid on
```

Task3

```
%Task 3: Designing a zero-forcing (ZF) equalizer for a 3-tap multipath channel

seqLen = 10^6; % Length of the binary sequence
ebN0dBVals = 0:10; % multiple Eb/N0 values
numTaps = 4;
errCounts = zeros(numTaps, length(ebN0dBVals)); % Initialize error count

for idx_ebN0 = 1:length(ebN0dBVals)

    % Transmitter
    inputSeq = rand(1, seqLen) > 0.5; % Generating a random binary sequence
    modSignal = 2 * inputSeq - 1; % BPSK modulation 0 -> -1; 1 -> +1

    % Channel model, multipath channel
    numPaths = 3;
    channelResp = [0.3 0.9 0.4];

    channelOut = conv(modSignal, channelResp);
    noiseVec = 1/sqrt(2) * [randn(1, seqLen + length(channelResp) - 1) + 1j * randn(1, seqLen + length(channelResp) - 1)]; % White Gaussian noise, 0dB variance

    % Noise addition
    receivedSignal = channelOut + 10^(-ebN0dBVals(idx_ebN0) / 20) * noiseVec; % Additive white Gaussian noise

    for idx_tap = 1:numTaps
        respLen = length(channelResp);
        hMat = toeplitz([channelResp(2:end), zeros(1, 2 * idx_tap + 1 - respLen + 1)], [channelResp(2:-1:1), zeros(1, 2 * idx_tap + 1 - respLen + 1)]);

        diracSeq = zeros(1, 2 * idx_tap + 1);
        diracSeq(idx_tap + 1) = 1;

        coeff = inv(hMat) * diracSeq.';

        % Matched filter
        filtSignal = conv(receivedSignal, coeff);
        filtSignal = filtSignal(idx_tap + 2:end);
        filtSignal = conv(filtSignal, ones(1, 1)); % Convolution
        sampledSig = filtSignal(1:1:seqLen); % Sampling at time T

        % Receiver - hard decision decoding
        decodedSeq = real(sampledSig) > 0;

        % Counting the errors
        errCounts(idx_tap, idx_ebN0) = sum(inputSeq ~= decodedSeq);
    end
end
```

```
simBER = errCounts / seqLen; % Simulated BER
theoryBER = 0.5 * erfc(sqrt(10.^(ebN0dBVals / 10))); % Theoretical BER

% Plot
close all
figure
semilogy(ebN0dBVals, simBER(1,:), 'bs-', 'Linewidth',2);
hold on
semilogy(ebN0dBVals, simBER(2,:), 'gd-', 'Linewidth',2);
semilogy(ebN0dBVals, simBER(3,:), 'ks-', 'Linewidth',2);
semilogy(ebN0dBVals, simBER(4,:), 'mx-', 'Linewidth',2);
semilogy(ebN0dBVals, theoryBER, 'ro-', 'Linewidth',2);
axis([0 10 10^-3 0.5])
grid on

%legend('sim-3tap', 'sim-5tap', 'sim-7tap', 'sim-9tap');
legend('sim-3tap', 'sim-5tap', 'sim-7tap', 'sim-9tap','AWGN Channel');
xlabel('Eb/No, dB');
ylabel('Bit Error Rate');
title('Bit error probability curve for BPSK in ISI with ZF equalizer');
```