Department of Electrical and Computer Systems Engineering
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Information and Networks, ECE3141

Lab 7: Pulse shaping and Eye diagrams

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1. Introduction

Transmission of digital data over a limited bandwidth transmission medium introduces distortion in the received signals. The result of data transmission over such channels is that each received pulse is affected by adjacent pulses, thereby giving rise to a common form of interference called *intersymbol interference* (ISI). You observed distortion of rectangular shaped pulses by limiting the bandwidth in lab 6, and observed how they get smoothed out and blur into one another. ISI can be a major source for bit errors. To minimise ISI, we want to control the pulse shape that we get after the transmitter filter, receiver filter and channel response are taken into account.

In addition, the received signals are impaired by noise and interference in telecommunication channels. Channel noise is another source of bit errors which arises in the transmission. A proper understanding of pulse shaping and channel noise is crucial to the performance analysis of a telecommunication system. Eye diagrams are frequently used in evaluating the combined effects of ISI and channel noise. Eye diagrams are obtained by synchronised superposition of all possible realisations of the signal of interest viewed within a particular signalling interval[1].

In this laboratory class, you will carry out the following as you investigate pulse shaping and noise in a digital communication system:

- Become familiar with signal processing blocks in a digital communication system.
- Understand a simple modulation scheme known as binary phase shift keying.
- Understand the pulse shaping types by visualising the impulse and frequency responses of pulses.
- Understand how to plot eye diagrams for a chosen pulse shape and interpret the information conveyed from the plots.
- Use scatterplots to understand the effect of channel noise.
- Evaluate the sensitivity of different pulse shapes to timing errors using eye diagrams and bit error rates.

[1] This sounds a bit complicated, but all it means is that we take all possible pulse shapes (including noisy ones) and look at them all superimposed over the top of one another. This allows us to see, for instance, the range of values that the pulses might take on as a result of noise, which we cannot see by looking at pulses in isolation.

2. Pre-lab

Prior to the laboratory class, you must read through this entire laboratory description and complete the pre-lab online quiz.

Make sure you are up to date with lectures, particularly those regarding transmission pulse shapes and the concept and value of eye diagrams. These are included in the week 10 lecture material.

You should also consider each exercise given, and familiarise yourself with the Matlab scripts that perform the required functions.

3. Digital Communication System

A generic digital communication system is illustrated in the block diagram of Figure 1.While some digital communication systems (such as wired Ethernet) apply digital pulses directly to the cable (i.e. they are baseband transmission systems), it is most common to carry the digital information by "modulating" a continuous-time sinusoidal waveform radio frequency (RF) carrier. Digital information is "keyed" or modulated onto the phase, frequency, and/or amplitude of the RF carrier. In its original form, digital data has steep transitions (e.g. from the "0" voltage to the "1" voltage or vice-versa) which need to be smoothed to transmit it over a band-limited radio channel. You saw in lab 6 that much of the signal energy may be removed when a sharp rectangular pulse passes through a bandlimited system. Pulse shaping is accomplished with the right choice of lowpass filters at the transmitter. These filters play an important role in transmission as they can be configured to suit time and frequency domain characteristics of the medium.

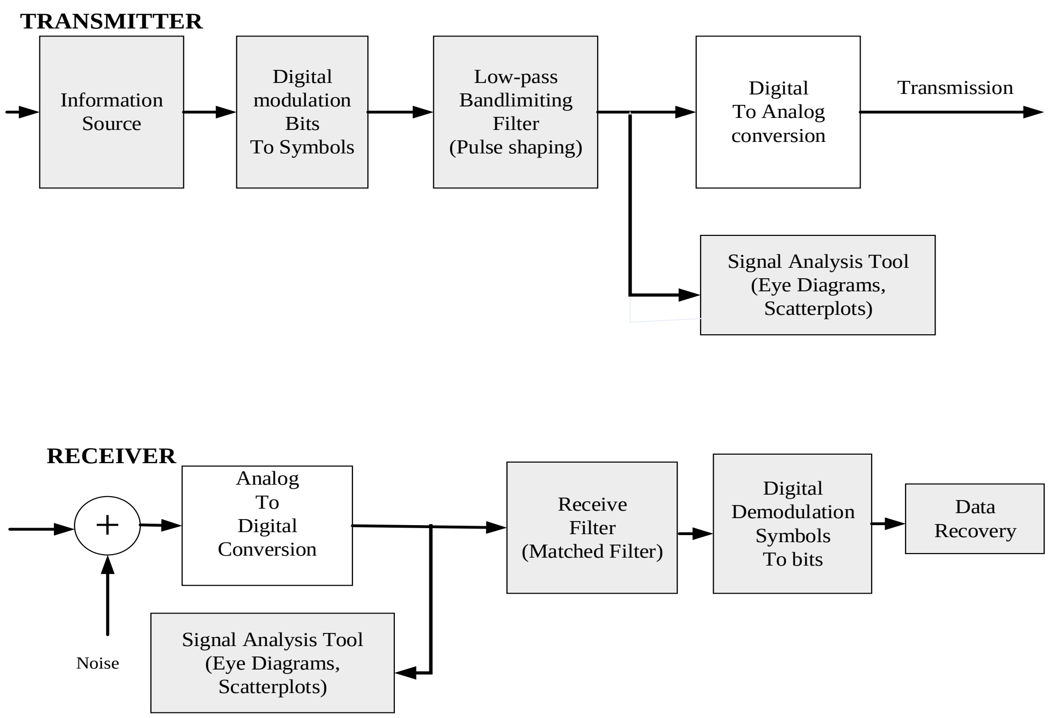


Figure 1. Block diagram of a generic Digital Communication system

The signal that is actually carried on the transmission medium is an analogue signal consisting of a series of carefully designed pulses, each representing a bit, or multiple bits, of digital data. The shape of each pulse is dictated by the characteristics of the band limiting filter. Conceptually, we can think of the filtering functions as actual blocks of analogue circuitry, and in earlier days and with simpler modulation schemes, the modulation, filtering and demodulation would have been implemented this way (so the D/A and A/D blocks would not be present). However, these days it is simpler, easier and more flexible to do all these operations in the digital domain, and only convert to analogue form for the actual transmission.

Referring to Figure 1, digital information source bits pass through a digital modulator where individual bit sequences are mapped onto a unique point in the symbol set (examples are discussed in Section 3.1 below). These discrete symbols acquire a pulse shape after passing through the low-pass filter before digital-to-analogue conversion and transmission over the noisy propagation medium. At the receiver, after analogue-to-digital conversion, the signal passes through a low-pass filter with characteristics matched to those of the transmitter filter. The output of the receiver filter is sent to a demodulator for data recovery from symbols.

"Matched" filters?

We talk of a receiver filter that is "matched" to that at the transmitter, but what does this mean and why is it important? When we demodulate the received signal at the receiver, we want to keep as much energy from each transmitted pulse as we can to help us make the decision about what pulse was most likely to have been transmitted. But at the same time, we want to filter out as much as possible anything else (specifically, noise) that might affect that decision. Hence the two filters (at transmitter and receiver) should be "matched". However, we will see later that "matched" does not mean "identical".

3.1 Binary phase shift keying (BPSK)

In carrier **phase** modulation (or "Phase Shift Keying", PSK), the information that is transmitted over a communication channel is impressed on the phase of the carrier[2]. If we want to distinguish between M possible symbols, and since the range of the carrier phase is $0 \le \theta \le 2\pi$, then the carrier phases used to transmit digital information via phase modulation are[3] $\theta_m = 2\pi m / M$, for $m = 0, 1, 2, \ldots, M-1$. For phase modulation, the general representation of a set of M carrier-modulated signal waveforms is

$$s_m(t) = Ag(t)\cos(2\pi f_c t + \frac{2\pi m}{M}) \tag{1}$$

If $M = 2$ then each transmitted symbol has one of two possible phases. A waveform can be used to carry more than one information bit, though. For instance, if we set M=8, then the choice of m will indicate which of 8 possible phases is defined, and this could represent which of 8 3-tuple bit patterns (000, 001, 010,… , 111) is communicated with each pulse. These higher order modulation schemes will be discussed in the next lab.

In Eq. (1), the time function *g(t)* defines the shape of the pulse that is used to carry information data and *A* is the signal amplitude. In PSK, *A* and *g(t)* are the same for each pulse

[2] Remember that we could modulate other characteristics of the carrier signal, which is defined by its amplitude, frequency and phase.

[3] This is just a mathematical way of saying that we choose phases for our signalling that are as far apart as possible in the 2π phase range. We are distributing the carrier phases that represent symbols, so they are distributed evenly around the circle, for example 0 and π for the case of M=2, or 0, $\pi/2$, π, $3\pi/2$ for M=4, etc.

(only *m* changes according to the data to be communicated), so the magnitude of each pulse is the same (only the phase changes). Therefore PSK signal pulses have equal energy[4].

In this lab, we consider the $M = 2$ digital modulation scheme called *binary phase shift keying* (BPSK), with two points in the symbol set. In this case, there are only two unique signal waveforms that carry information bits and, of course, only one data bit can be carried with each pulse. The two waveforms are

$$\begin{aligned} s_1(t) &= Ag(t)\cos(2\pi f_c t) \\ s_2(t) &= Ag(t)\cos(2\pi f_c t + \pi) \end{aligned} \tag{2}$$

The signal space diagram is a type of phasor diagram that shows the transmitted or received signals relative to a reference sinusoid, and it is shown for a BPSK modulator in ***Figure 2***. Since we only have 0° and 180° relative phase, the diagram is effectively one-dimensional. If other phases were transmitted, then they would be distributed on a circle. Only two possible signal phases are transmitted[5], but signal attenuation, distortion and noise will mean that a range of possible values might be received[6]. Our task at the receiver is to decide (hopefully correctly) whether each received symbol belongs to Region 1 or Region 2.

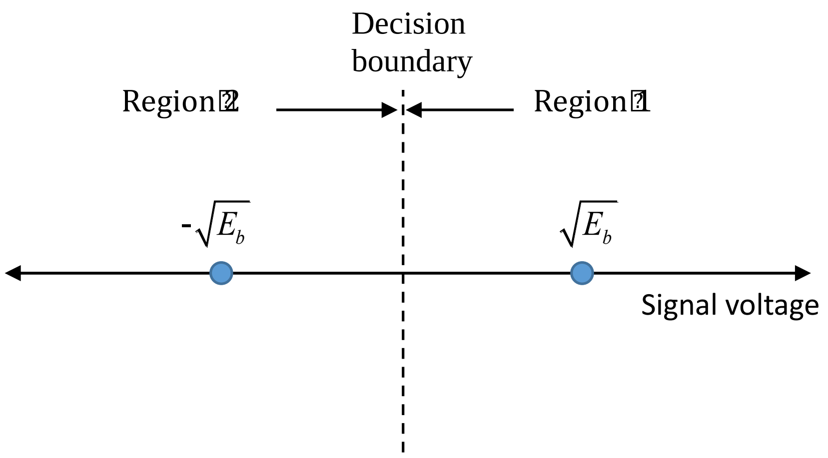


Figure 2. Signal space diagram (scatter plot) of a BPSK modulation

Confused by what is digital and what is analogue?

At the level of transmission of a signal over a communications medium, we are concerned with band limiting effects, additive noise and interference, and our objective at the receiver is to try to extract or deduce what the original signal was. Even if we transmit one of a discrete set of possible signal shapes, by the time it arrives at the receiver it will have been attenuated and distorted, and will have noise and interference added to it. It is no longer one of a discrete set of signals, but our job is to interpret this noisy, distorted signal to determine what was most likely sent. This is necessarily an analogue process; we're concerned with actual voltage levels and pulse shapes.

The signal that is used to modulate the transmission carrier could be either analogue or digital (by "digital", we mean one of a discrete set of possible levels, representing one or more binary digits). If it is analogue, then a continuously varying message signal determines

[4] Contrast this with, for example, a multi-level ASK system, in which different symbols are represented by different amplitudes.
[5] We accumulate as much of the energy in the pulse as we can to determine whether the original signal had 0° or 180° phase shift. What is labelled as "signal voltage" is actually based on the energy per bit. The term $\sqrt{E_b}$ will be discussed in lectures.
[6] As a result, the received points would be "scattered" a little bit away from the original transmitted point. For this reason, we also call these diagrams "scatter plots". The cloud of scattered points would have a range of phases near, but not exactly the same as the transmitted signal, and so would move out to occupy more of the two-dimensional phase diagram.

the amplitude, frequency or phase of the carrier at each instant. Common AM (Amplitude Modulation) radio is an example. If, instead, we use a digital code to dictate which of a discrete set of pulses is used to modulate the signal, then we have digital modulation (even though we still have to concern ourselves with analogue signal levels when we detect it, as noted above). So, if it was the amplitude we vary in a digital modulation system, it becomes Amplitude Shift Keying (ASK) to distinguish it from the analogue case of "AM".

Then we come to the actual implementation of the filtering, modulation and demodulation. Whether the modulation is digital or analogue, these functions are most easily implemented today in digital form. That is, the signals or pulses are sampled and the operations carried out using digital signal processing because it can be done so much more simply and flexibly. It just means that we need to convert to analogue voltages for transmission (the D/A block in Figure 1) and convert back to digital as soon as we can at the receiver (the A/D block).

3.2 Pulse Shaping

The choice of *g(t)* in Eq (1) will have a big impact on the amount of energy available at the receiver to determine which of the points on the constellation our pulse belongs to. Our first reaction might be to use a rectangular pulse – maximising the amplitude of the carrier throughout the pulse width. While a signal that is made up of rectangular pulses is neatly limited in the time domain, the sharp rising and falling edges cause high out-of-band[7] emissions in the frequency domain. This is demonstrated in the spectral magnitude response of ***Figure 3*** (a one-sided version of the sort of plot you observed in Lab 6). The magnitude response is plotted against normalised frequency. For a rectangular pulse of width T seconds, multiply the x-axis by 1/T to get the scale in Hz.

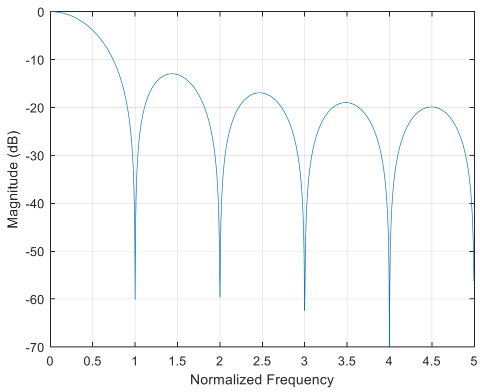


Figure 3. Magnitude response of a rectangular pulse

As can be seen in the Figure, spectral leakage outside the signal bandwidth (which we're defining as the first zero, which is at normalised frequency = 1) is very high, which would cause significant interference in adjacent frequency bands if we didn't filter it out. However, when we pass a rectangular pulse through a bandlimited channel, a lot of the available energy is filtered out, and we are left with just the low frequency components; the pulse spreads out in time causing ISI (Inter-Symbol Interference)[8], as you observed in Lab 6.

[7] OOB, or Out-Of-Band, emissions are the high frequency components that are beyond the bandwidth that we have been allocated to transmit in. If we don't remove them, they could interfere with someone else's transmission in an adjacent frequency band.
[8] What started as a square pulse will be smoothed out by the filter, becoming a much wider pulse with smooth rise and fall. If the pulses are close together (as they will be if we are trying to maximise the bit rate), then adjacent pulses will merge and overlap with one another, causing this "Inter-Symbol Interference".

We therefore conclude that the rectangular pulse shape is not practical for use in band-limited applications. A more practical pulse shaping filter that has been used in (amongst others) mobile communication systems is the raised cosine (RC) pulse shape which has been discussed in lectures. A RC pulse shape is known to have many useful characteristics making it an attractive alternative to the rectangular pulse shape. In ***Figure 4,*** the impulse and magnitude responses of RC pulse shapes for different values of the roll-off factor α are plotted on a normalised scale, so that T_b=1, and B=1/2T_b=0.5.

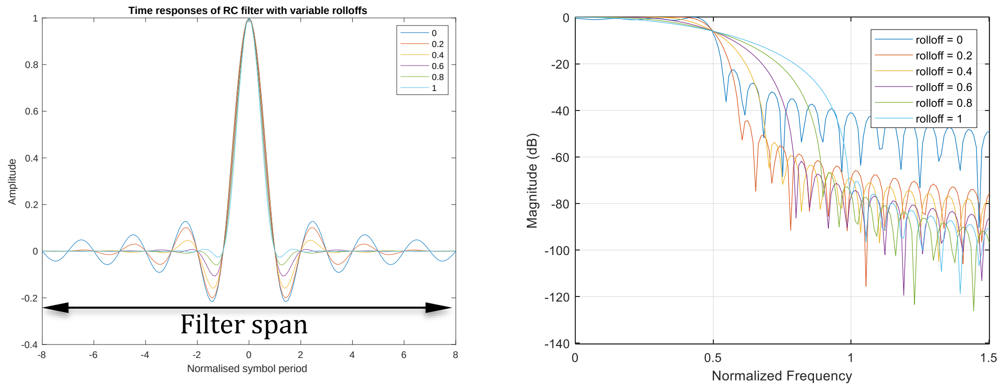


Figure 4. Impulse response (left) and spectral magnitude response (right) of an RC filter

We first observe from the time domain plot that the duration of an RC pulse is longer than one symbol period. This duration can be very long, extending for a number of symbol periods. In practice, this filter duration is limited to a finite number of periods[9] and referred to as the *filter span*. The second observation is that the RC pulse has smoother rising and falling edges compared to a rectangular pulse. These smooth transitions result in lower out of band (OOB) spectral emissions compared to a rectangular time domain pulse. For the RC pulse, the important parameter that exercises control over the time and frequency domain characteristics of the pulse is the roll-off factor α. The roll-off factor defines the amount of excess bandwidth occupied by a certain pulse shape and hence determines the transition band between the passband and the stop band of the magnitude response. The time domain characteristic or the impulse response of an RC pulse is given by

$$g_{rc} = \frac{\sin\left(\frac{\pi t}{T_b}\right)}{\left(\frac{\pi t}{T_b}\right)} \left(\frac{\cos\left(\frac{\pi t}{T_b}\right)}{1-\left(\frac{2\alpha t}{T_b}\right)^2} \right) \tag{3}$$

Note that the RC pulse is the product of an even function (within the large brackets) and a Sinc pulse (which is known to be an ideal Nyquist pulse). It can be shown from Nyquist pulse shaping theory that the RC pulse also satisfies the zero-ISI Nyquist criterion; that is, it has periodic zero values at integer multiples of T_b. The frequency response of an RC pulse is given by

[9] There are two reasons for this. First, we obviously can't implement an infinite-duration pulse in a practical system. But also, because the system is causal (we can't output any part of a pulse before the input to define which pulse it is has arrived!), then the more periods we try to include, the more delay we will be building into the system.

$$G_{rc}(f)=\begin{cases} T_b, & 0\le |f|\le \dfrac{1-\alpha}{2T_b}\ \text{(passband)} \\ \dfrac{T}{2}\left[1+\cos\left(\dfrac{\pi T_b}{\alpha}\left[|f|-\dfrac{1-\alpha}{2T_b}\right]\right)\right], & \dfrac{1-\alpha}{2T}\le |f|\le \dfrac{1+\alpha}{2T_b}\text{(transitionband)} \\ 0 & |f|>\dfrac{1+\alpha}{2T_b}\text{(out of band)} \end{cases} \tag{4}$$

Note that this is the frequency response for an ideal, infinite-extent RC pulse. (Our Matlab calculations do not, obviously, cover infinite time and so, while the OOB frequency components are small, they are not zero.) The absolute lowpass bandwidth B (that is, all energy is contained in frequencies less than this) is given by

$$B=\frac{1+\alpha}{2T_b} \tag{5}$$

We can represent (5) on a normalised scale for signal analysis that is independent of the data rate, and this is used in the frequency response plot in **Figure 4.** As can be seen from Eq (5), the occupied signal bandwidth increases as α increases. Even though a small value for α can minimise the occupied signal bandwidth, we can't simply choose any value for it as we will see later that there is a time-frequency trade-off involved here. The correct pulse shape for a system depends on the application.

3.3 Eye Diagram

As introduced in lectures, eye diagrams are obtained by synchronised superposition of all possible realisations of the signal of interest viewed within a particular signalling interval. That is, we overlay all the possible (or measured) symbol shapes over the top of one another. Eye diagrams are often used in signal analysis to understand robustness of the pulse-shaped signal to channel impairments and noise. The eye diagram derives its name from the fact that it resembles a human eye for binary waves[10]. An eye diagram provides a great deal of useful information about the performance of a data transmission system as shown in Figure 5 below.

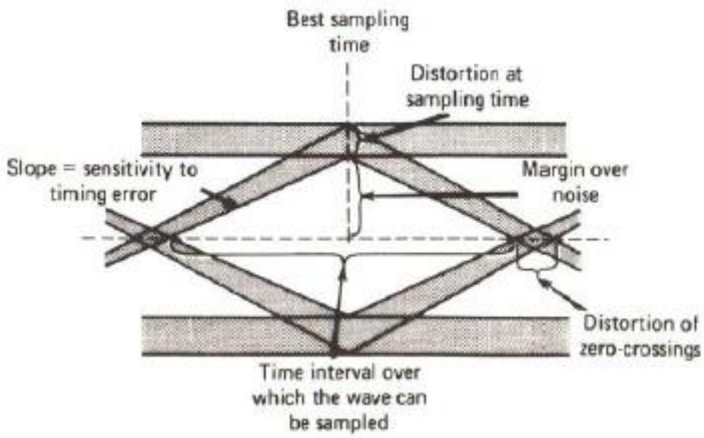


Figure 5 Interpretation of the eye diagram

Specifically, we understand the following

[10] You will see in lectures that we are not restricted to transmission using just two binary levels, if we use more levels, then the eye diagram looks like multiple eyes stacked on top of one another. We will explore such eye diagrams in the next lab.

- The width of the eye opening defines the time interval over which the received signal can be sampled without error from ISI. It is intuitive that the preferred time for sampling is the instant of time at which the eye is open the widest.
- Sensitivity of the system to timing errors is determined by the slope of the eye as the sampling time is varied.
- The height of the eye opening specifies the *noise margin* of the system
- Pulses with more distortion of zero-crossings imply susceptibility to synchronisation errors.

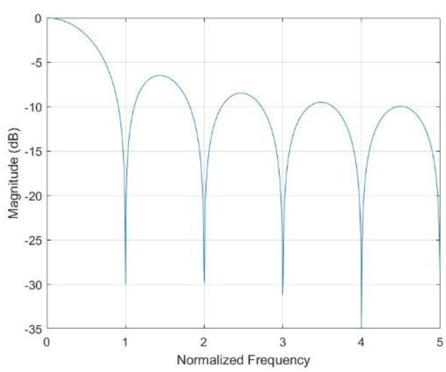
Exercises

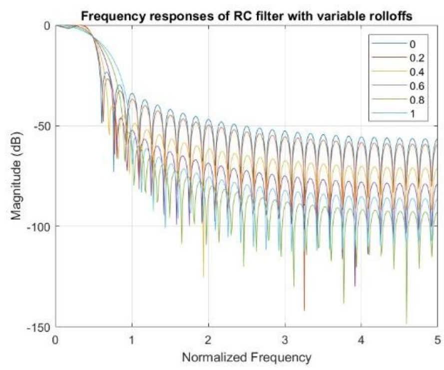
Download Matlab zipped folder named lab 7, unzip and save it in your working directory.

4. Pulse shaping filter responses

In this experiment, you will compare time and frequency domain properties of the rectangular and RC pulse shaping filters. Use files *Rectangular_freq.m* and *RC_freq.m* to complete questions below.

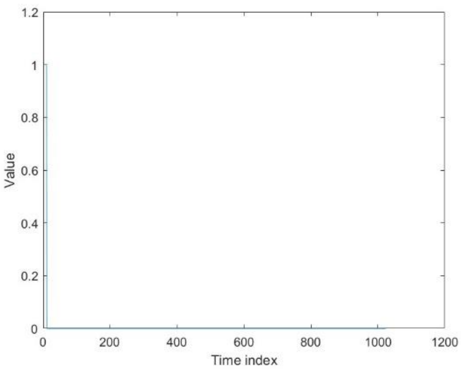
a) Open Matlab file (m-file) *Rectangular_freq.m* and run it. Inspect the m-file containing raised cosine pulse shaping filter design *RC_freq.m* and run it. Two figures are generated by each of these scripts, one in the time domain and the other in the frequency domain. Compare the frequency response of the rectangular pulse shape with that of the RC pulse. Which of the two exhibits higher OOB emissions? What is the reason for higher OOB emissions for this pulse?

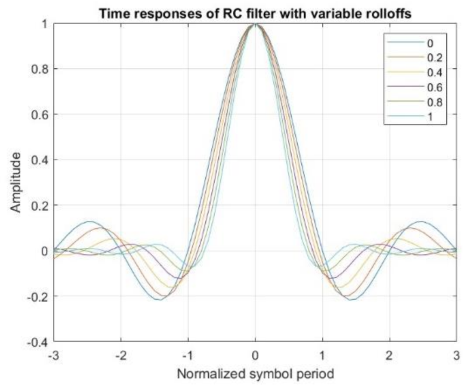




The rectangular pulse will exhibit higher OOB (Out of Band) emissions. This is because the RC pulse has smoother rising and falling edges compared to a rectangular pulse. The rectangular pulse is more limited in the time domain and the RC pulse is less limited in the time domain. This means that the RC pulse has a more limited bandwidth

b) Look at the time response plot generated by RC_freq.m. What effect does the increase in roll off factor (which is the parameter that controls the occupied bandwidth in the frequency domain) have on the time domain pulse shape?





The increase in roll off factor would decrease the amplitude and period on the time domain pulse shape. The increase in roll off factor would also reduce the bounds on the time domain for the signal which would increase the bandwidth of the frequency response of the filter.

c) What is the effect of increasing the roll off factor α on the frequency response in the passband $0 \leq |f| \leq \frac{(1-\alpha)}{2T_b}$, transition band, $\frac{(1-\alpha)}{2T_b} \leq |f| \leq \frac{(1+\alpha)}{2T_b}$ and the OOB $|f| \geq \frac{(1+\alpha)}{2T_b}$?

The effect of increasing the roll off factor on the frequency response in the passband is that it will make the frequency response resemble a square pulse. The range of the passband will decrease, and the range of the transition band will increase. The OOB range will decrease.

d) A certain design specification requires OOB emissions below -60dB outside normalised frequency equal to 1. Recommend a roll-off factor for an RC filter that meets the design specification with the filter span of 14. (Your recommendation should aim to minimise the value for roll-off and hence the occupied bandwidth. That is, we don't just want ANY value of α that will satisfy the design requirement; we want the smallest value that will.)

The roll-off factor for an RC filter that meets the design specification with the filter span of 14 is 0.2.

e) Can you meet the design specification of (d) with a shorter filter span equal to 6? (You will see that the roll-factor that met the design specification shows higher OOB emissions when the filterspan is reduced.) Write the roll-off factor that satisfies this specification.

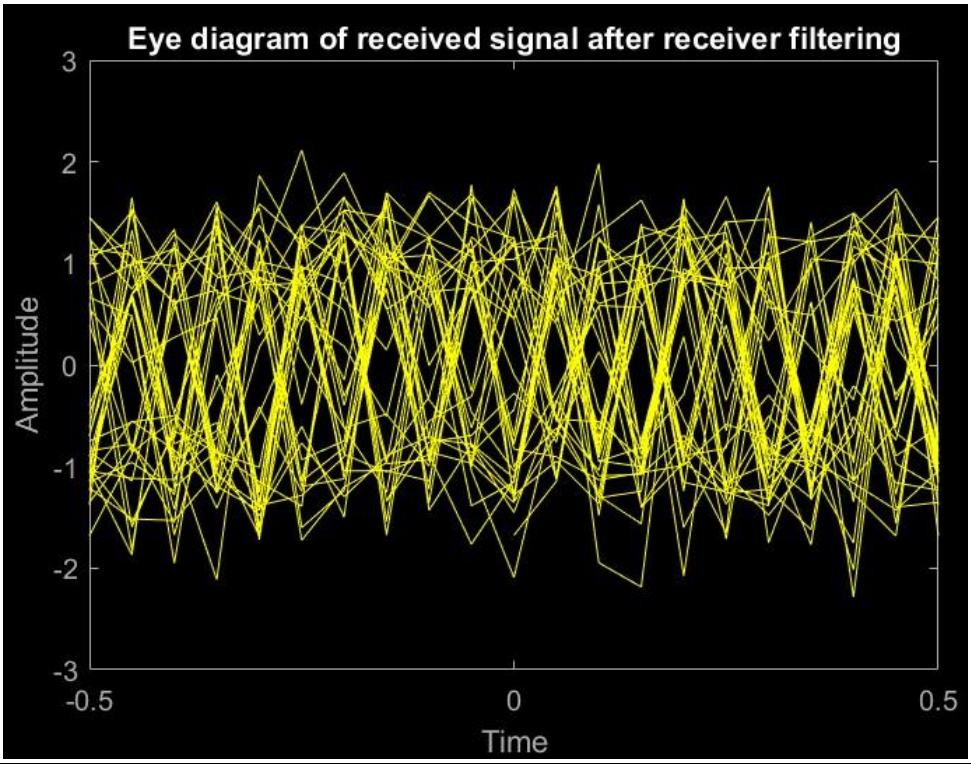
Yes, the design specification of (d) with a shorter filter span equal to 6 can be met. This roll off factor would be 0.8.

5. Eye diagrams

Open "Eyediagrams_bpsk.m" and use it to complete questions below.

a) Edit the line in the m-file to input a SNR equal to 5 dB. Copy the eye diagram of the receiver signal below and note the resulting bit error rate (BER) displayed in the command window.

Receiver eye diagram at 5 dB SNR:

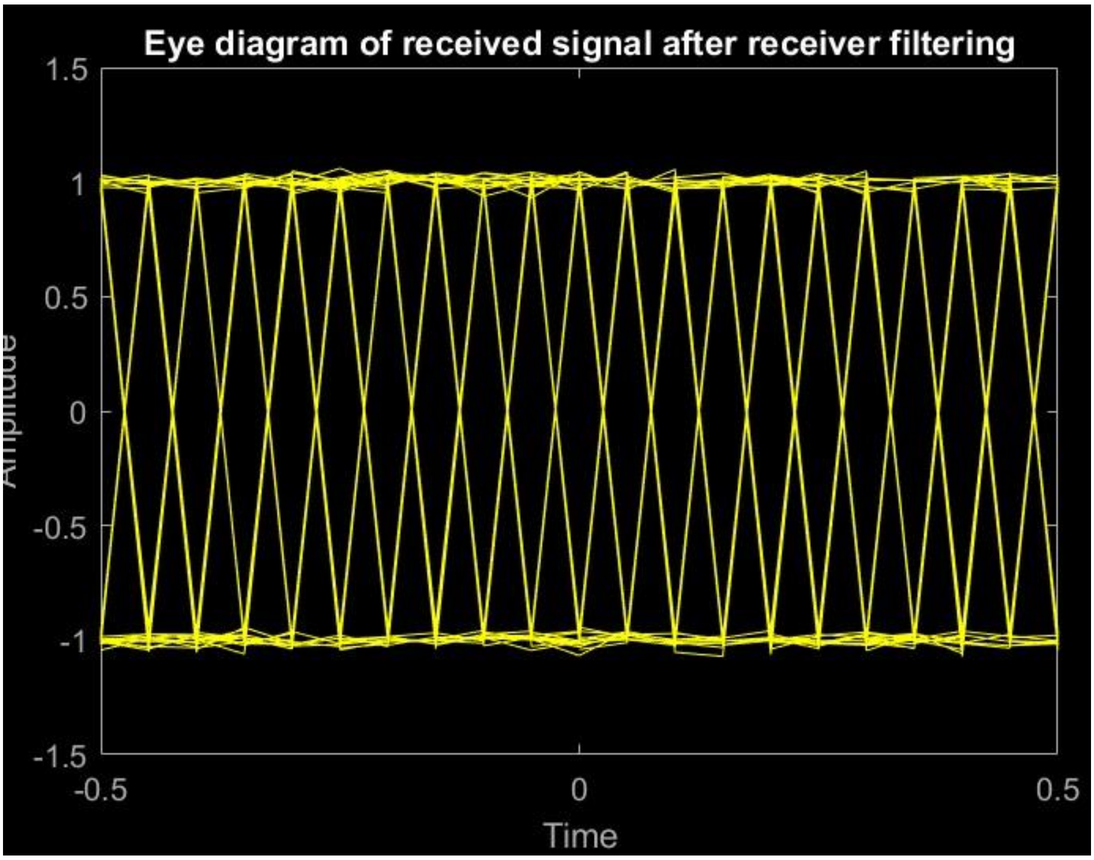


BER for SNR = 5dB:

The BER will be 0.005

b) Input SNR = 30dB and run the script again. Again, copy the eye diagram of the receiver signals and note the resulting bit error rate (BER) displayed in the command window.

Receiver eye diagram at 30 dB SNR:



BER for SNR = 30 dB:

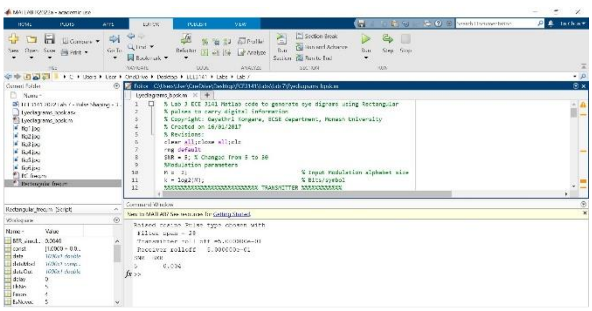
The BER will have a value of 0

c) Compare the eye diagram plots obtained for the received signal at SNR equal to 5 dB and 30 dB. Looking at just the eye diagrams, can you predict which of the two can result in a higher BER?

Based on the two eye diagrams plots obtained for the received signal, I can predict that the BER of the received signal at SNR equals to 5dB is higher. The height of the eye opening specifies the noise margin of the system. Since we can see that the eye diagram of the 30dB has a larger height, there will be a larger noise margin. This will lead to less errors as it would be less susceptible to errors. Pulses with more distortions of zero crossings implies that there is susceptibility to synchronisation errors. We can see that the eye diagram of the 30dB SNR has no distortions at the zero crossing. This means that it will be less susceptible to synchronisation errors. The 5dB SNR eye diagram will be the exact opposite. Based on the visual observation of the two figures, the figure when the SNR equals to 5dB look messier while the figure when the SNR equals to 30dB looks much cleaner and tidier.

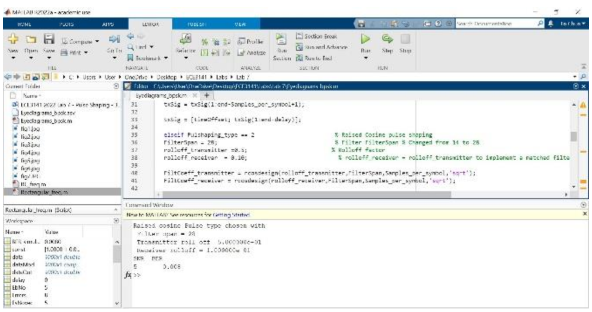
d) In the m-file, set the parameter filter span =28 and rolloff_transmitter = rolloff_receiver=0.5. This means that the receiver filter response is matched to the transmit pulse shape. At input SNR = 5dB, compare the BER of two systems: one with rolloff_transmitter = rolloff_receiver (matched filter) and the other with rolloff_transmitter > rolloff_receiver. Record the BER displayed at the Matlab command prompt for the two cases below.

BER_Matched:



The BER is equal to 0.004

BER_misMatched:

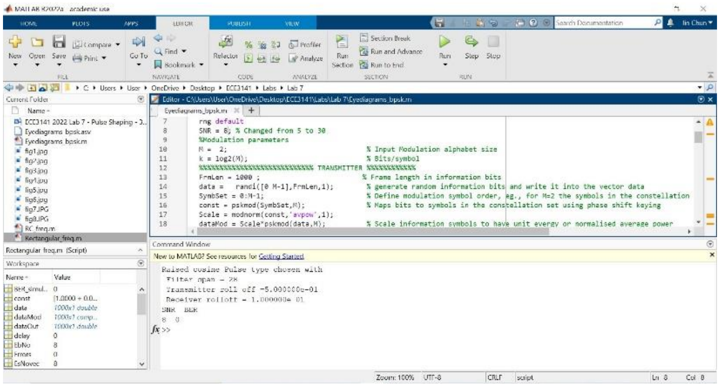


Rolloff_transmitter = 0.5

Rolloff_receiver = 0.10

BER = 0.008

e) Why do you think there is a difference? Is this difference changed when SNR is high?



There is a difference due to the matching of the roll off factors. If the roll off factor is matched, the SNR ratio would be maximized and results in a lower BER. The difference in roll off factors would also cause the signal at both sides to be filtered at different frequencies bandwidths.

When SNR is very high, BER will be 0. There will be no difference when SNR is high.

f) Assuming matched filtering, compare transmitter eye diagrams for roll-off factors of 0.1, 0.2, 0.3, 0.4 and 0.5, and observe the effect on the distortion introduced at the "zero crossings". (You may choose to comment out all other eye diagrams except the one at the transmitter output to limit the number of plots generated each time.) With the help of the description given in Figure 5, recommend a roll-off factor for the RC pulse that is least prone to time synchronisation errors.

When the roll-off factor has a value of 0.1, there will be a lot of distortions at the zero crossings.

When the roll-off factor has a value of 0.2, there will be lesser distortions compared when the roll-off factor has a value of 0.1 but still a lot of distortions.

When the roll-off factor has a value of 0.3, there will be lesser distortions compared to when the roll-off factor has a value of 0.2 but still a lot of distortions.

When the roll-off factor has a value of 0.4, there will be much lesser distortions.

When the roll-off factor has a value of 0.5, there will be very few numbers of distortions compared to all the cases above.

Based on the visual observation of the graph, we can see that the distortion of the zero crossing becomes less prominent as the roll-off factor is increased. The system will have lesser synchronization errors between the transmitter and the receiver.

With the help of the description given in Figure 5, the recommended roll-off factor for the RC pulse that is least prone to time synchronisation errors will be 1.

6. Time offset

In this experiment, you will compare the effect of time offset on the resulting BER for the two pulse shaping filters. In "Eyediagrams_bpsk.m", input pulseshapingtype = 1 to choose a rectangular pulse type and 2 to choose a RC pulse shaping filter. Time offset is modelled by the parameter "delay" which introduces a time offset in the number of samples. In the Matlab script, an over sampling factor of 10 is used. A sample delay corresponds to a synchronisation error of 10% of the symbol period.

a) Input *SNR = [5 10]* and *Pulshaping_type = 1* in the Matlab file. Introduce delay in number of samples = 0, 1, 2, 3. Note down the BERs for these delays in the table below.

Time Offset	BER at SNR=5 dB	BER at SNR=10 dB
0	0.002	0
1	0.005	0
2	0.033	0.001
3	0.075	0.012

Table 1: BER obtained from Matlab file "Eyediagrams_bpsk m", for various values of time offset

b) Input *SNR = [5 10]* and *Pulshaping_type = 2*. Then run "Eyediagrams_bpsk.m" for delay = 0, 1, 2, 3. Complete the table below

Time Offset	BER at SNR=5 dB	BER at SNR=10 dB
0	0.004	0
1	0.012	0
2	0.018	0.001
3	0.053	0.015

Table 2: BER obtained from Matlab file "Eyediagrams_bpsk.m", for various values of time offset

c) Comparing the BER results in Tables 1 and 2, which one exhibits more robustness to timing errors: the rectangular pulse shape or RC pulse shape?

The RC pulse shape will exhibit more robustness to timing errors. This is because RC pulse has lesser overall error compared with the rectangular pulse shape.

7. Conclusion

Raised cosine pulses are frequently used in practical implementations of radio systems where the signal bandwidth is shaped to meet a spectral specification. In this laboratory, you used eye diagrams of pulse shaped signals to understand the effect of AWGN and timing errors on the BER of a BPSK system. You compared time and frequency domain characteristics of two pulse shapes: rectangular and raised cosine pulses. You carried out experiments to understand the trade-offs associated with the use of two pulse shapes.

Before finishing, could each student please click on the "Feedback" icon for this laboratory on Moodle, to record some brief, anonymous feedback on this laboratory exercise.

Finally, please submit this completed report via Moodle by the stated deadline. In so doing, please be aware of the following:

- Even if you have had a mark assigned to you during the lab session, this mark will not be registered unless you have also submitted the report.
- Your mark may also not be accepted or may be modified if your report is incomplete or is identical to that of another student.
- By uploading the report, you are agreeing with the following student statement on collusion and plagiarism, and must be aware of the possible consequences.

Student statement:

I have read the University's statement on cheating and plagiarism, as described in the *Student Resource Guide*. This work is original and has not previously been submitted as part of another unit/subject/course. I have taken proper care safeguarding this work and made all reasonable effort to make sure it could not be copied. I understand the consequences for engaging in plagiarism as described in *Statue 4.1 Part III – Academic Misconduct*. **I certify that I have not plagiarised the work of others or engaged in collusion when preparing this submission.**

8. References

[1] ECE3141 Lecture material 2022

[2] Simon Haykin. 2009. Communication Systems (5th ed.). Wiley Publishing.

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