Pulse shaping for Digital Communication

EE340: Prelab Reading Material for Experiment 7

AUTUMN 2022

Why Digital Communication: In general, signals in the digital format are easier to store, transmit and process, compared to analog signals that are more susceptible to getting corrupted by noise and distortion. However, digital bit streams are not transmitted directly, particularly in case of wireless transmission.
In communications, digital signals need to be mapped to an analog waveform in order to be transmitted over the channel. The mapping process is accomplished in two steps:
(i) Mapping from source bits to complex symbols (also known as constellation points),
(ii) Mapping from complex symbols to analog pulse trains, which is studied in this part.

Data transmission systems that must operate in a bandwidth limited environment must contend with the fact that constraining the bandwidth of the transmitted signal necessarily increases the likelihood of a decoding error at the receiver. Bandwidth limited systems often employ pulse-shaping techniques that allow for bandwidth containment while minimizing the likelihood of errors at the receiver.

Digital Modulation Formats: As we know, the frequency components of a square wave are not band limited due to sharp transitions in it. Therefore, we cannot directly use data streams to transmit over a bandpass channel. One has to use band-limited analog representation of the bits to modulate over a carrier wave. One can have distinct amplitudes, frequencies or phases per bit or group of bits,leading to various modulation techniques as discussed below.

- **Amplitude Shift Keying (ASK):** The amplitude of the carrier wave is changed with the bit values.The simplest form of ASK is On-Off-Keying (OOK), in which the carrier wave is transmitted for bit '1' and nothing is transmitted for bit '0'.

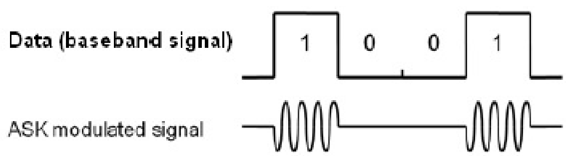


Figure 1: Amplitude Shift Keying (ASK)

- **Frequency Shift Keying (FSK):** In FSK the bit values are mapped to distinct frequencies at the transmitted (while the carrier amplitude is kept constant).

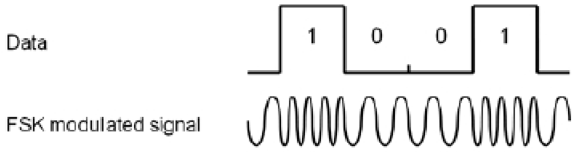
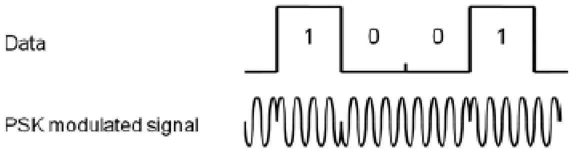


Figure 2: Frequency Shift Keying (FSK)

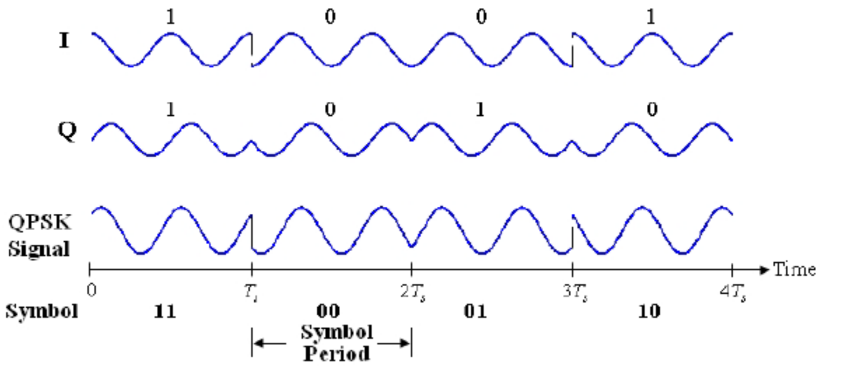
- **Phase Shift Keying (PSK):** In PSK, the bit values are mapped to distinct phases of the transmitted carrier wave (while the carrier amplitude is kept constant).

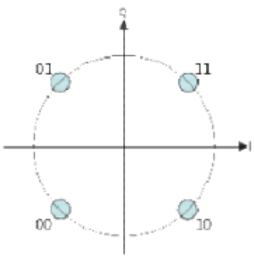


BIT	PHASE
0	0^0
1	180^0

Figure 3: Phase Shift Keying (PSK)

In QPSK (Quadrature Phase Shift Keying), we use 4 possible phases of the carrier, depending on 2 consecutive bits. As shown in Fig. 4, this can be achieved by independently multiplying each of the I and Q channel carriers, i.e. $\cos(\omega_c t)$ and $\sin(\omega_c t)$, with +1 or -1 and adding them.Show yourself that this scheme results in the carrier with possible phase values of 135°, 45°, +45° and +135°.





QPSK Constellation

Symbol	I, Q Logic Levels	I, Q Amplitude Levels	Carrier Phase
00	0, 0	-1, -1	-135^0
01	0, 1	-1, 1	$+135^0$
10	1, 0	1, -1	-45^0
11	1, 1	1, 1	$+45^0$

Figure 4: Quadrature Phase Shift Keying (ASK)

Figure 4 shows the QPSK signal, its symbol table and constellation. Two message bits represent one symbol in QPSK modulation, and duration of transmission of one symbol is called symbol period (Ts). The corresponding symbol rate is 1/Ts, and therefore the corresponding bit rate for QPSK is 2/Ts. In general, the carrier phase can take M distinct values, for which the modulation scheme is called M-PSK. For example, in 8-PSK the carrier phase takes the values 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° and each symbol represents 3-bits.

- **Quadrature Amplitude Modulation (QAM):** In general, the in-phase (I) and quadrature phase (Q) components of the carrier can independently be modulated with distinct amplitude levels to obtain M-QAM (which has M possible symbol values and represent log2M bits per symbol). QPSK is also called 4-QAM. In 16-QAM, I and Q components of the carrier are each independently multiplied by 3, -1, +1 or +3 and then added to get the 16-QAM symbol constellation shown in Fig 5.

The PSK and QAM signals are generally represented on the complex plane to show the constellation diagram (in-phase component amplitude is represented on the x-axis and quadrature-phase component amplitude is represented on the y-axis). The baseband I and Q signal amplitudes are sampled (one same each for one symbol) at the centre of the symbol period and added on the x-y plane to show the signal constellation. The constellation diagrams for a few of the modulation schemes are shown below:

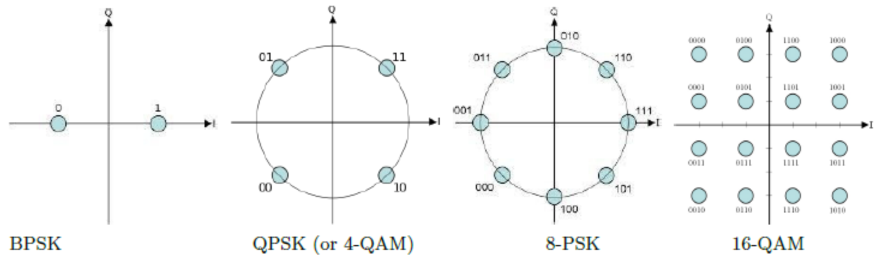


Figure 5: Constellation diagrams of some QAM and PSK modulation formats.

A Digital Communication Link: A very simplified version of a digital communication link is shown in the Fig. 6. The raw bits to be transmitted are first grouped to form symbols which are mapped to I and Q amplitudes. These amplitude waveforms are like square waves, which occupy infinite bandwidth because of sharp transitions. Hence, the waveforms have to be passed through low pass filter to smoothen these transitions. However, low-pass filtering also results in inter-symbol-interference (ISI).

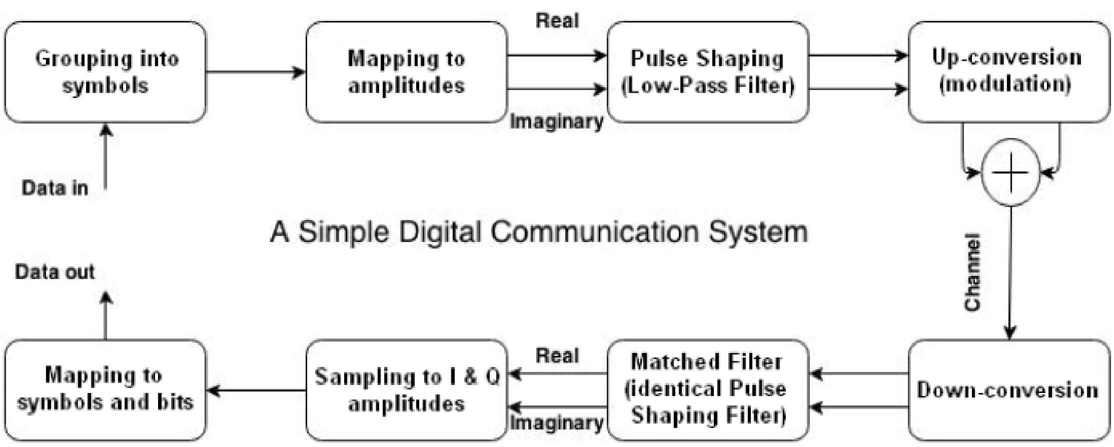


Figure 6: A simplified model of a digital communication system.

RECTANGULAR PULSE: Rectangular pulse is the most basic element of the digital signal. It is characterised by fixed amplitude,A, and defined time interval, T. Such a pulse is shown in Figure 1,where A = 1, T = To, with the pulse centered about the time origin at t = 0. In communication presence and absence of pulse denotes '1' and '0' respectively. Typically, a sequence of such pulses constitutes the transmission of information. The time period of each pulse is T, so the maximum pulse rate is 1/T pulses per second, which leads to a data transmission rate of 1/T bits per second.
These pulses are easy to implement but on the flip side the frequency content (or spectrum) associated with the sharp edges of pulse means large bandwidth in frequency domain is shown in Figure 2. On applying FFT to the pulse we get sinc(sin(x)/x) waveform , It is characterised by a single major lobe and the null points (where the spectral magnitude is zero) and always occur at integer multiples of 1/T, which is the pulse (or symbol) rate. Therefore, the null points are solely determined by the pulse period, T. In ideal sinc, nulls and peaks extend in frequency out to $\pm\infty$ with the peaks approaching zero magnitude.

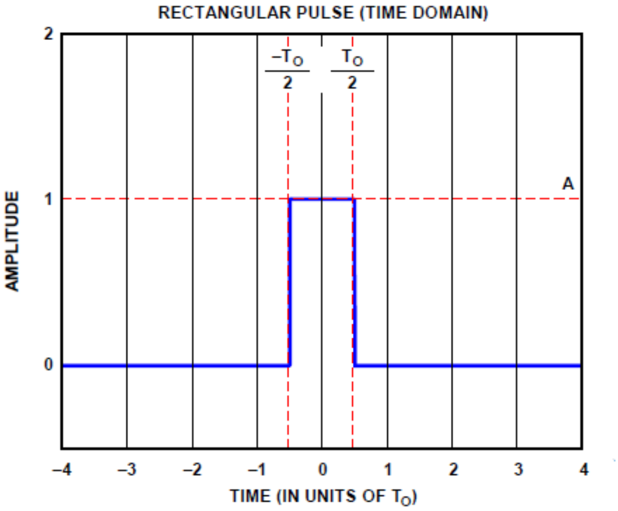


Figure 7: A Single Rectangular Pulse (T = To, A = 1)[1]

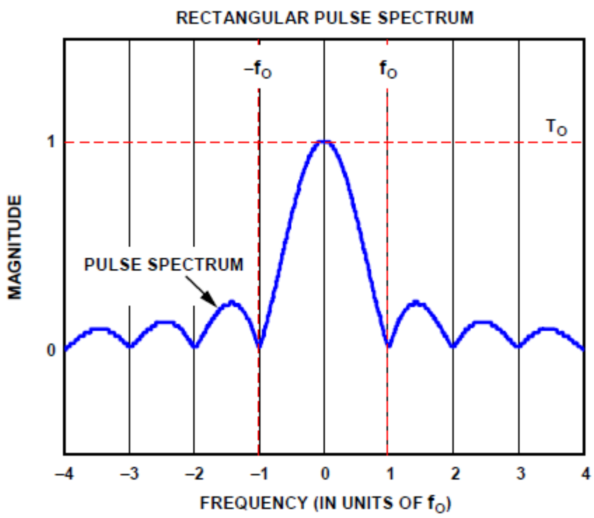


Figure 8: Spectrum of a Single Rectangular Pulse of Duration[1]

Pulse Shaping Filter: Bandwidth is a precious resource in communication, and as shown in Figure 8, the spectrum of a rectangular pulse spans infinite frequency. In such instances, the infinite bandwidth associated with a rectangular pulse is not acceptable. The bandwidth of the rectangular pulse can be limited on passing it through a low-pass filter. The act of filtering the pulse causes its shape to change from purely rectangular to a smooth contour without sharp edges.The act of filtering rectangular data pulses is often referred to as pulse shaping.
Unfortunately, limiting the rectangular pulse in frequency domain expands the signal in the time domain which exhibits damped oscillation. In other words, the smoothed (or filtered) pulse shows waves both before and after the pulse interval, but the rectangular pulse only shows nonzero amplitude during the pulse interval.These ripples associated with the pulses will interfere with the other pulses which may leads to decoding errors at receiver.This is also known as Inter-Symbol Interference(ISI) .So the choice of the filter will determine the bandwidth reduction while still maintaining the time domain structure which does not obstruct receiver decoding process.
One of the filter is raised cosine filter and its frequency response is given by

$$H_{rc}(f) = \begin{cases} T & 0 \leq |f| \leq (1-\alpha)/2T \\ T*(1+cos[\frac{\pi T}{\alpha}(|f| - \frac{(1-\alpha)}{2T})] & (1-\alpha)/2T \leq |f| \leq (1+\alpha)/2T \\ 0 & (1+\alpha)/2T \leq |f| \end{cases}$$

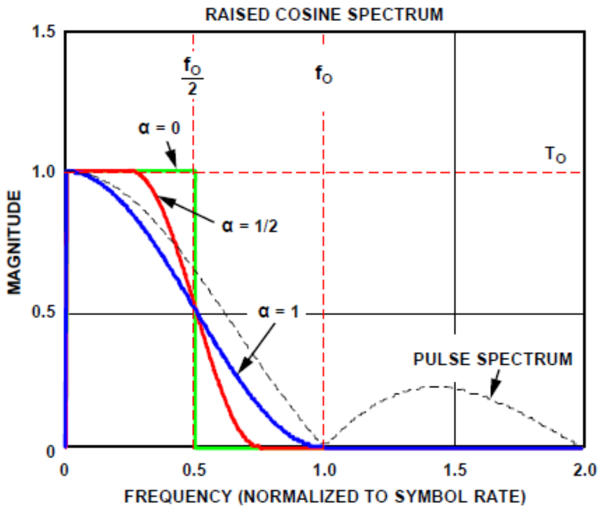


Figure 9: The Raised Cosine Frequency Response(normalized to T = 1)[1]

where:
T is the pulse period (equivalent to To in Figure 7).
α is the roll off factor.

The ripples result from the convolution of the rectangular pulse with the raised cosine impulse response (convolution is the process of filtering in the time domain). The impulse response (time domain) of the raised cosine filter is shown in Figure 4 with different values of roll-off factor. The most useful feature of this filter is that zero crossings of the impulse response coincides with the peaks of the adjacent pulses.If receiver samples at these instants, chances of decoding errors are very less i.e ISI reduces significantly.So if the overall channel transfer function is raised cosine spectrum than we get a better digital transmission. This is achieved by implementing **square root raised cosine filter** each on the transmitter side and receiver side.

$$H_{rrcf,Tx}(\omega).H_{rrcf,Rx}(\omega) = H_{rcf}(\omega) \tag{1}$$

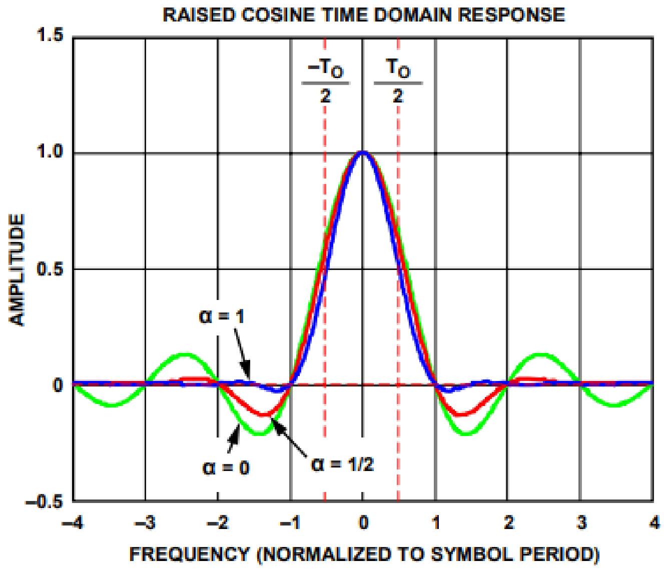


Figure 10: The Raised Cosine Time Domain Response[1]

EYE DIAGRAM

An eye diagram is used in electrical engineering to get a good idea of signal quality in the digital domain. The eye diagram takes its name from the fact that it has the appearance of a human eye. It is created simply by superimposing successive waveforms (The multiple copies, each delayed by a symbol duration from the previous copy)to form a composite image. The eye diagram is used primarily to look at digital signals for the purpose of recognizing the effects of distortion and finding its source.

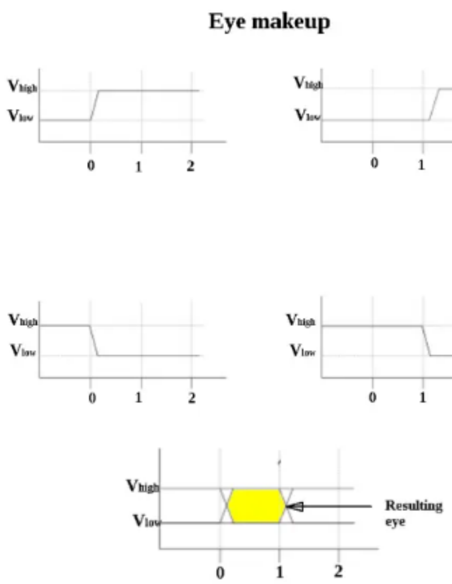


Figure 11: Here, the bit sequences 011, 001, 100, and 110 are superimposed over one another to obtain the example eye diagram.[2]

The eye diagram readily shows the ability to make a decision between signal levels; so the ideal eye would show that there is a lot of margin both in the vertical and horizontal axis to allow for a minimum error rate (what we would call a wide eye opening).As the effect of noise increases the opening of eye narrows down which may cause the wrong decision (this could be phase noise or jitter in the vertical direction and amplitude noise in the horizontal direction, or intersymbol interference which effects both directions).

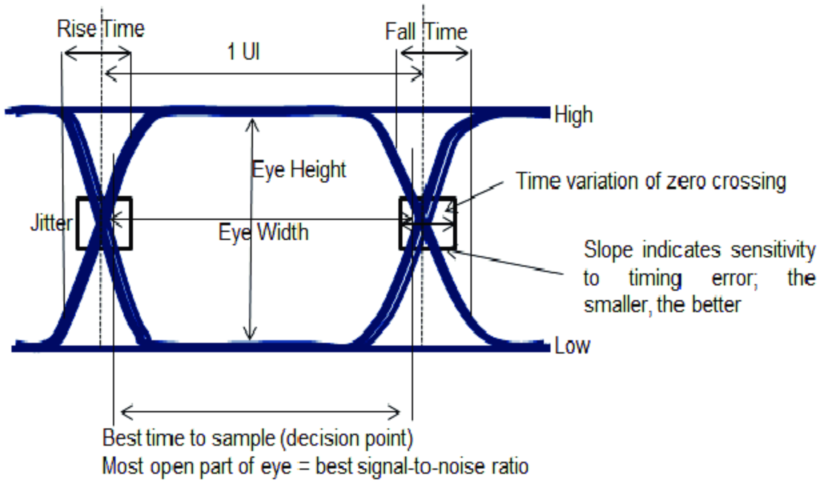


Figure 12: Interpretation of eye diagram[2]

Appendix: Blocks to be used in the experiment

Some of the blocks that will be used in the GNU-Radio based digital communications experiments are listed below:

Random Source
It generates random message symbols (non-negative integers) of values in a range [minimum, (maximum-1)]. Repeat must be on to generate message symbols continuously.

Chunks to Symbols It maps a stream of chunks (groups of k-bit symbols) to a stream of float or complex constellation points (or amplitudes). In the block, the symbol table can be given to directly map the symbol values to their corresponding real or complex amplitudes.

References

[1] K. Gentile, "Digital pulse-shaping filter basics," *Application Note AN-922. Analog Devices, Inc.(September)*, 2007.

[2] D. HERRES, "The eye diagram: What is it and why is it used?." https://www.testandmeasurementtips.com/basics-eye-diagrams/.