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Communications Lab, University of Toronto

Experiment 05: QAM

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Abstract
In this lab you will explore Quadrature Amplitude Modulation (QAM). This will be done by running `Simulink` models.

Keywords
In-Phase — Quadrature — Constellation Diagram — Eye Pattern

Contents

Introduction

Digital modulation schemes find application in optical communications, high-speed modems, cellular telephony, satellite communications and other means of communication where bandwidth efficiency is needed. The main objective of such modulation schemes is to maximize the number and speed of transmitted bits within a given bandwidth, while keeping the rate of error as low as possible.

QPSK, for instance, does this by shifting the angle of the carrier in four discrete angle values, while keeping the amplitude constant. Typical values are $\pm 45^\circ$ and $\pm 135^\circ$, representing two bits each. These two bits (called *dibit*) are Gray Coded. This coding results in only one bit of difference between adjacent values, aiming at a reduced bit error rate. In contrast, QAM maintains the frequency of the carrier, while changing the amplitudes of the in-phase and quadrature components. We will concentrate on 16-QAM in this lab, meaning that there will be four amplitude levels (two bits represented per level) for the in-phase component and four amplitude levels for the quadrature component. The bits representing adjacent levels are also Gray Coded.

Throughout the experiment, keep in mind that the golden objective of any communication system is to transport a message from one point to another without errors (or changes at all). For the particular case of the modulation methods to be seen here, the objective is to take a message, code it in bits, arrange them, transmit them, then receive them somehow to recombine them into the original message. This all happens in the presence of noise, relative movement between transmitter and receiver, and other complicating factors that affect the decoding of the message that is being transmitted. You may have heard a few years back about the first picture sent by a probe called *Philae* as it landed on *Comet 67P/Churyumov–Gerasimenko* (click here). Now consider that the probe was launched over 15 years ago, using the technology of the time, and that it met up a comet somewhere in the galaxy landing a probe onto it. Any signal transmitted from the probe takes 25 minutes to arrive at the receiver on earth. The image taken is here on earth for us to see as a result of the digital modulation and demodulation of the data sent while the comet is (was) in motion. Fast forward a few years and you might be video-calling someone halfway across the world on your mobile phone right now, while you move around downtown. The process is similar: fast encoding and decoding of bits so that the information is sent through reliably.

At the end of this experiment, you should have a better understanding of:

- Pulse Amplitude Modulation and Quadrature Amplitude Modulation and their demodulation;
- Constellation diagrams, and eye patterns for signals with multiple pulse amplitudes;
- Phase, noise and inter-symbol interference features present in the received signal;

Before starting the lab, complete the **lab preparation** and send it to the T.A. as you have been instructed. From this point on, you will use all simulation models found in the folder (click here) Experiment 5 - QAM. The second QAM simulation model presented here is a modified version from [1]. Please refer to it if you want to explore other digital modulation schemes further.

1. Quadrature Amplitude Modulation (QAM)

In QAM, you will have two orthogonal paths, one being modulated by a sine and one by a cosine carrier of the same frequency. The amplitude of these carriers is modulated in a predetermined number of levels, so these can be seen as two PAM systems in quadrature. In this case, 4 levels (each representing 2 bits). As they are orthogonal, each time the received signal is sampled (and the bits extracted), you will have one level of each carrier sampled, and each sample represents two bits, to a total of 4 bits being received. Then they are decoded and recombined.

1.1 Pulse Amplitude Modulation

Your first challenge is to figure out how many bits you will need per symbol if you are to design a basic 16-QAM system. After you convert your signal of interest to bits, you will group those bits in symbols and manipulate them appropriately to obtain a pulse amplitude modulated (PAM) signal, as Figure 1 indicates. This will be the PAM subsystem of your QAM transmitter.

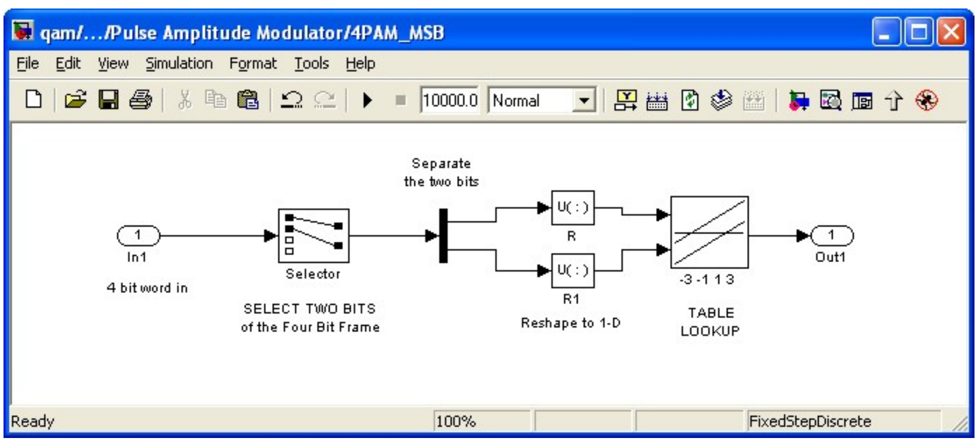


Figure 1. Pulse Amplitude Modulation Subsystem (for the two most significant bits)

The PAM signal is achieved by mapping the groups of bits to different levels with the use of a table. For instance, if the two input bits are $_b00$, the table will map to an output of -3, $_b01$ to -1, $_b10$ to +1 and $_b11$ to +3. The 16-QAM model provided to you has a PN sequence generator as a bit-source, which generates "frames" of 4 bits (zeros and ones), followed by two PAM sub-system, one for each half of the incoming 4 bit word.

1.2 In-Phase and Quadrature

The QAM system provided to you has a transmitter portion and a receiver portion, with a channel inbetween. The channel is an idealized model and will **not** insert any bandwidth limitation, but it will insert noise and phase distortion. There are two signal paths on the transmitter: in-phase and quadrature, which will appear also on the receiver.

The basic block of the 16-QAM transmitter is comprised by two PAM subsystems generating bit streams in two separate paths, as Figure 2 displays.

The incoming bit stream to the PAM subsystems is divided in frames of 4 bits. The two MSBs are passed through one of them, resulting in a sequence of 4 different values after the table lookup. The two LSBs are passed through the other PAM

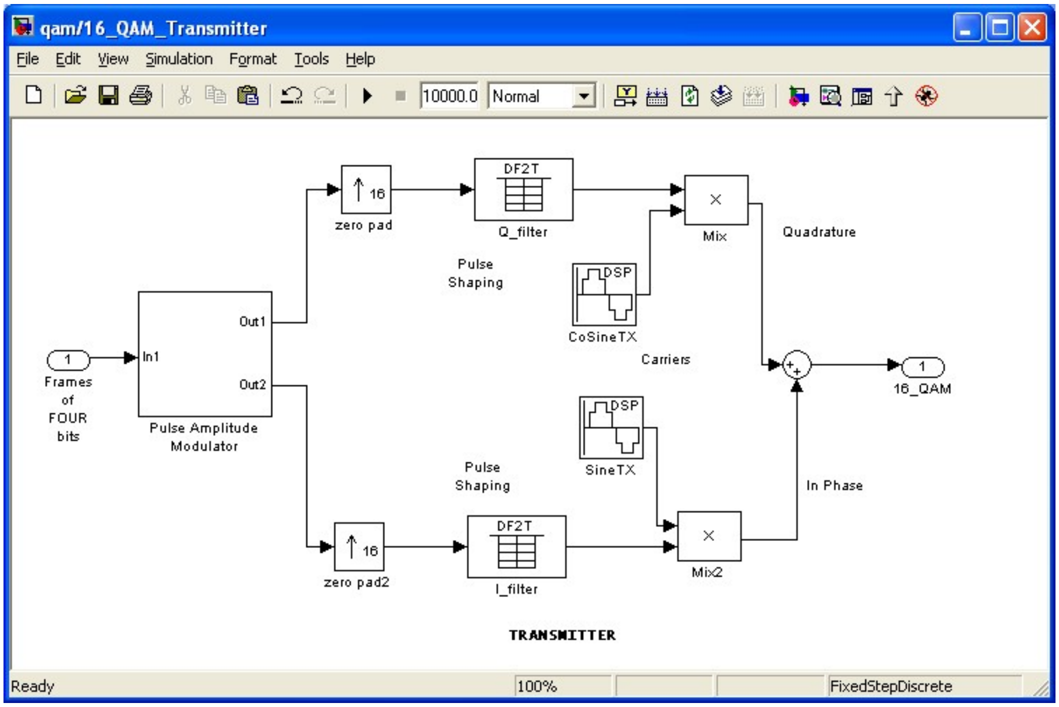


Figure 2. QAM Transmitter

subsystem. The output of each PAM subsystem will eventually form the in-phase and quadrature signals on the transmitter. The sequences are then interpolated (padded) with zeros and passed through the pulse-shaping filter, in order to mitigate any bandwidth limitations imposed by the channel (i.e., the rate is slowed down to fit into less channel bandwidth). Finally, each of these signals is mixed with its respective carrier. The carriers are 90 degrees apart, ensuring the orthogonality of both signals as they go into the channel after they are added.

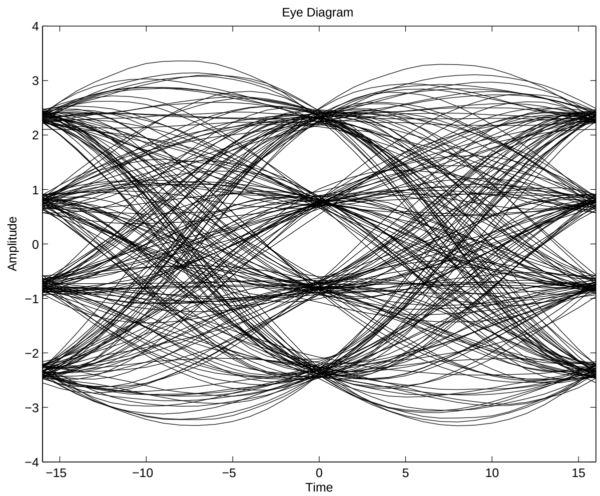
A brief inspection of the complete model provided to you will show you that the whole system is comprised of a transmitter (as shown on Figure 2), a channel and a receiver. The channel provided simply adds noise and/or phase delay, according to the switches you select. The receiver feeds the incoming signal first to two mixers with sine and cosine carriers. The path then leads to matched filters, a slicer and decision-making block. The resulting eye pattern and constellations are formed from the output of this block.

Both transmitter and receiver will need their respective pulse-shaping and matched filters, which you are to design using the filter design tool (`Filter Design Tool`). You are given a `Simulink` model containing only the block to perform the filter design on the lab web page. When you are done with the filter specifications, go under file/export (top-left corner on the tool) and give a name to your filter. This name is used in the `Matlab` workspace as a variable and must be used on the filter blocks on the QAM system to call your filter. If you export it as variable `a`, make sure all the filter blocks on the QAM system will be calling variable `a`. This will be done from the `Direct Form II Transposed` block (double-click on it and you will see). By defining your filters as a variable in the workspace, it will save you a lot of time.

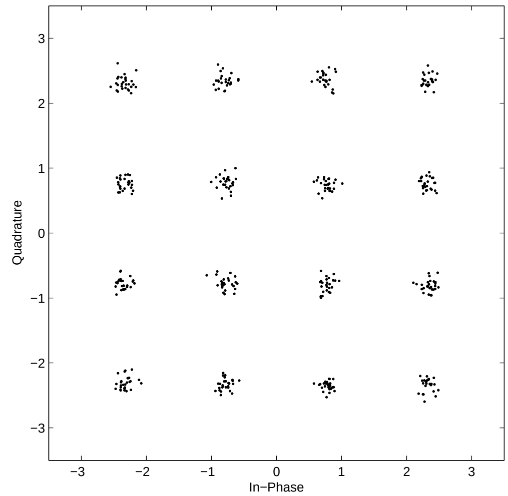
You will explore Square-root raised-cosine filters with different excess bandwidth. You have to choose the appropriate order and to figure out your Nyquist bandwidth for these filters. Remember, you have a sampling rate of 48KHz for this model, and there are zeros being interpolated to slow the rate down. On Figure 2, for instance, the interpolation is done by a factor of 16. Check now what interpolation factor is used in the model given to you. You might recall that you wish to shape the pulse in such way that when the zero-crossing of the pulse-shaping filter will happen at the exact time a new bit (or sample) occurs. Therefore, based on the impulse response (sync) that you desire for zero inter-symbol interference, you will determine the frequency cutoff for your filter.

Make sure you have downloaded all three models. Set up your filter model to export your filter design as requested and give the simple model a try now. Move to the answer sheet to answer the questions about the model.

Figure 3 presents the eye diagram and constellation diagram of a system using a 50% excess bandwidth root raised cosine TX-RX filters, and some noise. This is just a reference as you modify your system to perform different tasks. As the experiment progresses, you will come to observe a variety of features in these two diagrams.



(a) Eye Diagram



(b) Constellation Diagram

Figure 3. 16-QAM

1.3 A Look at BER

The second QAM model given in the course lab page also takes the input from a random generator. Like on the previous model, the bits are organized in symbols (groups of bits) and are sent in two paths labeled in-phase and quadrature. No pulse-shaping is done in this model, as it typically would be done in practice (as you just modelled above). As in the previous case, a sine and a cosine of the same frequency are used as carriers for the two paths. The same carriers are used at the demodulator. Also at the demodulator the bits are recombined to reverse the process done prior to the multiplication by the carrier.

This second model offers a means to calculate the bit error rate (BER) by feeding back each decoded bit from the output of the receiver, to be compared with the bit generated at the input to the transmitter. At this part of the experiment you will observe the effect of signal to noise ratio (in QAM is referred to as Eb/No).

With the model open, run it with default values to make sure it is working and move to the answer sheet.

2. Accomplishments

In this experiment, you have explored Quadrature Amplitude Modulation, in particular 16-QAM. You have observed the impact on the full system brought by the use of different filters, noise levels and phase distortion. You have also learned how to identify these problems through the use of the eye diagram and the constellation diagram, both of which are used very frequently as graphic tools in digital communications.

Acknowledgments

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References

[1] D. Silage. *Digital Communication Systems Using MATLAB and Simulink*. Bookstand Publishing, 2009.