Exploring QAM using LabView Simulation[*]

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Abstract

This module explores the topic of Quadrature Amplitude Modulation (QAM) through the use of National Instrument's LabView Modulation Toolkit. The QAM Transceiver simulation tool provides an excellent tool for learning about the most important aspects of QAM. This module first reviews basic theory of QAM, and then presents a series of simple exercises designed to introduce the reader to basic concepts such as noise, bandwidth, and pulse shaping.

1 Exploring QAM using LabView Simulation

1.1 Introduction

National Instruments offers a wide variety of toolkits to supplement the LabView development system. Fortunately, many of these are included in academic site licenses that are offered to colleges and universities at very discounted prices. In particular, the Modulation Toolkit includes a variety of valuable applications that can be used for classroom demonstrations, homework exercises, and laboratory experience. Accordingly, this module leads the student through a series of exercises designed to provide better understanding of **Quadrature Amplitude Modulation** (**QAM**) by using a simulated QAM transceiver provided in the toolkit. This transceiver provides excellent front panel control of important parameters of the QAM signal, and provides a real-time look and feel experience to further motivate student learning.

1.2 Theory

1.2.1 Quadrature Amplitude Modulation

QAM is a communication scheme that uses two carriers at the same frequency, but 90 degrees out of phase, i.e., in "quadrature," to modulate two separate message signals:

$s(t) = m_1(t)\cos(\omega_c t) + m_2(t)\sin(\omega_c t),$

where $m_1(t)$ is the "in-phase" message and $m_2(t)$ is the "quadrature" message. In the literature, these two signal components are often denoted "I(t)" and "Q(t)," respectively.

In practice, $m_1(t)$ and $m_2(t)$ can be simple analog signals such as speech or music, or they can represent digital information coded using pulse-amplitude modulation. Forward error correction, pulse shaping, and differential coding techniques are frequently applied to $m_1(t)$ and $m_2(t)$ to improve efficiency. The term M-QAM indicates that M voltage levels are used to encode n bits in each symbol, where $M = 2^n$. Often,

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n is chosen to be an even integer so that I and Q are each coded with n/2 bits or $2^{n/2}$ voltage levels. For example 256-QAM represents 8 bits/symbol, with 4 bits represented by 16 in-phase voltage levels and the remaining 4 bits represented by 16 quadrature voltage levels.

An alternative representation for the QAM signal is in terms of magnitude and phase:

$s(t) = E(t)\cos(\omega_c t - \theta(t))$,

where $E(t) = \sqrt{I^2(t) + Q^2(t)}$ and $\theta(t) = \tan^{-1}\frac{Q(t)}{I(t)}$. This leads to a useful base-band or "phasor" representation of the signal: $S(t) = E(t)e^{j\theta(t)} = I(t) + jQ(t)$, where E(t) is the "envelope" of the signal.

1.2.2 Noise and Bit Errors

In digital communication systems, the objective at the receiver is to correctly select the transmitted message symbols out of a finite set. The presence of channel noise complicates the task and causes bit errors. One important performance criterion in a digital communication system is the **bit error ratio** (**BER**), which is the ratio of the number of incorrectly received bits to the total number of transmitted bits. Usually, BER (abscissa) is plotted against **signal-to-noise ratio** (**SNR**) (ordinate). SNR is typically measured in terms of E_b/N_0, where E_b is the energy per bit and N_0 is the noise power spectral density.

Example BER curves for different values of M are shown in Figure 1. These are easily generated in MATLAB using the "Bit Error Rate Analysis Tool" ("**bertool**").

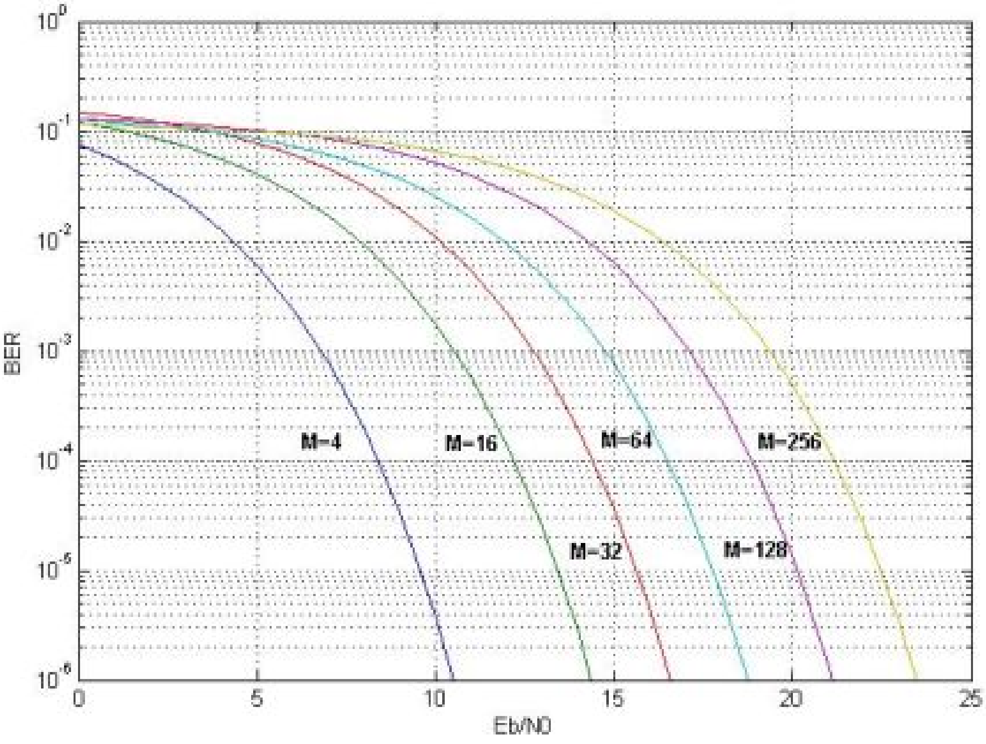


Figure 1

Figure 1. M-QAM BER Curve.

The figure shows that for low noise levels (i.e., SNR large), the BER is extremely small. However, as noise increases beyond a certain threshold level, the BER rapidly becomes unacceptable. For example, 4-QAM is reasonably robust for SNR values of 10 dB or more, but for smaller values, the BER quickly approaches 50% bit errors, at which point the signal is entirely lost. It's also interesting to note that larger values of M, i.e., more bits per symbol, require significantly higher SNR to provide comparable bit-error performance.

1.2.3 Pulse Shaping

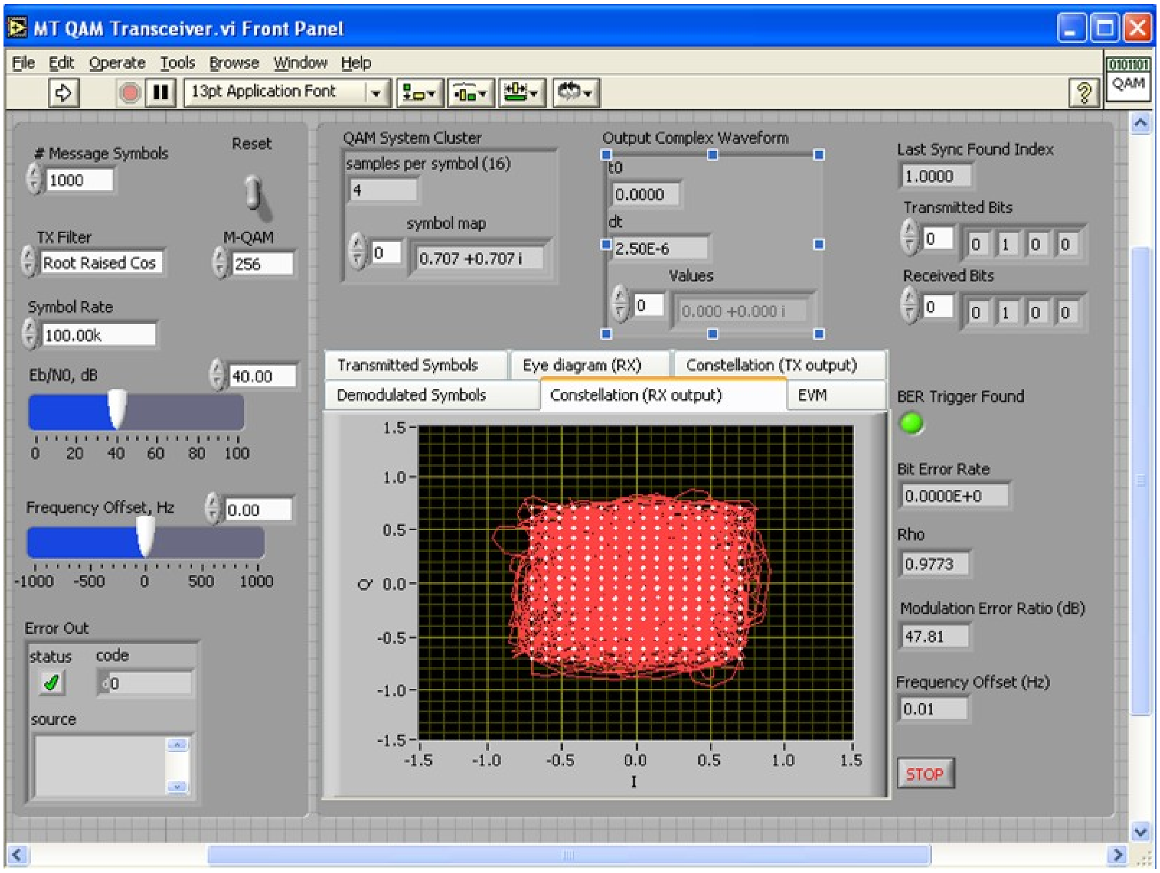
Real-world communication channels have limited bandwidth, either because of physical reasons such as a band-pass frequency response, or because of regulatory constraints imposed by the FCC. Restricting the bandwidth causes pulses to spread out in time, and causes them to overlap with neighboring pulses. The result is called "**inter-symbol interference**," or **ISI**. The conventional way to deal with ISI is to accept overlap, but carefully shape the pulses so that overlapping pulse waveforms have zero amplitude at each decision-making instant.

Since pulse shaping allows efficient communication to take place within limited bandwidth, an equivalent viewpoint is that it provides a way to minimize the bandwidth of the digital signal. For example, the ideal zero-ISI pulse can be shown to be a sinc function. It has a rectangular low-pass frequency response with cut-off frequency of R/2, where R is the symbol rate. Although the sinc pulse is not realizable (it's non-causal and has infinite duration), a related zero-ISI pulse shape, the "raised cosine" (RC) pulse, is often used in practice. The RC pulse spectrum is flat at low frequencies, and rolls off according to (1+cos(c f)), i.e., the roll off vs. frequency has a raised cosine shape. Its bandwidth ranges from R/2 Hz (at which point it is equivalent to the sinc pulse) to R Hz. The bandwidth is controlled by a roll-off parameter alpha, where alpha=1 gives the full bandwidth pulse (R Hz), and alpha=0 gives a sinc pulse (R/2 Hz).

The final pulse shape discussed here is the "root-raised cosine" or RRC pulse. Its Fourier transform is given by $P(f) = \sqrt{P_r(f)}$, where $P_r(f)$ is the transform of the raised cosine pulse described above. When used in a communication system, a pulse-shaping filter with response P(f) is used in both the transmitter and receiver. Thus, the overall response is the same as the raised cosine, $P_r(f) = P(f)P(f)$. Receivers whose front-end filters are matched to the received pulse frequency response are called "matched filter" receivers, and these are known to provide near-optimal performance in channels with white Gaussian noise. This explains the popularity of root-raised cosine systems, since they provide both low ISI as well as good performance in noise.

1.3 Simulation Software

This set of exercises is based on a National Instruments LabVIEW simulation **virtual instrument** or **VI**. The NI Modulation Toolkit includes a very powerful VI called "MT QAM Transceiver.vi". To access it, go to the "simulation examples" folder by the following steps: "Start" -> "All Programs" -> "National Instruments" -> "Modulation" -> "LabVIEW Support" -> "Modulation Examples Folder" -> "simulation examples" –> "interactive." Then, double click on the "MT QAM Transceiver.vi". The front panel is shown below.



# Message Symbols: 1000

TX Filter: Root Raised Cos

M-QAM: 256

Symbol Rate: 100.00k

Eb/N0, dB: 40.00

Frequency Offset, Hz: 0.00

Error Out: status ✓ code 0

QAM System Cluster: samples per symbol (16) 4; symbol map 0 0.707 +0.707 i

Output Complex Waveform: t0 0.0000; dt 2.50E-6; Values 0 0.000 +0.000 i

Last Sync Found Index: 1.0000

Transmitted Bits: 0 | 0 1 0 0

Received Bits: 0 | 0 1 0 0

Bit Error Rate: 0.0000E+0

Rho: 0.9773

Modulation Error Ratio (dB): 47.81

Frequency Offset (Hz): 0.01

Figure 2

Figure 2. Front panel of the M-QAM transceiver simulation software.

This VI implements a complete QAM transmitter and receiver. Adjustable added channel noise is controlled by the E_b/N_0parameter. Optional pulse shaping is also provided as in "TX Filter" parameter, which includes both raised cosine and root raised cosine pulse shaping filter. To start the simulation, click on the "run" button (upper left corner, shaped like a fat arrow).

1.4 Basic QAM Exercises

The following exercises are to familiarize you with basic operation of the M-QAM VI, and then to provide a basic foundation for the concepts involved in QAM communication.

1.4.1 Exercise: Understanding 4-QAM and waveform displays

Set the "M-QAM" parameter to be 4 (i.e., 2 bits per symbol), and change the "TX Filter" parameter to be "none." Keep all other parameters at their default values and start the simulation. By clicking the tabs over the waveform display, the VI provides several different ways to view the signal. These are patterned after those used in practical communication test equipment such as vector signal analyzers, and provide a great deal of information about the signal's characteristics. Please keep in mind that the displayed signal is measured following any processing such as integrators or filters in the receiver front end (such as the RRC filter discussed above).

Constellation Graph

The constellation graph at the transmitter end is shown below. The abscissa is the in-phase component and the ordinate is the quadrature component. Since M=4, there are four dots representing four possible combinations of amplitude and phase levels, which is equivalent to 2 bits/symbol. The vertical position of a signal sample (i.e., a dot) on the graph represents one bit of information, while its horizontal position represents the second bit.

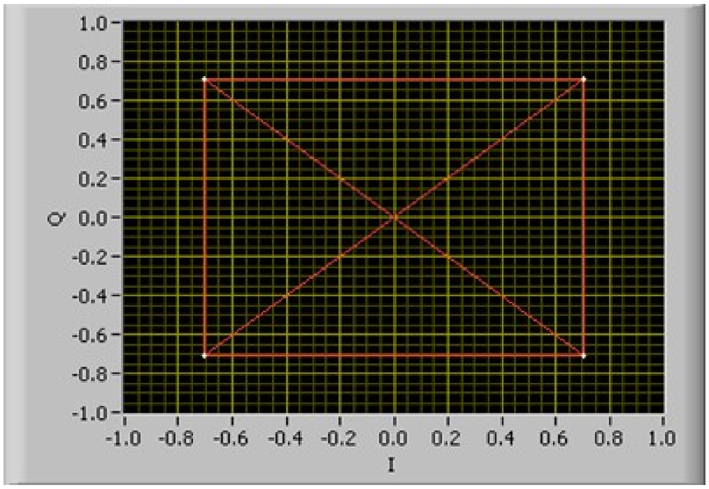


Figure 3

Figure 3. Constellation graph of 4-QAM at the transmitter end.

Eye Diagram

An eye diagram shows either I(t) or Q(t) on a standard oscilloscope display. The display is synchronized to show two or more full pulse durations, and persistence is used to show the history of many pulses. As a result, the traces show the range of possible amplitude values and shapes that the receiver must be able to deal with. An eye diagram is thus an effective way to examine the effects of distortions such as channel noise and ISI. The best time to sample the waveform and decode it is where the "eye" is most open When there is no distortion, the "eye" has the maximum opening possible, showing high separation between the "0" and "1" waveforms. When noise is present, the eye closes, indicating that voltage ranges for 1's and 0's are beginning to overlap and that bit errors are more likely.

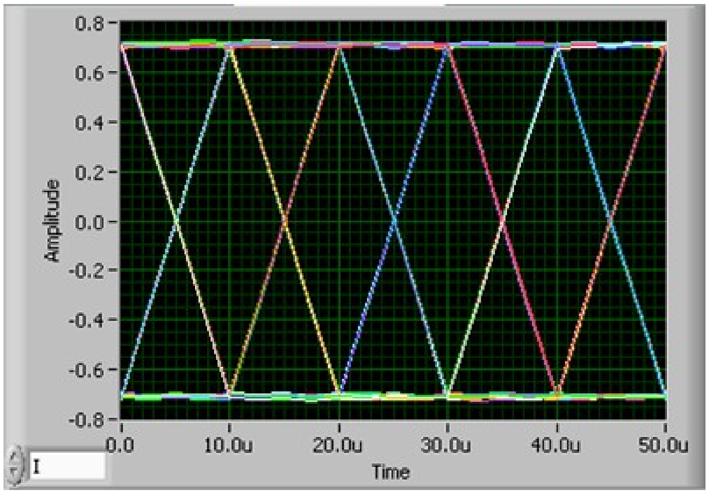


Figure 4

Figure 4. Eye diagram (in-phase) of 4-QAM at the receiver end with no noise.
Exercise: 16-QAM

1. Run the VI and observe both the eye diagram and constellation. Make sure you understand the relationship between these two displays. To help make the connection, try switching between in-phase and quadrature eye diagrams (the switch is at the lower left corner of the eye diagram).
2. Set up the simulation for 16-QAM. How many I and Q levels do you see in this case? How many bits per pulse?

1.5 Effects of Added Noise

To simulate the effect of channel noise, the simulation software provides an " E_b/N_0" parameter to change the SNR level. Recall from the introduction that this parameter controls the expected bit error ratio, and that the effect of added noise increases when more bits are encoded per pulse.

1.5.1 Example: 4-QAM, 10 dB Eb/N0

After setting the SNR (i.e., E_b/N_0) to 10 dB, the following eye diagram is seen. Noise is causing a great deal of waveform variation, but the eye is still open, implying that most bits will be decoded without error.

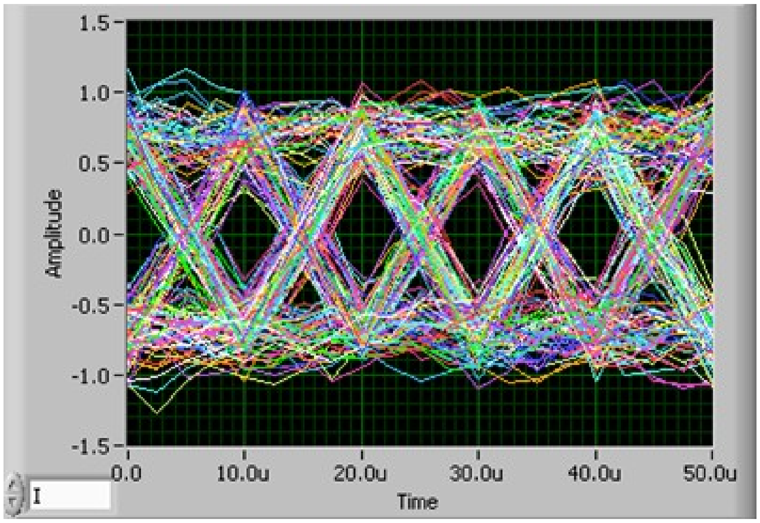


Figure 5

Figure 5. Eye diagram (in-phase) of 4-QAM with 10 dB SNR.

1.5.2 Exercise: Noise in QAM

1. Go back and look at the BER curve in Figure 1. Determine the E_b/N_0 value required for a BER of about 10^{-3}; below this threshold the channel can usually be considered unusable for most applications. Examine the eye-diagram for this case, as well as for cases where E_b/N_0 is a few dB higher or lower. Can you see the relationship between the BER curve and the corresponding eye diagram? Also observe the constellation plots for these cases.
2. Now set the VI for M=16. Adjust E_b/N_0 until the eye diagram indicates you've hit a threshold where bits can no longer successfully be decoded. Compare this with the threshold value of E_b/N_0 given by Figure 1. Can you see why increasing the number of bits/symbol makes the signal more susceptible to noise? Be sure to look at the receiver constellation plot, which shows this effect dramatically.
3. For fun, try M=64 or M=256. Although the situation may appear hopeless, modems using constellations this large or even larger are quite common (for example, digital cable HDTV uses 64-QAM or 256-QAM). Clearly these require very low-noise channels to operate!

1.6 Effects of Pulse Shaping

In earlier examples and exercises, we set the "TX Filter" to be "none," which means that rectangular pulse shapes are used. These are zero ISI pulses; however they are avoided in many practical applications due to excessive bandwidth requirements. Although we might expect to see rectangular-shaped pulses displayed in the eye diagram, the pulse shape we see appears to be triangular, with straight lines connecting the sample points. The reason for this is that the eye diagrams represent the output of a matched filter at the receiver.

A matched filter can be viewed in the frequency domain as a filter with frequency response matched to the pulse frequency response. In the time domain, this is a convolution of the received signal with a time-reversed local copy of the transmitted pulse. This is implemented as a multiplication of the two pulses followed by a "lossy" integrator. A lossy integrator sums received signal energy only over the most symbol period. This has the effect of improving SNR at the sample point at the end of the symbol period since the integrator accumulates signal energy over T seconds while noise power is unaffected by integration and remains at about the same level.

When rectangular pulses are used, the local copy of the waveform is just a constant, so the input to the integrator is just the received rectangular pulse sequence. The integration of the rectangle sequence results in either ramp shapes (when there is a symbol transition) or constant values (when there is no transition). At the end of each symbol period, the output peaks and the result is sampled. For RRC pulses, the matched filter output is the desired RC pulse as described above. And finally, when raised-cosine pulses are used at the transmitter, no receiver filtering is used as the signals are already zero ISI RC pulses and any filtering would destroy the ISI property. In the next section, we illustrate the effects of using different pulse shaping filters.

1.6.1 Example: 4-QAM with pulse shaping

Set up the simulation to give 4-QAM with “Raised Cosine” “TX Filter” and 40 dB E_b/N_0. Run the simulation. The eye diagram at the receiver end is as follows.

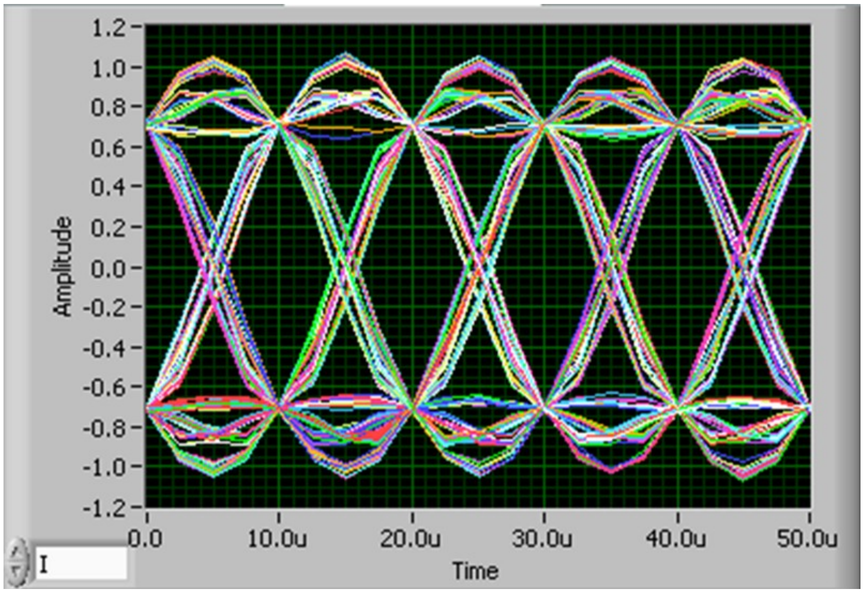


Figure 6

Figure 6. Eye diagram (in-phase) of 4-QAM at the receiver end with “Raised Cosine” pulse shaping filter.

Since the eye diagram is similar to an oscilloscope with persistence, we can get good idea of the pulse shape being used. This plot illustrates the important properties of zero-ISI pulses: First, note that the pulses are rounded and smooth – this results in minimal transmission bandwidth. Second, note that although the pulses are much wider than a single symbol duration, there is no interference from adjacent symbols as long as the receiver samples the waveform in the exact center of the eye.

1.6.2 Exercises:

- Repeat earlier experiments using different SNR values to see if pulse shaping affects performance in noise.
- Change the "TX Filter" to be "Root Raised Cosine", and observe the eye diagrams and constellation graph at the receiver. Compare your observation with "Raised Cosine" case. It should look the same since the combination of RRC pulse shaping at the transmitter and RRC matched filtering at the receiver results in a waveform that has raised-cosine performance.
- Now compare the constellation plots for RRC at both the transmitter and receiver. The transmitted signal constellations are significantly spread out in I-Q space, which does not seem to be a good thing! However, remember that the root-raised cosine is not a zero ISI pulse shape. It has the zero ISI property only after the receiver applies a matching RRC filter. Thus, what you're seeing is inter-symbol interference in the transmitted signal, and this will be removed by the receiver.