2006-1598: A COMPREHENSIVE SUITE OF TOOLS FOR TEACHING COMMUNICATIONS COURSES

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A Comprehensive Suite of Tools for Teaching Communications Courses

Abstract

Both the U.S. Naval Academy and the University of Wyoming offer a wide variety of electrical engineering courses concerning communications. Additionally, required design courses offer opportunities for exposure to a wide variety of real-world communication systems and topics. Whether these courses are discussing the basics of analog and digital communications, or the details of advanced digital modulation schemes and error performance, until very recently, we have found it exceeding difficult to perform communications systems demonstrations and the subsequent signal analysis without a phenomenal amount of specialized hardware and personal effort. This all changed when both schools started using a National Instrument (NI) vector signal analyzer (VSA) and vector signal generator (VSG). Both of these functions are contained within a standalone PXI chassis. These hardware functions are enabled and controlled by LabView and the vast array of toolkits available from NI. This paper discusses the use of this hardware and software in both the lecture and design environment.

1 Introduction

Both the U.S. Naval Academy and the University of Wyoming offer a wide variety of electrical engineering courses concerning communications. This includes, but is not limited to, Introductory Communications Theory, Modern Communications Systems, Data Networks, Fiber Optics, and Wireless and Cellular Communications Systems. Additionally, required design courses offer opportunities for exposure to a wide variety of real-world communication systems and topics.

Whether these courses are discussing the basics of analog and digital communications, or the details of advanced digital modulation schemes and error performance, until very recently, we have found it exceeding difficult to perform communications systems demonstrations and the subsequent signal analysis without a phenomenal amount of specialized hardware and personal effort. This all changed when both schools started using a National Instrument (NI) vector signal analyzer (VSA) and vector signal generator (VSG). Both of these functions are contained within the standalone PXI chassis shown in Figure 1. These hardware functions are enabled and controlled by LabView and the vast array of toolkits available from NI.

The use of spectrum analyzers in the classroom is not new. Mehrl, et al.[1] proposed a PC soundboard based audio-band spectrum analyzer, while Morrow, et al. introduced more powerful real-time DSP hardware-based spectrum analyzers.[2] Although these systems are useful, their limited frequency range severely restricts the range of applications that can be studied.

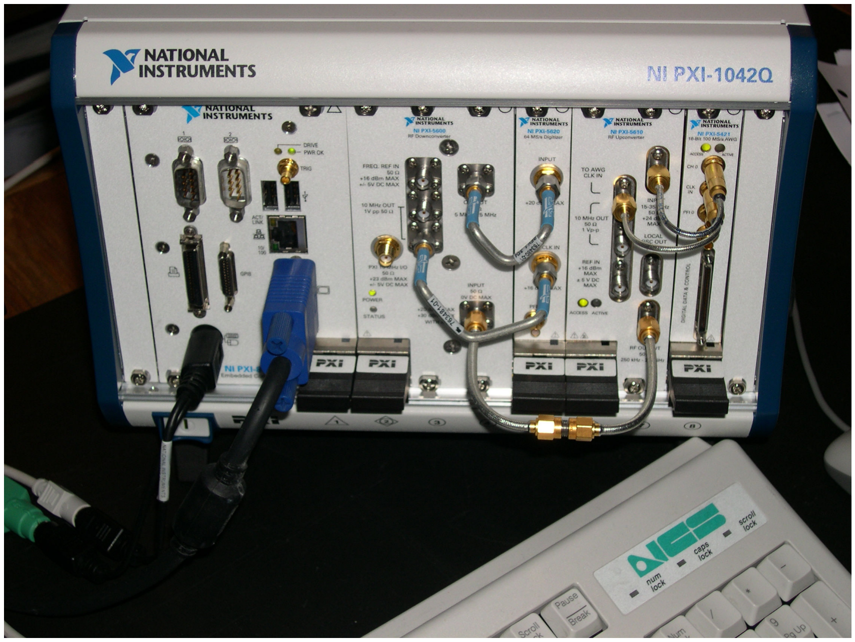

Figure 1. A National Instruments PXI chassis configured for communications systems use.

The advantages of using a full-fledged VSA and VSG were recently demonstrated by Welch, et al.[3] who discussed its use in a laboratory-based course on special communication topics. This was a very rewarding experience that indicated such wide-band instruments could be valuable teaching tools in a variety of communication courses.

2 Description of the Hardware

NI's PXI system provides a tremendous amount of capability for use in the classroom or student laboratory environment. The PXI is a configurable backplane chassis that can be adapted to a wide range of applications. In our case, the system includes a PC-compatible controller running Windows XP professional, an NI 5421 arbitrary waveform generator (AWG), an NI 5610 RF upconverter, an NI 5600 RF downconverter, and an NI 5620 digitizer. As shown in Figure 2, the AWG outputs a 20 MHz bandwidth signal at an intermediate frequency (IF) of 15 MHz. This is fed to an upconverter that spans 250 kHz to 2.7 GHz. The matching downconverter outputs a 15 MHz IF signal that is processed by the digitizer. All of these systems are controlled by a sophisticated yet fairly user-friendly set of LabView programs that take care of signal generation as well as signal acquisition for real-time display and analysis. The modules are interconnected as desired using semi-flexible SMA-to-SMB coaxial cables. For example, the upconverter output and downconverter input can be connected directly together, or can be attached to antennas as shown for capturing or producing real-world signals.

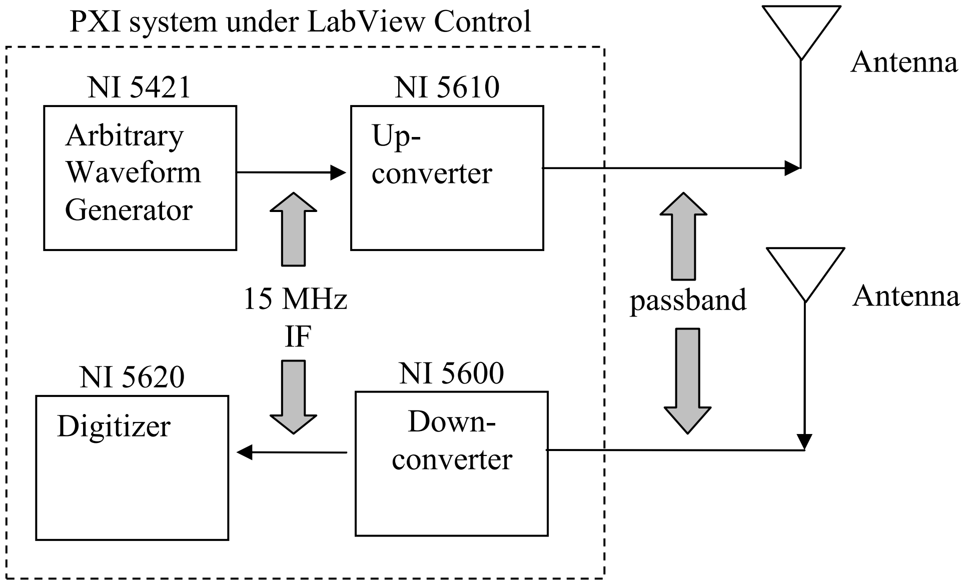

Figure 2. Block diagram of the PXI communication system configured for wireless use.

3 Educational Uses of the PXI System

While inexpensive audio-band signal analyzer systems are useful at showing concepts of signal spectrum and I/Q modulation, the benefits of using a professional grade tool for displaying the properties of real-world signals captured in real-time are difficult to understate. In the following sections we provide a few examples of the many ways the PXI system can be used to enhance classroom teaching. We use the PXI system primarily as a classroom demonstrator as it's cost (about $39K including educational discount) usually precludes purchasing one for every student workbench. However, the system *can* be used for some student lab exercises with students working in teams who schedule its use. A few examples of this approach are also suggested below. Finally, although it is impractical for individual students to regularly have access to the PXI system, the NI Modulation toolbox provides for the next best thing. Included software simulation modules make it possible for students to use LabView-equipped workstations to experiment with sophisticated communication systems and signals, and get an "almost" real-world experience. Some options for this approach are discussed toward the end of the paper.

3.1 The PXI as a Classroom Demonstrator

Although the PXI would be valuable in many communications-related courses, we've only had the opportunity to apply it in the basic Communication Theory class. We illustrate its use in delivering four important concepts:

- The concept of the radio spectrum
- The spectra of broadcast AM or FM radio
- The concept of in-phase and quadrature (I/Q) signals
- The effects of noise in communication.

Table I lists LabView modules provided in the Modulation Toolbox specifically designed for the PXI system that allow ready access to a variety of communication modes.

Generation	**Analysis**	**Simulation**
FSK Signal Generation	Cumulative power distribution	AM, FM, PM transceiver
PSK Signal Generation	Demodulate AM, FM	DQPSK Transceiver
AM Signal Generation	FSK Deviation and Trellis	FSK, MSK, PSK, QAM BER simulation
QAM Signal Generation	I/Q analysis and plotting	PSK, FSK, MSK, QAM transceiver
AM with Noise Generation	MSK Deviation and Trellis	Rayleigh Fading
General I/Q Signal	PSK eye and 3D eye	Rician Fading
FM Signal Generation	QAM eye and 3d eye	
PM Signal Generation	QAM demod	

Table I: PXI LabView Modules in the NI Modulation Toolbox.

The early weeks of the communication theory course are typically spent reviewing signals theory and can easily extinguish any initial student interest. This is a great time to bring in the PXI on a regular basis to illustrate some basic concepts and generate some excitement. Therefore, early on we discuss the radio spectrum and the basic idea of frequency multiplexing. The true scale of the spectrum is difficult for most people to envision. For example, new ultra-wideband (UWB) signals can have bandwidths of over 500 MHz, but what does this really mean? With an antenna attached to the downcoverter, the provided “RFSA Demo Panel” is used as a spectrum analyzer to zoom in and out to show locations and bandwidths of AM, FM broadcast, as well as the analog cell phone band. The huge bandwidth of a UWB signal becomes clear when we see that all broadcast AM and FM stations, many police and fire channels, as well as the first 20 TV stations all fit within the first 500 MHz of the spectrum. In these demonstrations, best results are obtained using a preamplifier to make up for heavy attenuation due to our building. A snapshot of the screen is shown in Figure 3.

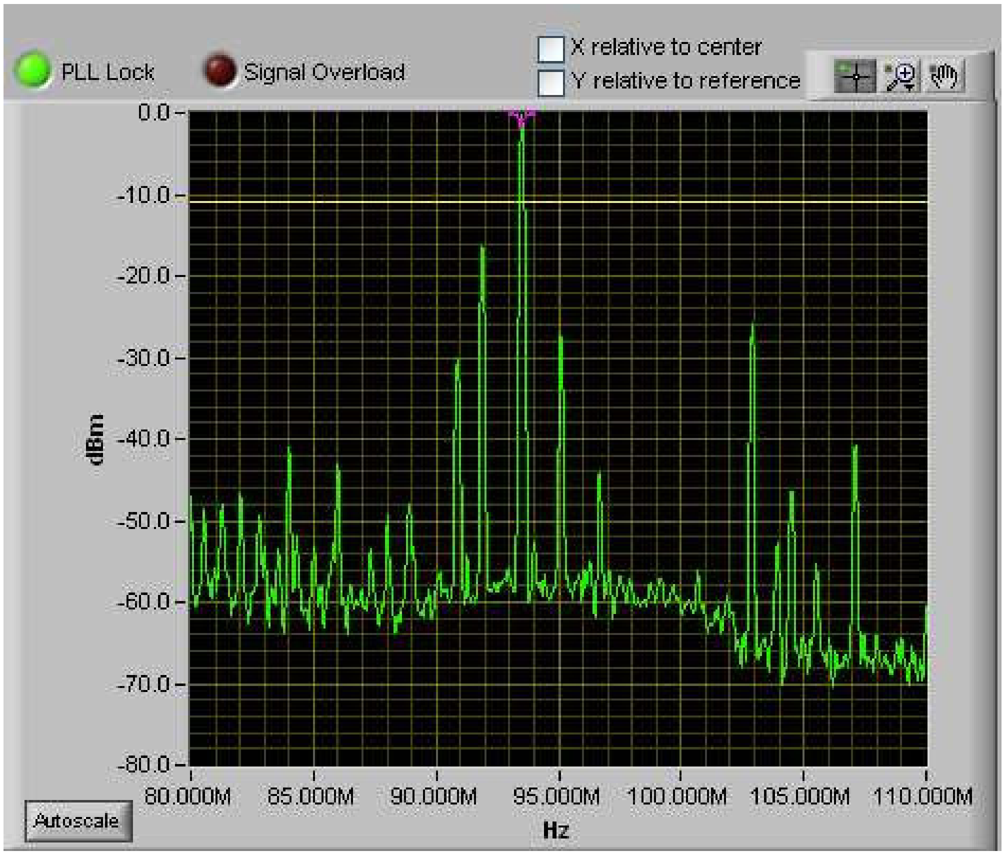

Figure 3. Broadcast FM spectrum showing many local stations.

Later in the semester, we discuss the composite audio signal used in broadcast FM radio. Basically, this means that prior to modulation, an audio signal is constructed comprising the sum of the monophonic (left + right), stereophonic (left - right double-sideband modulated to 38 kHz), and a 19 kHz pilot tone. This signal is then FM modulated and sent to the antenna. To illustrate this seemingly strange procedure, we started with a provided LabView program (i.e., Virtual Instrument, or "VI") designed to demodulate an FM signal and added the capability to compute and display the composite audio spectrum. In class, we watch the various spectral components rise and fall in real time while listening to the FM station on a portable radio. It's a very useful demonstration. An example screenshot is shown in Figure 4.

Figure 4. Screenshot showing composite audio spectrum from a real-time FM broadcast.

At about mid semester, the concept that signals can be decomposed into two orthogonal components called the "in-phase" (I) and "quadrature" (Q) is introduced. This material is extremely difficult for students because it relies on complex math representations of the signal. However, a thorough understanding of this idea is crucial for discussion of analog techniques such as single sideband (SSB) as well as many M-ary digital communication schemes such as quadrature amplitude modulation (QAM). Using the PXI system to demonstrate these ideas in real-time does a great deal to help students understand and absorb these difficult concepts.

We often begin the discussion by noting that FM is a constant envelope technique, but has an angle that increases with time. In I/Q space, the signal traces out a circle, as shown in Figure 5. In this case, the low signal-to-noise ratio (SNR) of signals in our building results in a "fat" circle due to noise modulation of the envelope. Later, we discuss M-ary digital communication schemes. The ability to generate, for example, 4- or 16-QAM signals, and then display them is extremely effective. The VI's allow parameters such as symbol rate and pulse shaping to be varied in real time, making it much easier to illustrate these concepts. Figures 6 and 7 show screenshot examples for a 16-QAM eye diagram and I/Q plot with pulse shaping. These dramatically show how susceptible such schemes are to increasing levels of noise, as discussed later.

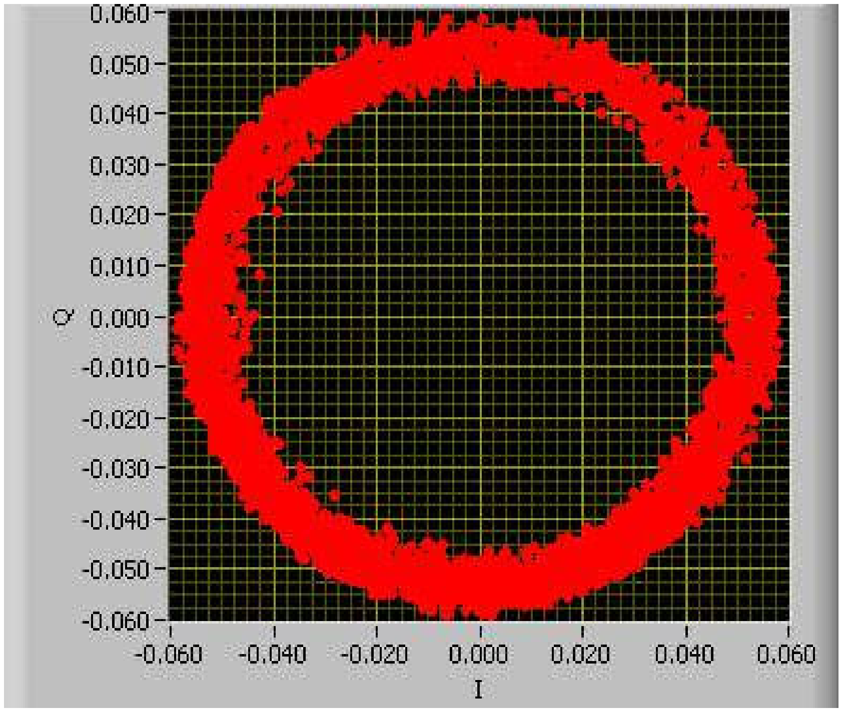

Figure 5. Screenshot showing I/Q plot of a broadcast FM signal.

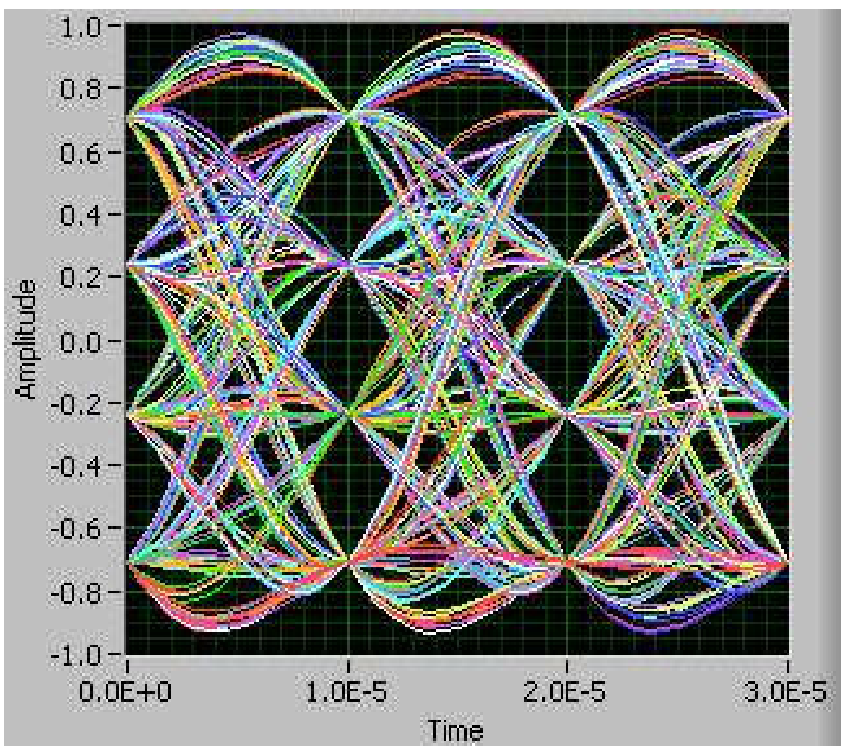

Figure 6. Screenshot showing one half of the demodulated 16-QAM eye diagram when pulse shaping is used. Eye diagrams are useful for understanding the noise margin for a given system, as well as the potential sensitivity to timing errors.

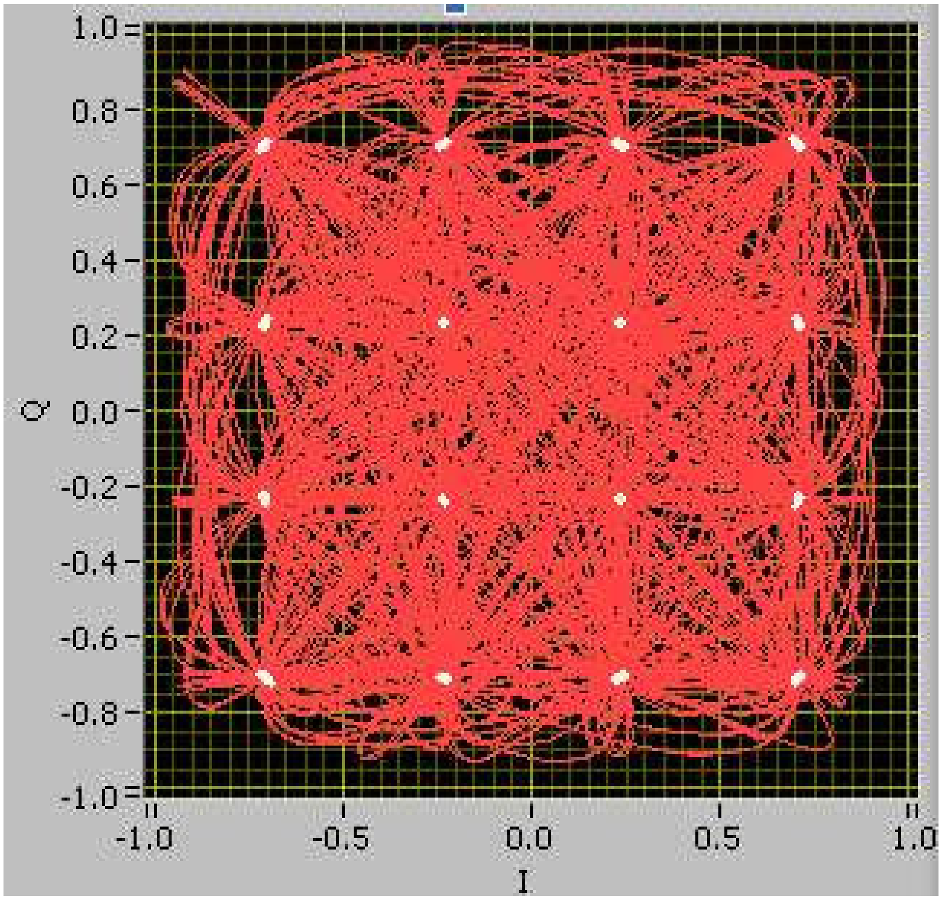

Figure 7. Screenshot showing eye diagram of demodulated 16-QAM signal with pulse shaping.

As another example of what can be done using the PXI, we demonstrate the effects of multi-path interference using an in-class experiment. With an antenna attached to the downconverter, the spectrum analyzer VI is used to measure the strength of a small portable transmitter operating in the 800 MHz band. Students take turns carrying the transmitter to pre-chosen locations down the hall and then slowly change positions by increments of about 25 cm. In the classroom, students plot received signal strength in dBm as a function of position, which often shows deep fades in signal over relatively small distances. This illustrates typical challenges modern cell phones and Wi-Fi systems have to overcome to provide acceptable service, even in more or less benign environments.

Finally, it is important to note that the I and Q signals can be captured and stored through minor modifications to the LabView VI's. An instructive exercise is to have the students demodulate a real-world signal using Matlab. For example, suppose an FM signal is captured and stored in a Matlab vector "s" such that the in-phase and quadrature components are represented as the real and imaginary parts. We can extract the signal envelope as "envelope = abs(s)" and the instantaneous phase as "theta = angle(s)". Since the FM phase is the integral of the message signal, the message signal can be extracted by differentiating the phase using "m = diff(theta)". When students complete these rather esoteric operations and then output a recognizable audio signal, it strongly reinforces the connection between the math and the physical signal.

3.2 Using the Modulation Toolbox Simulation VI's

Using the PXI system is especially effective in demonstrating the effects of noise and interference on digital communication systems. As we've discussed the system so far, the generation and demodulation process does not explicitly introduce noise, and the only noise present is whatever might be present at the downconverter antenna. Better control is provided by the LabView simulation VI's, which provide students easy access to accurate modeling of communication systems in noise. A nice benefit of these VI's is that they are available on any of our systems with LabView installed. Therefore, although students don't have full-time access to the PXI system, they can utilize the simulation VI's as needed. We have found these modules to be extremely well written, and provide a near real-world experience very similar to what they would see if they were using the PXI. Figure 8 is an example of 16-QAM with E_b/N_0 = 15 dB, clearly showing the effects of added noise "closing" the eyes and making bit errors more likely. Figure 9 is the corresponding I/Q constellation diagram. Students are given the exercise of adjusting the noise level until effective communication becomes impossible ("threshold" effect), and compare to theoretical values discussed in class.

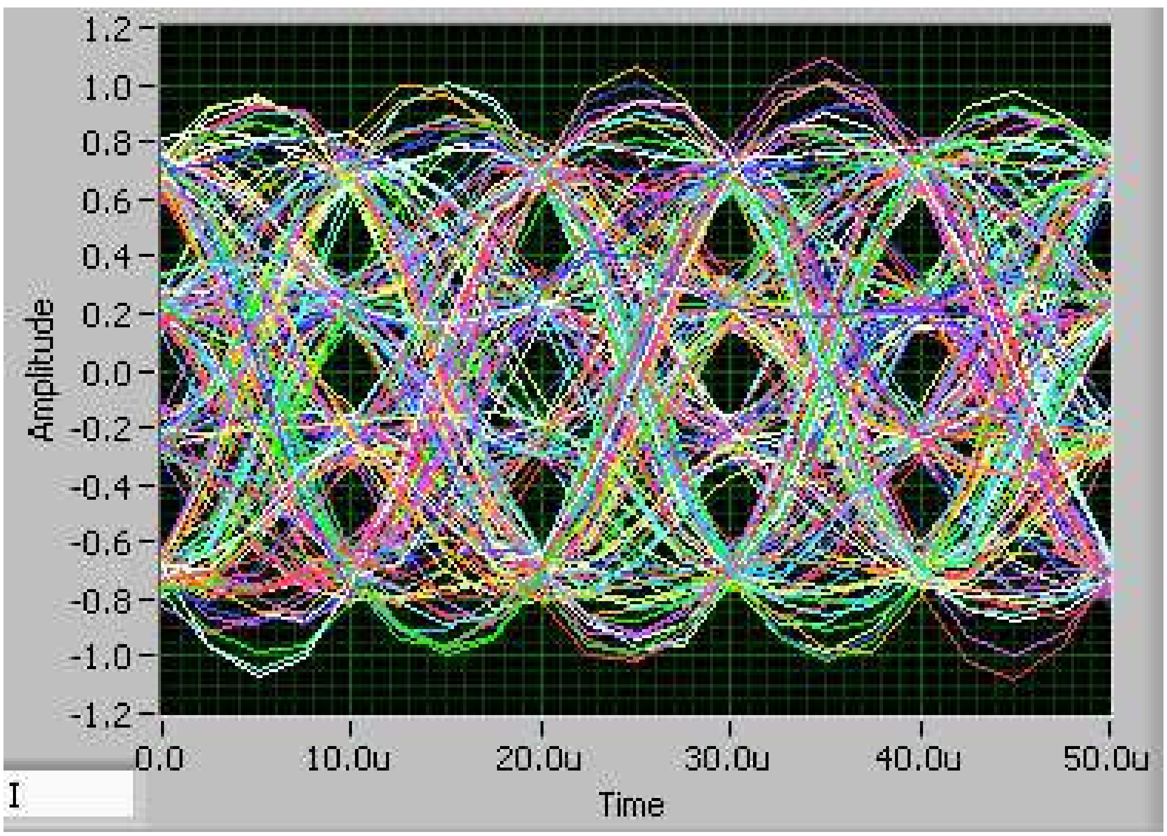

Figure 8. Screenshot of eye diagram for 16-QAM and E_b/N_0 = 15 dB, showing "eye closing" and increase bit errors.

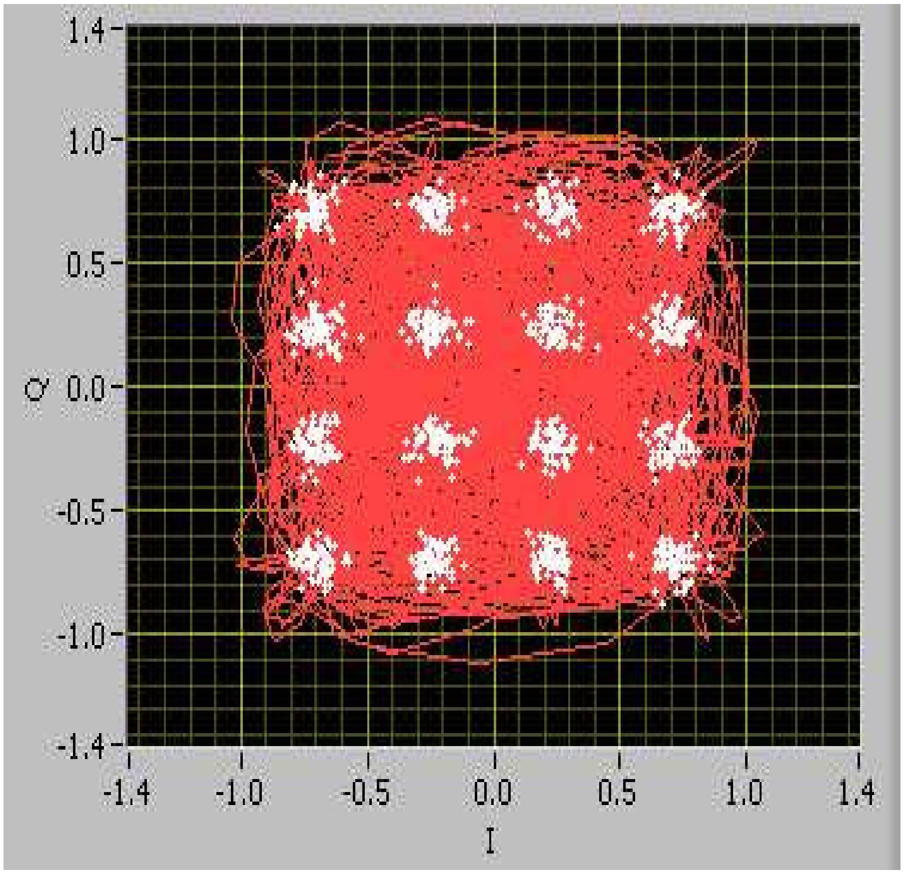

Figure 9. Screen shot showing 16-QAM constellation with E_b/N_0 = 15 dB. This illustrates how added noise makes bit errors more likely since the sample locations begin to overlap with additional noise.

As a final example, we note that the main goal of this communication theory course is to give a one-semester survey of the most important communication topics. This leaves little time for development of formal bit-error rates and probability of error for different systems. However, the basic performance of various systems is discussed, and the LabView simulations come in quite handy. For example, students can work with the simulator to find the parameters of an FSK system that will achieve a given bit error ratio using the minimum amount of spectral bandwidth. This involves selecting a modulation index (which increases the bandwidth and reduces the error rate), choosing different pulse shaping values, and figuring out how many bits per pulse to use. As an example, Figure 10 shows the BER curve for 2-FSK and 1500 Hz frequency deviation with 10,000 symbols/sec. Students can change to 4-, 8-, 16-, 32-, 64-, or 128-FSK, can modify the frequency deviation, can use continuous or discontinuous phase, and can select the transmitter filter (none or Gaussian) in order to achieve their design goals. After each set of parameters is entered, they run the simulation and quickly get the BER graph. These parameters are discussed only broadly in class, but using this package the students get a good feel about how they impact system performance.

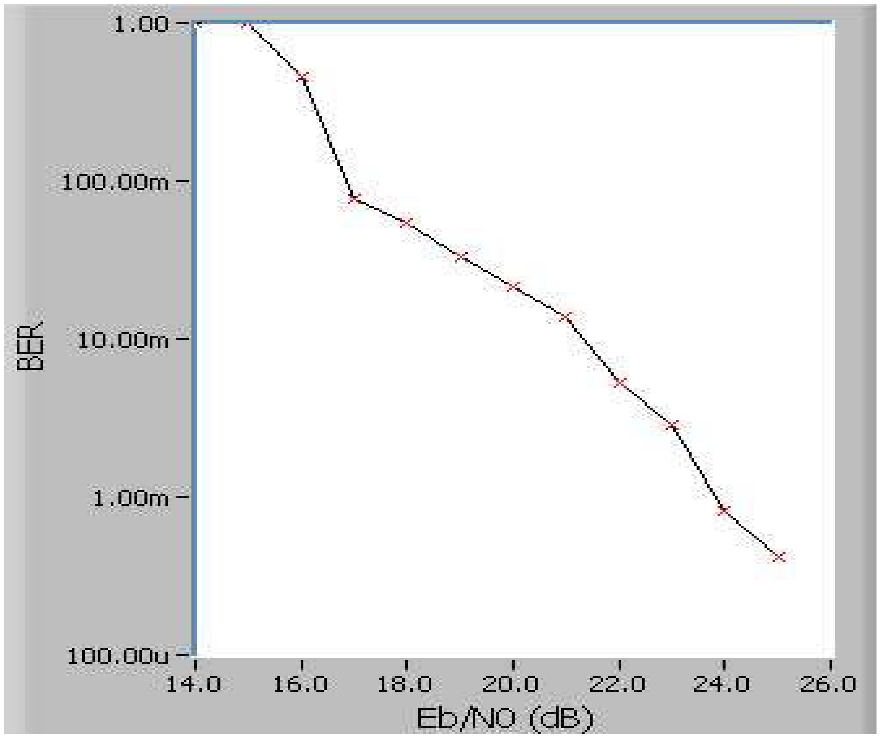

Figure 10. Screenshot of a BER plot for 2-FSK using Gaussian filtering and continuous symbol phase.

3.3 Senior Design Projects

A few students have also had the opportunity to use the PXI chassis as the basis for a senior design project. Only two of these projects will be discussed.

In the first project the students wanted to control an RC (remote controlled) car using the PXI chassis. This project required the reverse engineering of the modulation schemes employed by the car's manufacturer to control the throttle and steering. This was accomplished by capturing and recording the RF signals associated with the remote control system. The recorded signals were then demodulated using Matlab. The demodulator specifications were determined and regenerated using the transmitter capability of the PXI chassis. Video capability and remote access via the internet are also being attempted.

In the second project the student wanted to design a system that detects and then jams an 802.11b WLAN system. This is a combination of the spectrum analyzer function and the transmitter/signal generation function that were previously discussed. Since both of these functions already exist, this project was largely about timing. Specifically, given a co-located transmitter and receiver (both units being inside the same PXI chassis) the system need to be reconfigured to "listen" for an 802.11b signal, and then jam (transmit) during time periods when the receiver was not "listening."

4 Conclusions

The PXI system is an outstanding addition to any department teaching communications or signals related classes. Its use in the classroom as a demonstrator is especially valuable, providing a way to exhibit and explain some of the most difficult concepts in an engineering curriculum. The provided LabView modules provide instant access to powerful signal generation and analysis capabilities, and can be readily modified for any desired pedagogical requirement. While it may not be practical to purchase PXI systems for each student workbench, a single system can be effectively used for communication projects by teams of students. The LabView Modulation Toolbox allows students to individually experience the power of a professional quality arbitrary waveform generator and vector signal analyzer.

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5 References

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