

## **AC 2007-3034: LOW-COST VECTOR SIGNAL ANALYZER FOR COMMUNICATION EXPERIMENTS**

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# Low-Cost Vector Signal Analyzer for Communication Experiments

## Abstract

Vector signal analyzers (VSA) are systems that provide real-time analysis of in-phase and quadrature components of RF signals, as well as providing spectral analysis and other signal measurement features. VSA's would be an ideal addition to any undergraduate communications laboratory because of their ability to investigate the many types of signals prevalent today. Unfortunately, most VSA's are priced well beyond the budgets of typical undergraduate ECE departments. This paper describes a novel low-cost VSA that uses basic PC data acquisition (DAQ) cards to capture signals of interest and real-time processing of signals with LabVIEW and MATLAB. This VSA system provides a user interface that has much of the basic functionality of standard hardware VSAs, but with the limitation that bandwidth is constrained by the sampling rate of the DAQ. The system provides real-time plots of I/Q constellations. We describe the user interface as well as example laboratory experiments, where students get hands-on experience with a variety of signals such as BPSK, QPSK, and QAM. Any undergraduate lab with workbenches outfitted with standard PC and data acquisition equipment will be able to make use of this novel VSA.

## 1. Introduction

Many universities offer a laboratory component as part their introductory digital and analog communication course. In traditional undergraduate teaching laboratory environments, many communication topics are difficult to convey because of their complexity in implementation. In the first reference<sup>1</sup>, a framework for meaningful hands-on undergraduate communication laboratories was introduced using a set of LabVIEW-based exercises that interact with computer-controlled industry-standard test and measurement equipment. This environment allows the students to explore a wide range of communication concepts using actual real-world signals and a balance between what is provided for the students and what the students need to design and implement to reinforce a particular concept. This paper expands on previous work<sup>1</sup> by introducing a low-cost vector signal analyzer (VSA) built around a PC based data-acquisition (DAQ) card using LabVIEW and MATLAB. The second reference<sup>2</sup> describes the use of hardware VSA's in undergraduate labs. This paper goes on to describe a number of student laboratory exercises which use this VSA.

Most undergraduate textbooks<sup>3-6</sup> do an excellent job of describing signal constellations that would be observed for signals such as QPSK and QAM, but few mention VSA's as the test equipment used to measure these constellations. By introducing VSA's in the laboratory, students get exposure to equipment used in the communication industry and hands on experience with real-time I/Q techniques. Many students find I/Q concepts to be difficult to understand. By having the students work with real-time I/Q signals in the laboratory, a goal is to make these concepts less abstract and more meaningful to the students.

Many test instruments can be created for undergraduate laboratories using a data acquisition card and LabVIEW. While the speed of operation of these instruments is usually limited by the acquisition rate of the data acquisition card and the computing power of the PC, the basic

functionality can compare with that of more expensive equipment. This lower speed of operation and basic functionality is adequate for educational laboratory exercises.

In this case, the novel VSA system provides a user interface that has much of the basic functionality of standard hardware VSA's, but with the limitation that bandwidth is constrained by the 1.25 MSa/s sampling rate of the DAQ. The system provides real-time plots of I/Q constellation as well as signal spectrum displays. The user interface is described as well as example laboratory experiments, where students get hands-on experience with a variety of signals including BPSK, QPSK, and QAM. Non-idealities such as I/Q gain mismatch are also explored. Any undergraduate lab with workbenches outfitted with standard PC and data acquisition equipment will be able to make use of this VSA.

The paper is organized into the following sections. Section 2 describes the theory of operation of the low-cost vector signal analyzer. Section 3 gives examples of how the VSA can be used in undergraduate communication laboratory exercises. The final section concludes the paper.

## 2. VSA theory of operation

The vector signal analyzer is implemented using National Instruments' LabVIEW and Mathworks' MATLAB. The combination of the two software packages allows easy data acquisition as well as an easily modifiable processing code. The entire project could be accomplished completely in either LabVIEW or MATLAB, but difficulties in implementation resulted in the combination of the two used here.

LabVIEW is used to interface with the data acquisition card and sample the analog communications waveform. MATLAB then provides all of the processing to demodulate the signal and generate the vector signal output. A LabVIEW based front panel provides a GUI to control the relevant processing settings and to display the final data result. An overview diagram of the vector signal analyzer implementation is shown in Figure 1.

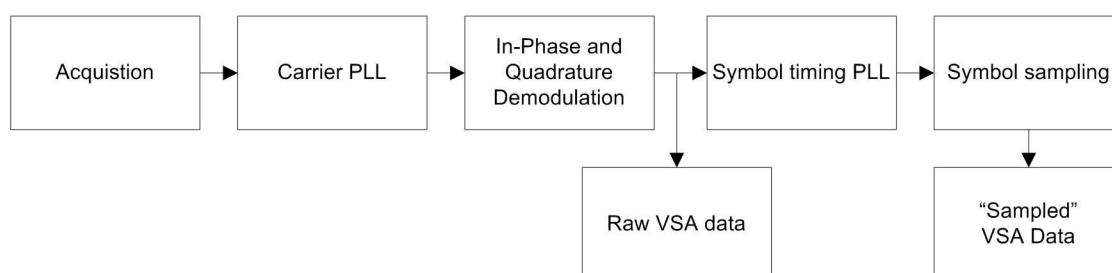


Figure 1 – Block diagram of Vector Signal Analyzer

The first stage of the MATLAB processing implements a simple phase locked loop (PLL) to determine the modulating carrier. Many different PLL algorithms could be used to acquire the carrier signal timing. Our software VSA implements a very basic PLL algorithm based on the trigonometric identity  $2 \cdot \sin(\omega t + \phi) \cdot \cos(\omega t + \theta) = [\sin(2\omega t + \phi + \theta) + \sin(\phi - \theta)]$ , with  $\omega$  as the carrier frequency,  $\phi$  as the PLL phase, and  $\theta$  as the carrier phase. By modulating a sine output of the PLL by the input carrier, the phase error between the two is contained in the baseband sine term. Taking an arcsine of the DC value determines the amount of this phase error. Since the

data is acquired in blocks as part of the LabVIEW acquisition method, an average of the carrier phase is calculated and used to create a final locked carrier.

Once the carrier phase has been locked, the VSA demodulates the original waveform into an in-phase (I) and quadrature (Q) component. The in-phase term is the component in phase with the carrier, the quadrature component is the component in phase with  $\sin(\omega t)$ . This is detailed in  $x(t) = I(t) \cdot \cos(\omega t + \theta) + Q(t) \cdot \sin(\omega t + \theta)$ , where  $x(t)$  as the acquired input signal,  $I(t)$  as the in-phase term, and  $Q(t)$  as the quadrature term.

Once demodulated into the I and Q components, the VSA now has a raw representation of the input communications signal that includes effects of noise and pulse shaping. These individual I and Q samples are plotted on a two-dimensional graph in Figure 2a. However with every sample of the input waveform plotted, the I-Q plot is difficult to interpret. A very simple symbol averaging system is implemented to alleviate this problem.

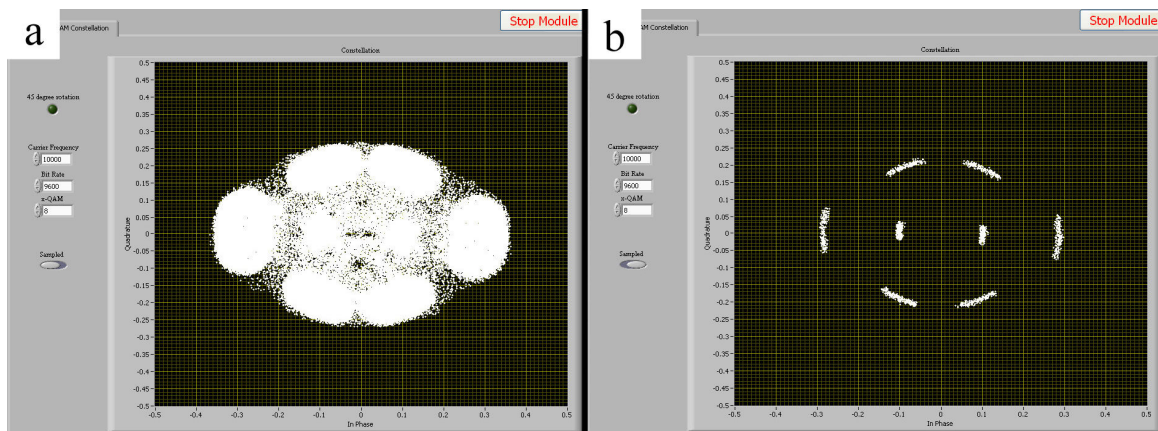


Figure 2 – (a) Raw VSA output for 8 QAM, and (b) symbol averaged output

It first attempts to acquire the symbol timing and then averages the signal across each symbol interval as is done in a classic correlation receiver. This has the effect of reducing noise power, and collapsing each symbol to a single point. The VSA plot shown in Figure 2b is much clearer than that in 2a, and it is much easier to extract the relevant information.

### 3. Student experiments using the VSA

In this section we describe how the VSA can be used in communication theory laboratory exercises. Ideally, these exercises are introduced after the students have learned about digital line codes. Those concepts are now extended to carrier communication systems, where multi-level line codes are modulated with AM, PM, etc., to produce binary phase-shift keying (BPSK), M-ary PSK (M-PSK), M-ary frequency shift-keying (M-FSK) and others. Objectives of VSA-oriented labs are to give hands-on experience using a VSA, give better understanding of I/Q modulation techniques, demonstrate bandwidth-savings possible by using these schemes, and illustrate how line-code pulse shaping ideas are easily applied to carrier systems.

Our lab setup uses a Windows-based workstation to integrate a suite of test equipment including an FFT-capable sampling oscilloscope, signal generator, power supplies, analog-to-digital

converter, and Texas Instrument DSP Starter kit (DSK). The DSK includes a TMS 320C67x DSP, memory, and I/O to interface to the PC. In this application we use the DSK running WinDSK6 software<sup>7-10</sup> to generate communication test signals. The “CommDSK” feature of WinDSK6 provides a wide range of test signals including M-PSK (M=2, 4, 8, 16), as well as 8-QAM and 16-QAM. Provisions are made for pulse shaping, adding noise or interference, and adjusting I and Q gain. In addition, the second stereo channel can be used to output the baseband or modulated I and Q signals. All of these signals can be studied using either the FFT-scope or LabVIEW modules such as VSA and spectrum analyzer.

Students are asked to investigate a sequence of digital carrier systems beginning with BPSK. This can be viewed as a 2-level line code input to a DSB-SC modulator, i.e.,  $y(t) = m(t)\cos(\omega t)$ , where  $m(t) = +c$  (for bit  $b_k=1$ ) and  $-c$  (for  $b_k=0$ ), where  $c$  is some constant. The VSA displays signals that are in phase with  $\cos(\omega t)$  (called the “I” component) on the x-axis, and signals that are in phase with  $\sin(\omega t)$  (called the quadrature or “Q” component) on the y-axis. Students are asked to predict what they’ll see before running the experiment. In this case, there is no quadrature component, so the VSA displays “clouds” at  $\pm c$  on the x axis. The VSA output for BPSK is shown in Figure 3a.

Next, the students look at QPSK. One way to view this is as a 4-level line code input to a phase modulator:  $y(t) = \cos(\omega t + m(t))$ , where  $m(t)$  has four values representing 2 bits per symbol:  $m(t) = \pi/4, 3\pi/4, -\pi/4$ , and  $-3\pi/4$  corresponding to bits  $b_k b_{k-1} = 00, 01, 10$ , and  $11$ . In this case,  $y(t)$  has both I and Q components, i.e.,  $I(t) = \cos(m(t))$  and  $Q(t) = \sin(m(t))$ . A common difficulty students have in understanding QPSK is that it is often explained in class by using phasors. For example, if  $y(t) = A \cos(\omega t + \theta)$ , then the phasor is  $Y = A e^{j\theta} = A \cos(\theta) + j \sin(\theta) = I + jQ$ . Unfortunately, many students form a mental block whenever the “j” appears; thus a goal of this lab is to drive home the point that I is the amplitude of the cosine component and Q is simply the amplitude of the sine component. No imaginary signals are actually transmitted!

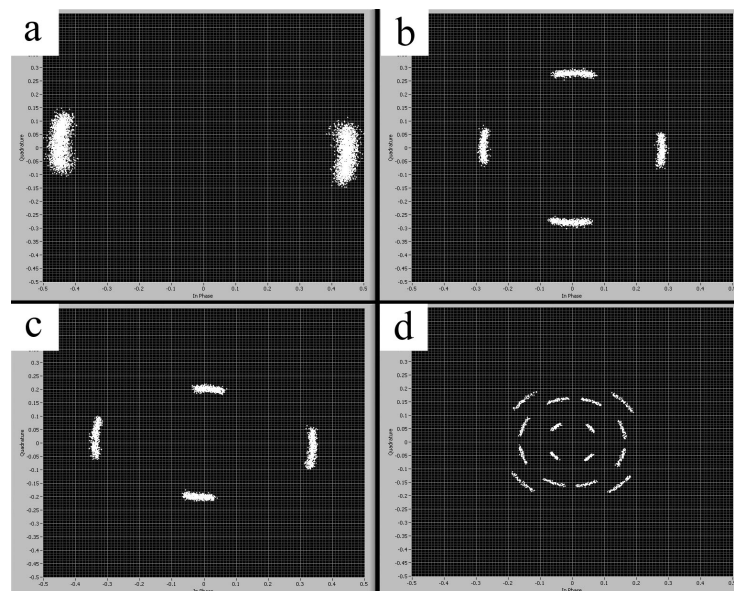


Figure 3 – Shows VSA output for (a) BPSK, (b) QPSK, (c) QPSK with I gain larger than Q gain, and (d) 16-QAM. Apparent phase errors are due to unresolved issues in the VSA software.

The VSA display for QPSK is shown in Figure 3b. Phase uncertainty in our algorithm causes the constellation points to spread out radially, but this problem is expected to be resolved soon. In order to deepen their understanding of I/Q concepts, students are asked to modify the I and Q gain relationship using the CommDSK software and predict the effect on the constellations. An example of increasing the I gain relative to Q gain is shown in Figure 3c. This shows the direct relationship between gain and the location of symbol clouds in the VSA diagram.

To give students further insight, they can simultaneously look at the separate I and Q waveforms using the oscilloscope and correlate this with what they see on the VSA display. For example the baseband I and Q waveforms are simple digital line codes whose amplitudes correspond to the x and y offsets on the VSA display. Furthermore, by using the pulse shaping option in CommDSK, students can see that this results in simple shaping of the baseband line codes. The resulting improvement in spectral efficiency can be observed using a LabVIEW-based spectrum analyzer.

Finally, 16-QAM is studied. Now, the I and Q components each represent 2 bits, so each branch requires a 4-level line code. As before, this can be verified by having students look at the baseband I and Q signals using the oscilloscope. This experiment is very effective at illustrating that not only the phase but also the amplitude of a signal can be varied to represent multiple bits per symbol. The encoding scheme simply assigns selected amplitudes to the I and Q components. Students are asked to determine as a homework or prelab assignment the value of I and Q for several digital words.

A typical VSA display for 16-QAM is shown in Figure 3d. Several important concepts can be emphasized using this example. First, while viewing the QAM spectrum, CommDSK is used to change the modulation technique from 16-QAM to 4-QAM while holding the bit rate fixed. Since bandwidth primarily depends on the symbol rate, students observe that the bandwidth expands immediately by a factor of 2 since 4-QAM requires double the symbol rate as 16-QAM for the same bit rate. Another valuable experiment is to have the students add Gaussian white noise to the signal using the “AWGN” option in CommDSK. As the noise level increases, the constellation clouds begin to overlap resulting in increased bit errors. Students can determine how much noise is required to cause significant overlap, and they can compare this with values of predicted bit-error rate curves provided in the text book. This provides a very physical feel for the basic cause of bit errors in QAM systems.

#### **4. Conclusions**

This paper proposes that student understanding of I/Q-based modulation schemes can be aided through use of VSA-based lab experiments. Although hardware VSA's are generally too expensive for use in most undergraduate communication labs, it is possible to provide a similar experience using a low-cost LabVIEW/MATLAB-based emulator. The software is available from the authors.

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