2006-508: TEACHING DIGITAL COMMUNICATIONS IN A WIRELESS WORLD: WHO NEEDS EQUATIONS?

Dennis Silage, Temple University

DENNIS SILAGE (silage@temple.edu) is a Professor in the Department of Electrical and Computer Engineering at Temple University. He has a Ph.D. in Electrical Engineering from the University of Pennsylvania, where he was on faculty from 1975 until 1984 when he joined Temple University. He is a Senior Member of the IEEE and director of the System Chip Design Center (www.temple.edu/scdc), which researches the application of programmable gate arrays in digital signal processing and digital communications. He teaches undergraduate and graduate courses in these areas. He is the trustee of the Temple University Amateur Radio Club (K3TU, www.temple.edu/k3tu), which he has integrated into the undergraduate communications curriculum and capstone senior design projects. Dr. Silage is a past chair of the Middle Atlantic Section of the ASEE and now the Secretary/Treasurer of the ECE Division of ASEE.

Teaching Digital Communications
in a Wireless World: Who Needs Equations?

Abstract

Digital communication is traditionally taught by examining the temporal and spectral response and the bit error rate performance of a system in the presence of additive noise as only a set of analytical equations. This approach seems to provide little insight or motivation for the undergraduate student. Undergraduate courses in digital signal and image processing extensively utilize simulation as an adjunct to understanding, but digital communications seems to be a laggard. An undergraduate curriculum in digital communications has been developed that couples the traditional analytical approach with the simulation of the system for further design, analysis, insight and motivation.

Bit by Bit Communication

Digital communication systems convey information from a source or transmitter over a channel to a sink or receiver. Modern communication systems often do so in the presence of additive channel noise and mild to severe channel and system non-linearities which tend to corrupt the transmission. Traditionally examining the performance of a digital communication system as only a set of analytical expressions, even if noise and non-linearities can somehow be described adequately, seems to provide little insight or motivation for the undergraduate student.

The sea change in this material is the introduction within the last decade of channel noise and non-linearities in the analysis of digital communication systems for the undergraduate student. Prior to this time, analog and digital communication systems were presented by analytical equations without channel noise and non-linearities and with a supplemental hardware laboratory without significant variability[1] (for example, jitter). An undergraduate curriculum in digital communications has been developed that couples the traditional analytical approach and text with the simulation of the system as interconnected models (tokens) for design and analysis.

One illustration of this concept is that the requisite analytical expressions provide a nearly automatic solution to the spectrum of a modulated signal, but are these spectra really what occurs? Another illustration is that the relative bit error rate (BER) performance of the simple single point sampler and the more complex matched filter or correlation receiver in baseband rectangular pulse amplitude modulation (PAM) with additive white Gaussian noise (AWGN) can be now be compared.

There is something rewarding for the undergraduate student in assembling a digital communication system from models, executing a simulation and then obtaining the spectrum of the signal or the comparative performance of receiver architectures in AWGN, all without benefit of the analytical solution or, for that matter, any equations at all. A digital communication system simulation allows its virtual construction to explore the *what-ifs* of design in the presence of channel noise and synchronization in demodulation. The typical block diagrams of digital communication system, which are proffered in a conventional text as if their mere appearance will somehow validate the analytical solution, can now be verified and further analyzed.

Can You Hear Me Now?

Audio *.wav* files can also be used as an input to the simulation to provide a perceptible assessment of the performance of a digital communication system. For example, μ-law companding (compression and expansion) of a speech signal for pulse code modulation (PCM) is routinely featured in a standard text. However, in this approach to teaching digital communication systems the μ-law companding PCM system is also simulated and the speech processing is audible.

An analysis of BER in PCM with AWGN and a speech signal can also be presented with the audible performance as a tangible reminder of the effect. These audio *.wav* files as input have been shown to entice the undergraduate student and provide a memorable experience. They now have the opportunity to go beyond the lecture course or even the digital communication hardware laboratory with its traditional experiments[1].

SystemVue by Agilent Technologies Eagleware (www.eagleware.com) provides the comprehensive digital communication system simulation environment and a recent text[2] provides supplemental support to any existing undergraduate course text. *SystemVue* is a descendant of the continuous system modeling program paradigm.

SystemVue simulations have been provided in a graduate text[3] as an addendum, but without the pervasive explanation suitable for an undergraduate course or laboratory in digital communication systems. A partial lesson survey of binary phase shift keying (BPSK) bandpass modulation and demodulation will illustrate this approach of using digital communication simulation to elucidate principles.

It's Only a (Binary) Phase

BPSK is a modulation technique that encodes binary information as only the phase of a sinusoidal carrier. BPSK can be simulated in *SystemVue* with the system configured with *Tokens* within the *Design Window* (Figure 1). The specifics of the *SystemVue* simulation are not appropriate for the intent of the lesson survey here. However, a detailed description of this BPSK digital communication system simulation in *SystemVue* is available[4].

The source (*Token* 9) is an audio *.wav* file that provides a perceptible performance of the BPSK digital communication system with bit errors due to an AWGN channel (*Tokens* 0 and 21). However, an observed BER measurement (*Token* 37) is also provided for a comparison to the analytical solution for P_b, the probability of bit error for BPSK binary data transmission in AWGN.

The BPSK transmitter metasystem (*Token* 4) encapsulates several tokens and converts the audio *.wav* file at 8 k samples/sec to a PCM output bit stream at a data rate r_b = 64 k b/sec (T_b = 15.625 μsec) with an 8-bit analog-to-digital converter, a 3-bit counter, and an

8-bit multiplexer. The phase modulator (*Token* 20) provides a BPSK signal with a carrier amplitude $A_c = 5$ V and a carrier frequency $f_c = 250$ kHz.

The normalized power spectral density (PSD) of the BPSK transmitted signal in the *SystemVue* simulation is derived from the analysis window (*Token* 46) and verifies the analytical solution[5] presented in the course lecture which contains a $sinc^2$ term centered at f_c and with spectral nulls at $f_c \pm r_b$ Hz (Figure 2).

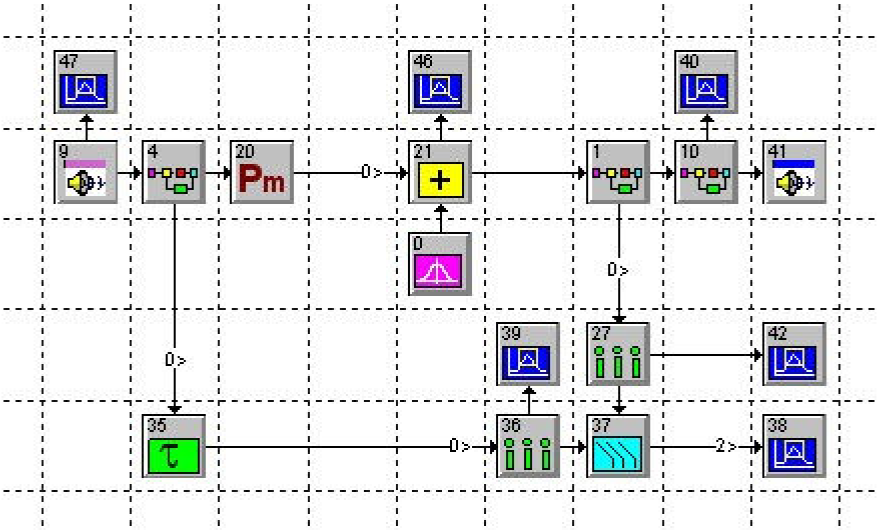

Figure 1. The *SystemVue* simulation of the BPSK digital communication system with BER analysis.

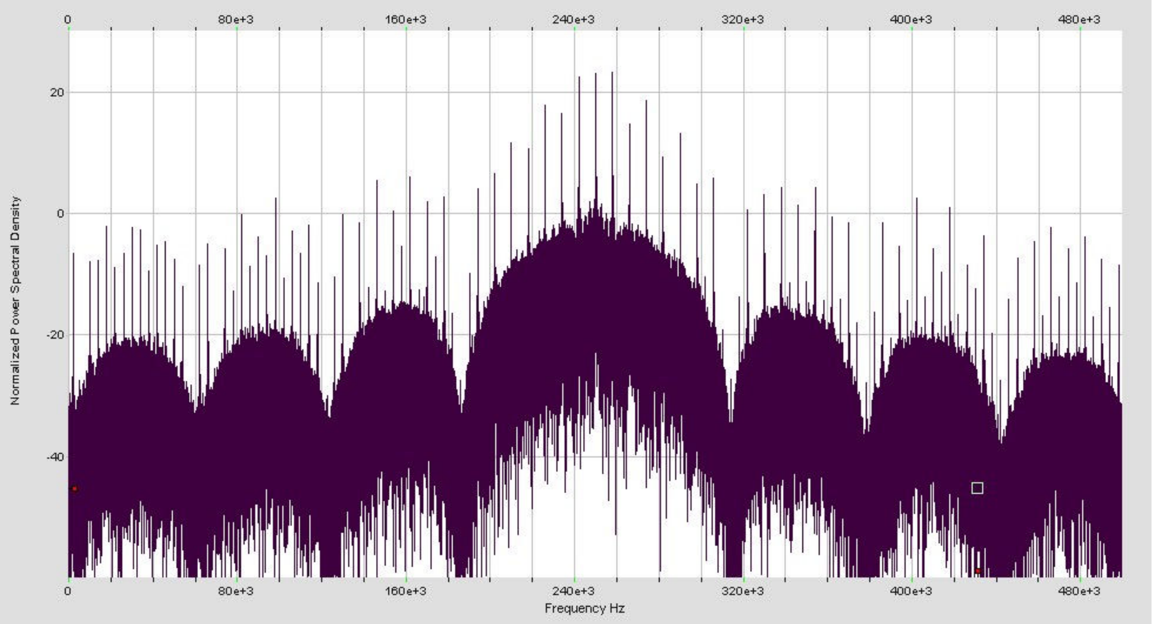

Figure 2. PSD of the BPSK transmitted signal for the audio *.wav* file input from the *SystemVue* simulation.

But what is the source of the periodic impulses observed in the PSD? This is an intriguing illustration of the *what-if* of digital communication system design that can be posed to the undergraduate student and is not featured in a standard text. The PSD of the BPSK transmitter now with a pseudonoise binary data input does not display these impulses (Figure 3). The periodic impulses are spaced every 8 kHz and the students soon arrive at the reasonable conclusion that they are due to the original 8 k samples/sec in the original *.wav* input file.

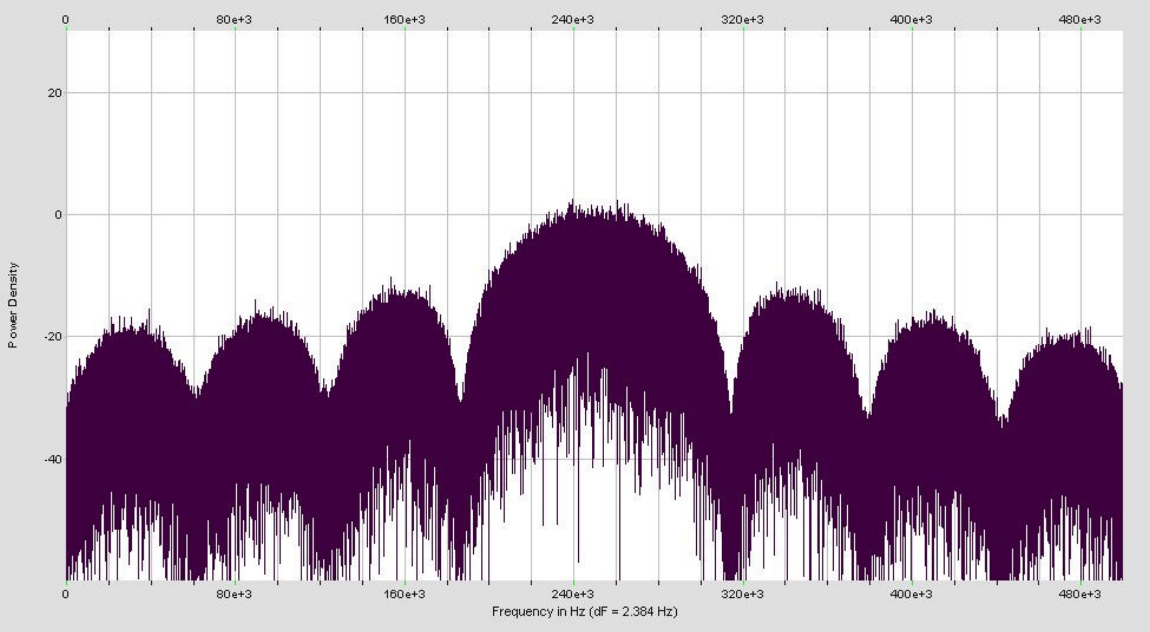

Figure 3. PSD of the BPSK transmitted signal for pseudonoise input from the *SystemVue* simulation.

The autocorrelation of the BPSK transmitted signal in the *SystemVue* simulation shows periodic relative maxima spaced every 125 μsec (1/8000) as predicted by the Wiener-Khintchine theorem[5] (Figure 4). This is a fascinating introduction to the characterization of digital communication signals that is usually not analytically presented in a standard text with any degree of conviction.

The first metasystem (*Token* 1) of the BPSK receiver implements an optimum matched filter or correlation receiver for symmetrical signals with perfect carrier and bit time synchronization (Figure 5). The second metasystem (*Token* 10) regenerates the audio *.wav* file with an 8-bit serial to parallel shift register, an 8-bit latch and an 8-bit digital-to-analog converter.

The theoretical P_b for a symmetrical BPSK signal in AWGN and with optimal reception, assuming that the apriori probabilities of the binary data and the energy per bit are equal ($P_0 = P_1 = 0.5$ and $E_b^{\,0} = E_b^{\,1} = E_b$), is presented in the course lecture[5].

$$P_b = \mathrm{Q}\left(\sqrt{\frac{2E_b}{N_o}}\right)$$

The function Q is the complementary error function and N_o is the power spectral density of the AWGN. The optimal threshold (*Token* 3) for the correlation receiver is set as $\tau_{\text{opt}} = 0$. *SystemVue* can calculate the statistics of the PCM binary data for the audio *.wav* file

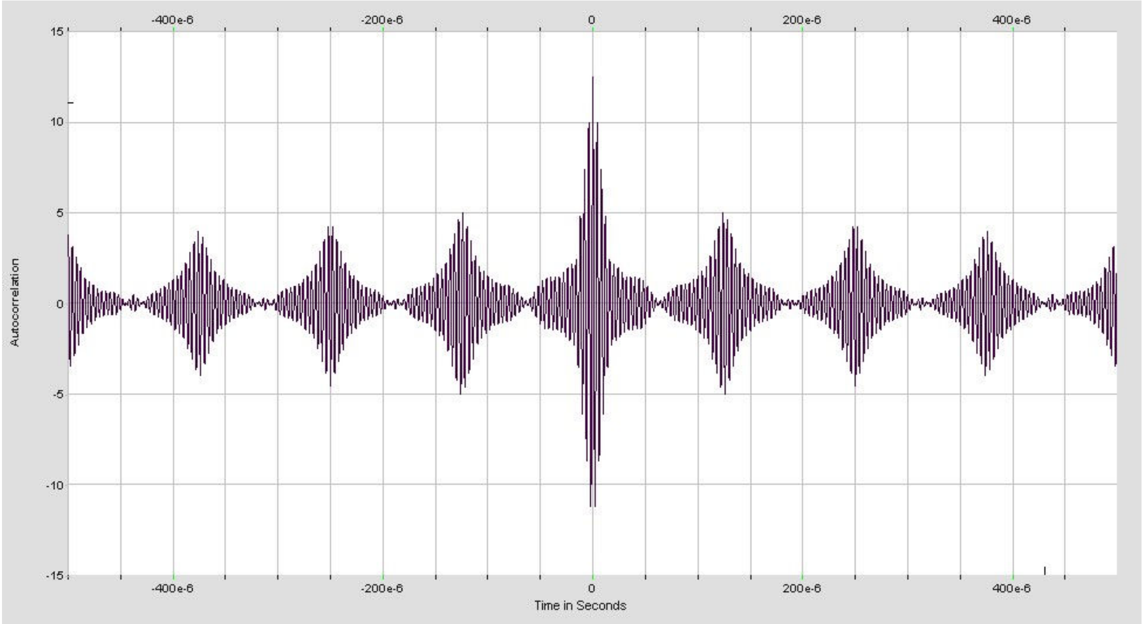

Figure 4. Autocorrelation of the BPSK transmitted signal for the audio *.wav* file input from the *SystemVue* simulation.

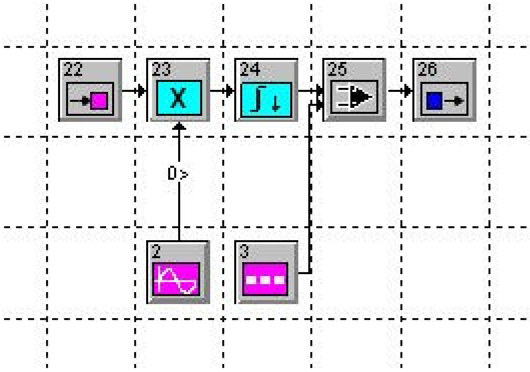

Figure 5. Optimum matched filter or correlation receiver in *SystemVue* for symmetrical bandpass signals with perfect carrier and bit time synchronization.

and reports that $P_1 = 0.58$ and $P_0 = 0.42$. The energy per bit is equal for the symmetric BPSK signal with $E_b = A_c^2 T_b/2 = 1.953 \times 10^{-4}$ V^2-sec.

As another illustration of the *what-if* of digital communication system design, the undergraduate students are given a question again not covered by a standard text. Is P_b

affected by the assumption of equal apriori probability not being valid with $\tau_{opt} = 0$ and can the audio *.wav* file be heard with AWGN? Executing the *SystemVue* simulation showed no significant difference between the observed BER and theoretical P_b here (Figure 8). The students were also enthralled to hear that the audio *.wav* file was still discernable even at $E_b/N_o = 0$ dB (Figure 6).

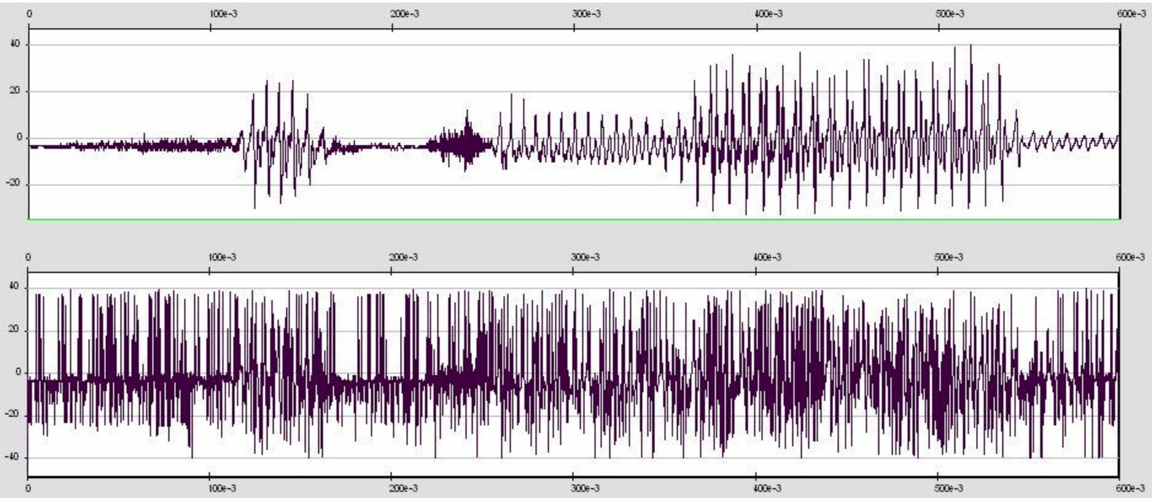

Figure 6. Input audio *.wav* file and the recovered audio *.wav* file from the *SystemVue* simulation of 8-bit PCM BPSK with $E_b/N_o = 0$ dB.

Finally, the degradation in BER performance that occurs when the carrier frequency and phase must be recovered by the receiver in a digital communication system might be discussed but rarely is featured by a standard undergraduate text. Here the reference signal for the correlation receiver is derived from the received signal with AWGN by squaring (*Token* 42), bandpass filtering (*Token* 43) and processing by a phase-locked loop[2,5] (PLL) (*Token* 44) in the first metasystem of the BPSK receiver (Figure 7). For the undergraduate student this exercise represents a practical introduction to the specification, utilization and performance of the PLL in digital communication systems.

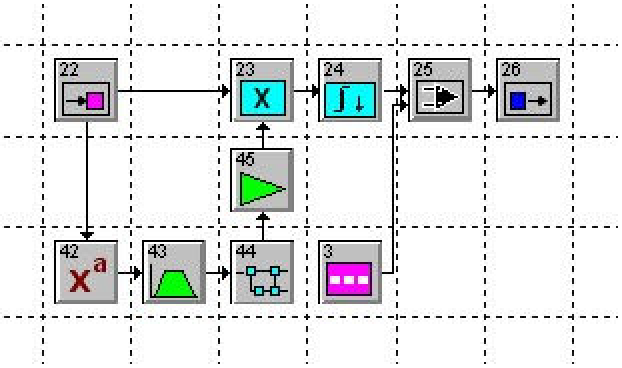

Figure 7. Carrier frequency and phase recovery in the correlation receiver in *SystemVue* for symmetrical bandpass signals.

The *SystemVue* simulation for the BER performance in AWGN for both the BPSK correlation receiver with perfect carrier and bit time synchronization and with carrier recovery provides the undergraduate student with a telling lesson in the tradeoffs inherent in digital communication system design (Figure 8).

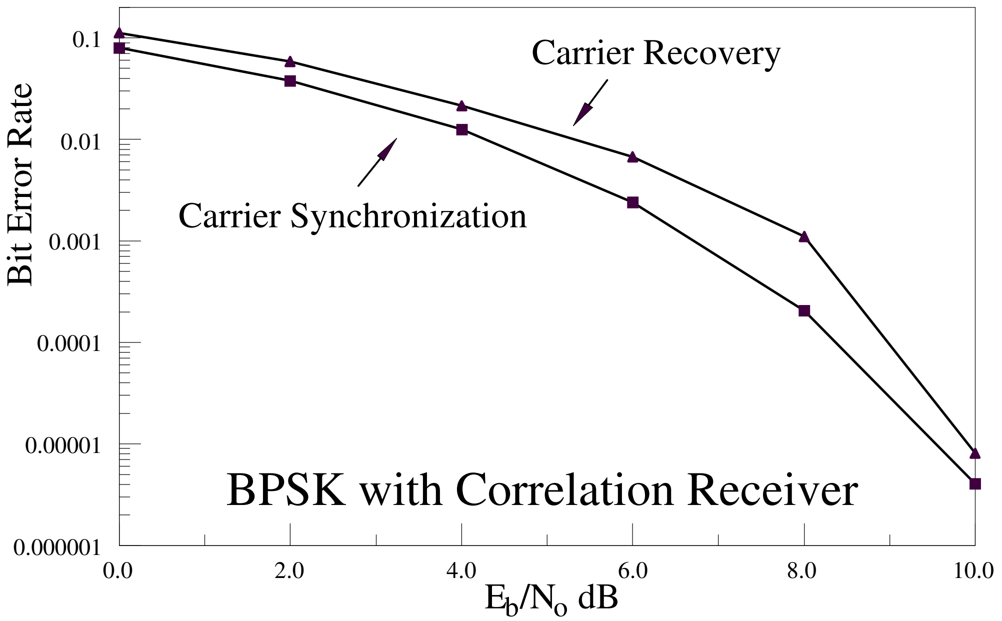

Figure 8. Bit error rate from the *SystemVue* simulation with carrier synchronization and carrier recovery for BPSK with the correlation receiver.

It's All in How You Do It

Digital communication systems have been taught in the undergraduate curriculum with this approach of integrating the analytical solution and the *SystemVue* simulation for over nine years. Course materials have been developed to support the requisite standard text of the curriculum[4]. Although a few texts are available that purport to include this approach, only a very few approach the pervasiveness required to develop the concept from baseband to bandpass modulation, synchronization, source coding, and multiplexing for the undergraduate student[2]. Employing a *computational script* in Matlab, as some texts do, merely verifies the analytical equation. Even a short inclusion of simulation techniques with a block diagram interface as a demonstration does not seem to imbue the undergraduate student with the same level of confidence that PSD and BER measurements and audio *.wav* file verification made throughout the course and laboratory can provide.

Two other environments that support the key premise here of utilizing simulations to imbue the teaching of digital communication systems with more insight for undergraduate students is *Matlab/Simulink* by Mathworks and *VisSim/Comm* by Visual Solutions. However, the *Simulink* digital communication blockset requires several additional toolboxes in addition to the standard *Matlab/Simulink* student edition. The recent text[2] using *SystemVue* provides an inclusive and complete environment for simulation in which model parameters can be modified, although new models cannot be developed in the *SystemVue Textbook Edition*.

The digital communication system laboratory or projects using *SystemVue* that accompany the lecture course allows the exploration of topics in simulation which are not in the text and whose results are more experiential[1,4]. The incalculable value for the undergraduate student seems to be the experience provided by the *what-if* of the results.

But Does it Work?

The assessment of the coupling of the traditional analytical approach with the simulation of a digital communication system has been obtained by extensive interviews of alumni who remain in the area and are employed by a variety of companies engaged in digital communication design and application. These professionals have found their experience with the *SystemVue* simulation of a digital communication system has facilitated their understanding and transition to design in other environments such as *Visual System Simulator* by Applied Wave Research.

The feedback obtained from the alumni has been used to improve the presentation of the concepts in the digital communication system course and to develop a second undergraduate course in telecommunication engineering. Course feedback surveys are also used to gauge the response of the undergraduate student to this approach with questions such as: "*What do the digital communication simulations teach you?*" and "*How do the digital communication simulations help you to examine the analytical results presented in the text?*".

Acknowledgement

Agilent Technologies Eagleware (www.eagleware.com) supports the use of advanced digital communication simulation software in undergraduate and graduate courses and research by providing *SystemVue* to the academic community.

1. Dennis Silage, *Augmenting Hardware Experiments with Simulation in Digital Communications*, Proceed 2003 ASEE Annual Conf.

2. Dennis Silage, *Digital Communication Systems using* SystemVue, Da Vinci Engineering Press, Thomson Delmar, 2006.

3. Bernard Sklar, *Digital Communications: Fundamentals and Applications*, Prentice Hall, 2001.

4. *astro.temple.edu/~silage/digitalcomm.htm*

5. Harold Stern and Samy Mahmoud, *Communication Systems Analysis and Design*, Pearson Prentice Hall, 2004.