Teaching Digital Communications in a Wireless World with MATLAB/Simulink: Who Needs Equations?

Dennis Silage
Electrical and Computer Engineering
Temple University

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 blocks 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 demonstrating that the relative bit error rate (BER) performance of the simple single point sampler verses the more complex matched filter or correlation receiver in baseband rectangular pulse amplitude modulation (PAM) with additive white Gaussian noise (AWGN) .

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. 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 pulse code modulation (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].

MATLAB/Simulink by The Mathworks (www.mathworks.com) provides the comprehensive digital communication system simulation environment and a recent text[2] provides supplemental support to any existing undergraduate course text. *MATLAB/Simulink* simulations in digital communications have been provided in a 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

Binary phase ship keying (BPSK) is a modulation technique that encodes binary information as only the phase of a sinusoidal carrier. BPSK can be simulated in *MATLAB/Simulink* with the system configured with *Blocks* in Simulink (Figure 1). The specifics of the *MATLAB/Simulink* simulation are not appropriate for the intent of the lesson survey here. However, a detailed description of this BPSK digital communication system simulation in *MATLAB/Simulink* is available[2].

The data source is the *Random Integer Generator* block from the *Comm Sources, Communications Blockset* which produces random, uniformly distributed binary integers (0 and 1) at a data bit time T_b = 1 msec or a data rate $r_b = 1/T_b$ = 1 kb/sec. The non-linear BPSK modulator is the *PM Modulator Passband* block from the *Communications Blockset* with parameters of a fixed amplitude of ± 1 V, a carrier frequency f_c = 20 kHz, phase offset θ = 180°, and an initial modulation gain (or phase deviation factor k_p) of 180°/V (or π/V).

The normalized power spectral density (PSD) of the BPSK transmitted signal in the *MATLAB/Simulink* simulation is obtained by the *Spectrum Scope* block from the *Signal Processing Sinks, Signal Processing Blockset*. The PSD of BPSK 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 (20 ± 1 kHz) (Figure 2).

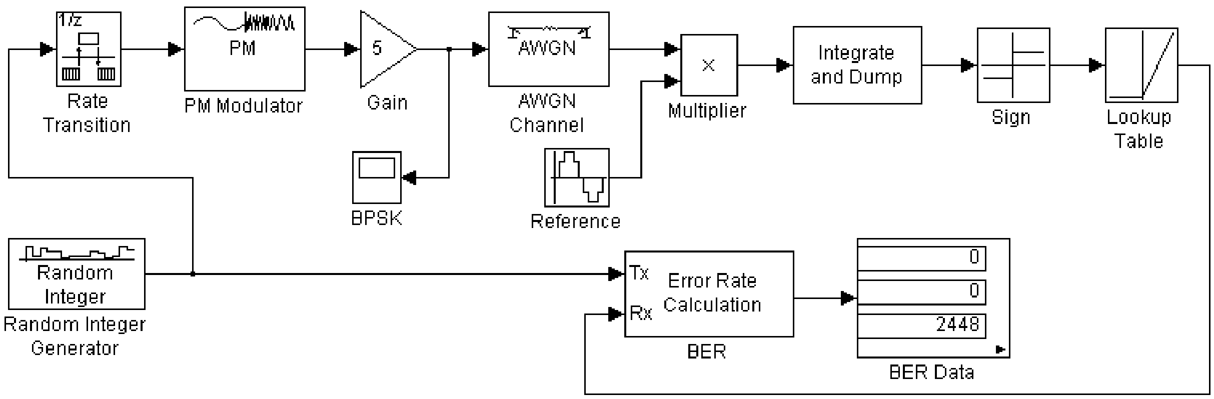

Figure 1. The *MATLAB/Simulink* simulation of the BPSK digital communication system with BER analysis.

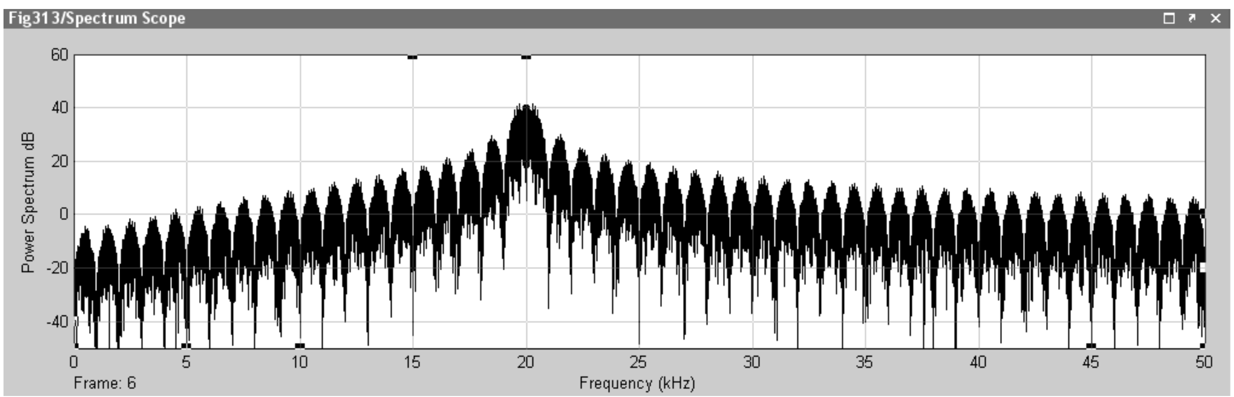

Figure 2. PSD of the BPSK transmitted signal from the *MATLAB/Simulink* simulation.

The BPSK receiver implements an optimum matched filter or correlation receiver for symmetrical signals with perfect carrier and bit time synchronization (Figure 3). The theoretical probability of bit error (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 for the correlation receiver is set as $\tau_{\text{opt}} = 0$. *MATLAB/Simulink* can calculate the statistics of the binary data and reports that, as expected, $P_1 = 0.501$ and $P_0 = 0.499$. The energy per bit (E_b) is equal for the symmetric BPSK signal with $E_b = A_c^2 T_b/2 = 1.953 \times 10^{-4}$ V^2-sec.

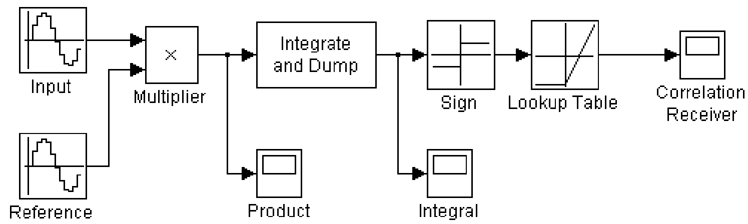

Figure 3. Optimum matched filter or correlation receiver in *MATLAB/Simulink* for symmetrical bandpass signals with carrier and bit time synchronization.

An illustration of the *what-ifs* of digital communication system design supported by integrating *MATLAB/Simulink* simulation into the lecture content occurs when the undergraduate students are given a question in the form of a laboratory assignment not covered by a standard text. For example, is P_b for BPSK affected by the assumption of equal apriori probability not being valid with $\tau_{opt} = 0$ or what is the affect on P_b for BPSK if the energy per bit differs ($E_b^1 \neq E_b$) or the optimal threshold is misadjusted ($\tau_{opt} \neq 0$)? These anomalous conditions provide experiential learning for the undergraduate student.

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 simulation for over ten 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, P_b and BER measurements and audio *.wav* file verification made throughout the course and laboratory can provide.

The digital communication system laboratory or projects using *MATLAB/Simulink* 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-ifs* and their results.

But Does it Work?

Direct assessment of this pedagogical approach of coupling the traditional analytical approach with the simulation of a digital communication system has been obtained by having selected topics taught and examined traditionally one semester, followed by the same topics with the integration of simulation the following semester. An indirect assessment has been by extensive interviews of alumni who are engaged in digital communication design and application. Their feedback has been used to improve the presentation of the concept in the course and to develop a second undergraduate course in telecommunications. 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?*".

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

2. Dennis Silage, *Digital Communication Systems using MATLAB and Simulink*, Bookstand Publishing, 2009.

3. John Proakis, Masoud Salehi and Gerhard Bauch, *Contemporary Communication Systems using MATLAB*, Thomson Engineering, 2004.

4. *http://astro.temple.edu/~silage/digitalcommMS.htm*

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

DENNIS SILAGE (silage@temple.edu) received the PhD in EE from the University of Pennsylvania in 1975. He is a Professor, teaches digital data communication, digital signal processing, and signal and data processing architectures using the FPGA. Dr. Silage is the recipient of the ASEE 2007 National Outstanding Teaching Award and is a Past Chair of both the Middle Atlantic Section and the ECE Division of the ASEE.