Enhanced Learning – Combining MATLAB Simulation with Telecommunication Instructional Modeling (TIMS™) in a Senior Level Communication Systems Course

Paul B. Crilly, Ph.D. and Richard J. Hartnett
Department of Engineering, Electrical Engineering
U.S. Coast Guard Academy

In this paper we present the successes of combining MATLAB™ simulation methods with the Telecommunication Instructional Modeling System (EMONA-TIMS™) to provide experiential learning in our senior level wireless communication systems course. Using TIMS™ our students develop, implement and then test real-world communication hardware using real signals such as demodulated audio from a local broadcast station and thus are engaged in "real-world" modulation and demodulation techniques and hardware. They thus develop a more intuitive sense for how the modulation and demodulation processes are carried out. The MATLAB™ simulation approach achieves several objectives which include: (a) instructs students on how to put together a proper simulation, (b) provides the flexibility to change various system parameters, much more so than with fixed hardware, and (c) is the starting point for a software define radio (SDR) system. We find the synergy in combining these two approaches in our communication systems course greatly enhances the achievement of our learning objectives. Course feedback on these pedagogical methods has been positive. The TIMS™ provides a practical understanding of the abstract concepts of modulation and demodulation and their related time and frequency components; the MATLAB™ coding gives them the tools to test out various ideas including those that support their senior capstone projects.

Corresponding Author: Paul b. Crilly, paul.b.crilly@uscga.edu

I.   Introduction

For many, the topics in communication systems, specifically modulation, demodulation and noise are relatively abstract topics that can be challenging to students. As faculty, we try to find ways to create excitement for the subject matter. After all, communication systems have always been a hot area of electrical engineering where theory, technology and applications continue to evolve.

As in many electrical engineering systems courses with a laboratory component, the theory can be reinforced via computer simulation, while in other cases, the traditional hardware experiments are still the best approach. Some students prefer simulations, while others prefer hands on experimentation [1],[2],[3]. Some researchers have commented [4] that a TIMS™ based experimentation approach garners high marks for student satisfaction, and has increased their skill and confidence in experimental methods. Furthermore, the TIMS™ system can contribute toward attaining ABET student outcome 3b (ability to conduct experiments as well as analyze and interpret data). Our experience is consistent with these observations. We believe that a combination of simulation and hardware experiments had multiple advantages and we take this approach in our senior-level communication systems course.

We have observed that an "experimental TIMS™ based approach [4] enables students to feel engaged in "real-world" modulation and demodulation. Especially as they see the signals at various stages of modulation and demodulation being plotted on an oscilloscope and spectrum analyzer. For example, in a class lecture, we describe the process in which a baseband message is converted to a suppressed carrier single sideband modulated (SCSSB)

signal by plotting the spectrum at the various stages of the SCSSB modulation process. Seeing this process unfold on a spectrum analyzer becomes an "ah ha" moment for our students. Especially since we are using real signals. It is more than a computer simulation and makes all the difference in terms of depth of knowledge. There is nothing like having the students to construct, and test the "real thing."

On the other hand, using computer simulation has the following advantages: Computer modeling using such tools as MATLB™ and/or LabVIEW™ provides the widest flexibility in configuring a communication systems and we can easily see the effects of interference and noise in the channel and thus facilitating the measurement of probability of error (P_e) or interference immunity. For example, students can build various demodulators, and then readily see how each type affects probability of bit error, P_e for a given signal-to-noise ratio. Students learn how a given function block works by constructing it via computer commands and are forced to think about the underlying specifications such as sampling rate, etc. These software tools also help fulfill the ABET student outcome "k" – ability to use the techniques, skills and modern engineering tools necessary for engineering practice. Computer modeling is a starting point for our students when they pursue software defined radio (SDR) designs.

We have found the synergy in combining the two pedagogical approaches in most the labs of our communication systems course and our experience suggests this result in enhanced student comprehension. Typical student comments are that the TIMS™ experiments help reinforce the concept maps for modulation, demodulation, encoding and decoding. The precise nature of software such as MATLAB™ (i.e. false assumptions or ignored subtleties simulations force students to understand the underlying assumptions of what it takes to create a working communication system, particularly one that will eventually be implemented using SDR .

In this paper we will describe how we use the TIMS™ and MATLAB™ systems to create the following communication systems: (a) conventional AM, (b) SCSSB, (c) FM, and (d) PCM. Within PCM, we also emulate the companding process. We then describe how these various experiments are augmented by MATLAB™ simulations.

II. Communication Systems Lab Platform

The platform for our Communication Systems Labs is shown in Figure 1. As observed this rack system consists of the following equipment: (a) EMONA TIMS™-30, (b) Agilent DSO 6034A Digitizing Oscilloscope, (c) Agilent 89410 Vector Signal Analyzer, (d) Agilent 33220A Function Generator, (e) Rolls 35 Watt Stereo Power amplifier, and (f) an AM/FM tuner with stereo speakers. The system in Figure 1 also shows how the patch cables are used to interconnect the various modules.
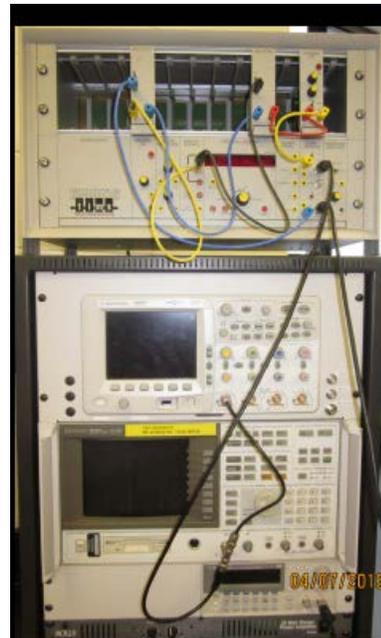

Figure 1. Communication Systems laboratory platform.

The EMONA TIMS™ has modules that can implement almost every analog and digital communication building block/function, as often seen in textbooks. Building blocks include signal sources, multipliers, adders, amplifiers, quadrature phase shifters, filters, PCM encoders and decoders, and VCOs. The 33220A and AM/FM tuner serve as signal sources. The DSO

6034A and 89410 systems allow us to see the signals in the time and frequency domain respectively.

Students also have access to Windows 7.0 work stations, where they are able to transfer data from the 89410 signal analyzer to MATLAB™ for later analysis as well as use the MATLAB™ to simulate a communications system and/or process (e.g. demodulation).

III. Communication Systems Laboratory Projects

At this time our lab exercises consists of the following: (a) review of Fourier Series, (b) Amplitude modulation and demodulation, (c) SCSSB modulation and demodulation,(d) Frequency modulation and demodulation,(e) Pulse Code Modulation with and without companding. We will be adding a direct sequence spread spectrum lab. In this paper we will focus on three of the above labs – the AM, both large carrier and suppressed carrier forms, SCSSB, and FM.

Amplitude Modulation (AM) Generation and Demodulation

This lab consists of the following parts: (a) MATLAB™ study of AM generation, (b) MATLAB™ study of envelope detection, (c) MATLAB™ study of I & Q demodulation, (d) a TIMS™ study of large carrier AM (LCAM), (e) a TIMS™ study of suppressed carrier double sideband (SCDSB), and (f) a TIMS™ study of production detection.

A. Studying AM using MATLAB™

Students implement AM using AM with a single tone message and various degrees of modulation indices and then plot these in the time and frequency domains. They can observe how the plots change as a function of modulating frequency and modulation index and to see the effects of over modulation. Because the MATLAB™ is emulating an AM process, they have to consider minimum sampling rates too.

Students then use MATLAB™ to implement an I & Q demodulator. They readily see how errors in the local oscillator frequency

do not affect the message clarity, whereas with ordinary product detection (i.e. just a multiplier and LPF) large errors can cause the demodulated signal to have significant distortion, and with small errors, the message has a time-varying envelope. To illustrate this point, we have the students simulate an I+Q receiver as shown in Figure 2. The input is a SCDSB whose modulating signal is a music file and the output feeds to a speaker. We purposely alter the local oscillator frequency such that $f \rightarrow f_c + f_\Delta$. Our students readily hear that even with errors in the local oscillator frequency, as long as the $v_i(t)$ and $v_q(t)$ components are within the LPF pass band, the audio output is undistorted.
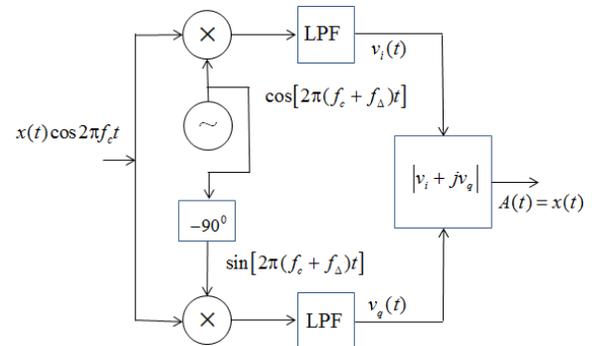

Figure 2. I+Q Quadratue receiver for detection of AM and SCDSB signals with error in local oscillator frequency.

We present the following derivation to show how the quadrature receiver's output is not affected errors in the local oscillator frequency.

Consider a SCDSB of $x_c(t) = 2x(t)\cos 2\pi f_c t$. We add a phase shift network to the local oscillator to give outputs of $\cos[2\pi(f_c + f_\Delta)t]$ and $\sin[2\pi(f_c + f_\Delta)t]$. When the incoming SCDSB signal is multiplied by these and LPFed, the output of each LPF is $v_i(t) = x(t)\cos 2\pi f_\Delta t$ and $v_q(t) = x(t)\sin 2\pi f_\Delta t$

Taking the magnitude of $v_i(t)$ and $v_q(t)$ we get the envelope,

$$A(t) = \sqrt{x^2(t)\cos^2(2\pi f_\Delta t) + x^2(t)\sin^2(2\pi f_\Delta t)} = x(t)$$

Giving us our original message. In contrast, if we used just the ordinary product detector (i.e.

just the $v_i(t)$ component, our receiver's output would be

$$A(t) = x(t)\cos 2\pi f_\Delta t \neq x(t)$$

Note our original message is being modulated by a $\cos 2\pi f_\Delta t$.

Students also implement an envelope detector. In this case, by writing the MATLAB™ code for each stage (i.e. rectifier, LPF, DC block) the student receives a better understanding of each stage's function.

B. Studying AM using TIMS™

Students then use TIMS™ to generate both LCAM and SCDSB using the audio oscillator, multiplier and adder modules. The carrier frequency is 100 KHz. They vary the amplitude and frequency of the single tone modulating signal and then see the result of the various generation stages on both the oscilloscope and spectrum analyzer. We then have the students change the message source to a demodulated audio signal coming from the FM tuner and observe the in both the time and frequency domains.

We then have the students demodulate the SCDSB signal using product detection which consists of a feeding the modulated signal into a multiplier module and then to a low pass filter (LPF) module. The LPF output feeds to a speaker so students are able to listen to their demodulated audio. The local oscillator's phase can be varied and thus students learn about the importance of the aligning the carrier phase with that of the local oscillator. Students see the effects on the audio quality when they vary the pass filter's gain and bandwidth, as well as the local oscillator's phase. Student feedback suggests that this sensory experience reinforces important signal processing concepts.

Suppressed Carrier Single Sideband (SCSSB) Generation and Demodulation

A. Studying SCSSB using MATLAB™

Students modify their SCDSB code to generate a SCSSB signal by the phase-shift method. Specifically, they write a code to implement the Hilbert transform that serves to eliminate the upper sideband. In doing this exercise, not only does he student learn that there is an alternative method to the filter method of SSB generation, but gain a deeper understanding of the Hilbert transform.

Again, as in the SCDSB and AM cases, we first start with a single tone message and plot the SCSSB signal in both the time and frequency domains. We then pose the question, "How does your signal differ from a carrier only AM signal?" The answer being that except for the frequency of the impulse, the two look identical, in other words, the envelopes of both signals will be flat. Hence if we want to see a time varying envelope with SSB, and/or to check for system linearity, we need a two tone message.

B. Studying SCSSB using TIMS™

The TIMS™ system implements a SCSSB signal using the phase shift method. We connect the TIMS™ modules together to create a SCSSB transmitter and receiver system and observe the signals on both the oscilloscope and spectrum analyzer. As we with MATLAB™ work, we start off with a single tone message and observe that it produces a flat signal with a flat envelope. We then add a second tone to our message to produce an output that looks like a SCDSB signal with a single tone message.

Frequency Modulation (FM) and Demodulation

The FM lab consists of several parts: (a) a MATLAB™ investigation of where an FM signal is demodulated from in-phase and quadrature (*I & Q*) data, (b) MATLAB™ generation of FM and then demodulation via a slope detector, and (c) TIMS™ generation of FM via a voltage controlled oscillator (VCO) and then demodulation of FM using a phase-lock-loop (PLL) and slope detection.

A. Studying FM using MATLAB™

After students study FM signals, they implement in MATLAB™ code three methods of FM demodulation. These are (a)

demodulation from I & Q data, (b) frequency discriminator techniques, (slope detection), and (c) the PLL.

For FM demodulation from I & Q data, we provide students with an FM message that has been translated to baseband and in I & Q form and in .mat format. We then ask them to write a MATLAB™ code that will demodulate and play the resulting audio file.

In performing FM demodulation on the I & Q data we point out that FM is angle modulation whereby the message is embedded in the angle generated by the $I + jQ$ data. They use the same receiver as shown in Figure 2, except instead of calculating the magnitude of the I and Q component, they calculate the angle. Specifically, $\phi(t) = \tan^{-1} Q / I = v_i / v_q$, and are *interested in the changes in this angle over time-radians/second*. Thus when presented with the $I + jQ$ data it would appear relatively straightforward to simply take the inverse tangent of $I + jQ$ data. However, students are forced to deal with the proverbial "nitty-gritty" subtleties of the MATLAB™ functions, the mathematical difference between FM and PM, and that the inverse tangent function returns angle values between $\pm\pi$. Therefore, we ask them to dig deeper into the mathematical definition of FM and angle modulation. After considerable coaching, they realize that in order to extract the message out of the baseband $I + jQ$ data they must unwrap the angle formed by the $I + jQ$ vector and then take the time derivative of the angle. The specific code that does this function is $y = diff (unwrap(angle(S)))$. In the end, they are able to use the MATLAB™ commands "sound" or "audio player" to listen to the message. Student feedback on this part of the lab is extremely positive.

We then have our students generate an FM signal with carrier frequency of 5 KHz, modulating frequency of 100 Hz, modulation index of 1, and sampling frequency of 22050 Hz. We then use a slope detector to extract the 100 Hz message from this FM signal. Note that the slope detector is based on the Fourier transform pair [5]:

$$\frac{dv(t)}{dt} \Leftrightarrow j2\pi f V(f)$$

Thus if the incoming signal passes through a low or band pass filter, and its spectra is in the system's filter's rolloff (slope) region, the multiplication by a slope in the frequency domain is a differentiation in the time domain. Differentiating an FM signal in the time domain converts it into an AM signal which is readily demodulated using an envelope detector.

From this experience, students learn the following FM signal processing concepts: (a) that a low pass or bandpass filter does indeed take the time derivative of the signal, and (b) that by taking the derivative of an FM signal converts it into an AM signal which in turn can be demodulated using an envelope detector.

B. *Studying FM Using TIMS™*

In this section, we have the students generate an FM signal using the VCO module, with a 100 kHz carrier frequency and a single tone message from the Agilent 89410A waveform generator. The FM signal is plotted to an oscilloscope and spectrum analyzer. For a given modulating frequency and amplitude, we get the expected output FM spectrum that looks identical to the Bessell function lines described in the FM chapter of most undergraduate communication systems textbooks. Note the students readily observe how the message parameters of frequency and amplitude affects the argument of the Bessell function which in turn affects the number of, the spacing and amplitude of the FM spectral lines.

We first have the FM signal demodulated using slope detection where the FM signal is fed to a LPF where the carrier frequency lies in LPF transition region, thus creating a derivative function in the time domain. The resulting derivative signal is then fed to an envelope detector, where the message is heard on a speaker.

Next we form FM detection via a phase lock loop (PLL) which consists of a multiplier, low pass filter, an amplifier and a VCO. The block diagram for our PLL detector is shown in Figure 3. In order for this to work properly, we advise

the students to (a) make sure the VCO frequency is identical to the incoming carrier frequency, (b) the amplifier gain is sufficiently high, and (c) the LPF is relatively wideband. If these parameters are all properly, set, demodulation is successful and the message is heard from the speakers.
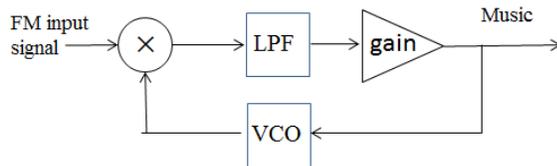

Figure 3. Block diagram of PLL detector for FM demodulation.

When the students adjust the VCO gain, LPF bandwidth, and even center frequency, they are usually able to get their PLL demodulator to work within 15-20 minutes. At the same time, in adjusting these parameters, they see how each one will affect PLL "lock" and if any one parameter deviates too much, lock is broken.

Conclusions

We have presented a laboratory experience that combines the flexibility of MATLAB™ simulation experience plus the hands on TIMS™ system to enhance student learning of communication systems theory. While we can debate the relative merits of simulation versus actual hardware, we do both and the student response in terms of their learning and enthusiasm for the subject are positive. The TIMS™ based approach reinforces the "concept map" or block diagram approach to modulation and demodulation as presented in the textbook. The MATLAB™ simulation is valuable too because they learn how to set up a proper

simulation as well as well as it being the first step toward implementing an SDR system. Although we are in the early stages of assessment, we have observed several advantages in combining these two pedagogical approaches based on student feedback and improved student comprehension.

References

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