AC 2011-657: SATELLITE COMMUNICATIONS, DATA COMMUNICATIONS, AND SIMULATION

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Satellite Communications, Data Communications, and Simulation

Abstract

Many undergraduate programs in electrical and computer engineering require a course in linear systems, signal processing, or communications. While students recognize the importance of developing a deeper understanding of the fundamental concepts, they find the content of these courses mathematical and harder to grasp. Without compromising the rigor of the required concepts, we strived to make the course fun, with application based, hands-on laboratory projects. We describe two third-year level laboratory projects used in a linear systems and signal processing course. These projects can be used in communication, computer networks, and information systems courses. One project addresses topics in satellite communications and the other covers data communications.

Introduction

Years of experience by many educators coalesce around the widely-held belief that laboratories and hands-on learning are critical to understanding and long term retention of fundamental concepts in engineering. Taslidere, Cohen, and Reisman conclude that "undergraduate and graduate students want more hands-on demos that link theory to real applications."[1] However, according to Corter, Nickerson, Esche, Chassapis, Im, and Ma, some students find the labs to be tedious and an ineffective use of their time for the benefit derived[2,3]. Guzelgoz and Arslan assert that a course with many theoretical concepts can be enhanced by hands-on experimentation[4]. In addition, they recommend a project with both written and oral presentations. Ma and Nickerson cite conceptual understanding, design skills, social skills and professional skills as desired outcomes of laboratory work [5].

Feisel and Rosa identify three types of engineering labs-- development, research and educational--with the latter being most important for students, since they "learn something that practicing engineers are assumed to already know."[6]

Greenberg, Delgutte and Gray state that "hands-on exercises are not effective when …they are not tightly coupled to the intended learning objectives.[7]" Furthermore, they emphasize the importance of building on students' prior coursework. They suggested a format of lectures, labs, lab reports, and homework when no lab reports are required.

Ferre, Giremus and Grivel have tried to make their course more appealing by focusing on small-group based learning projects[8]. Wright, Morrow, Allie and Welch suggested ways to enhance engineering education and outreach[9], and Turner and Hoffbeck suggested ways to put theory into practice using software[10].

We have tried to consider the findings of educators to develop new laboratory projects for our linear systems and signal processing course. The course is a junior-level undergraduate electrical engineering course focusing on both time domain and the frequency domain, using the Fourier and Laplace transforms. Students completing this course will understand the basic analysis and design techniques for both continuous-time and discrete-time signals. This course addresses some of the ABET Criterion 3[11] by providing students with the opportunities to apply knowledge of mathematics to solve engineering problems, to design and conduct experiments in the laboratory, to use laboratory equipment to solve engineering problems, and to use programming (MATLAB) to solve engineering problems. In this paper, we present two new laboratory projects.

Each laboratory project was discussed first in class and students were assigned homework based on the project, followed by 3 hour lab to improve their understanding of the major concepts. Students wrote project reports (learning by writing).

The relevant learning goals for the course addressed by these two projects are to develop the ability to:
 a. identify and use signal models,
 b. develop models of engineering systems, physical systems, and social systems,
 c. analyze continuous-time system models by applying Fourier methods, and frequency response methods,
 d. develop computer models using available software packages for analysis and design, and
 e. communicate laboratory and project results in written and oral reports.

The satellite communications project provides excellent applications of important concepts of signals: time shift, amplitude scaling, delay, echoes, and fading. We introduced students to a satellite communication system where a signal is transmitted from a ground transmitter, received by the satellite after some delay, and reflected back to the ground receiver. Students analyzed the signal received by the ground station as the sum of the signal sent from the station and the signal reflected back from the satellite. This interesting project helped students to review sinusoidal signals, phasors, power, and to understand the effect of delays, echoes and fading. In addition, the students simulated the system using **,** Matlab® and Simulink®, while getting to implement fundamental concepts they had previously learned in earlier courses[12,13]. This project addressed learning goals a, b, d and e.

The second project focused on Fourier analysis of periodic signals and applications to data communication. Students were given the task of analyzing an 8-bit ASCII character, transmitted at a particular bit rate over a communication link with a given bandwidth. Specifically, students determined the harmonic content and time-response of both the transmitted and received signals. Students programmed the *Agilent 33220A 20 MHz Function Generator* to create the ASCII character and designed a filter to view and analyze the output response[14]. Students also used MATLAB and Simulink to simulate the communication model. This project reinforced concepts of periodic signals, Fourier series, harmonics, phase shift, signal power, bit rate, link bandwidth, Nyquist's theorem and Shannon's theorem for data transmission on a noisy channel. This project addressed learning goals a, b, c, d and e.

Since these projects were discussed in class, the order of the boxed questions that follow the description of the projects has been modified slightly from the original assignments for a more linear presentation in this paper.

Satellite Communications Project

Communication devices provide us with excellent applications of important concepts studied in circuits class. The students used their background in sinusoidal signals and learned how to apply them to satellite communications[15,16]. The basic idea is to demonstrate the effects of delays (time shift), echoes (reflection), and fading. In addition, students had an opportunity to use Matlab and Simulink, which increased their appreciation of the fundamental concepts.
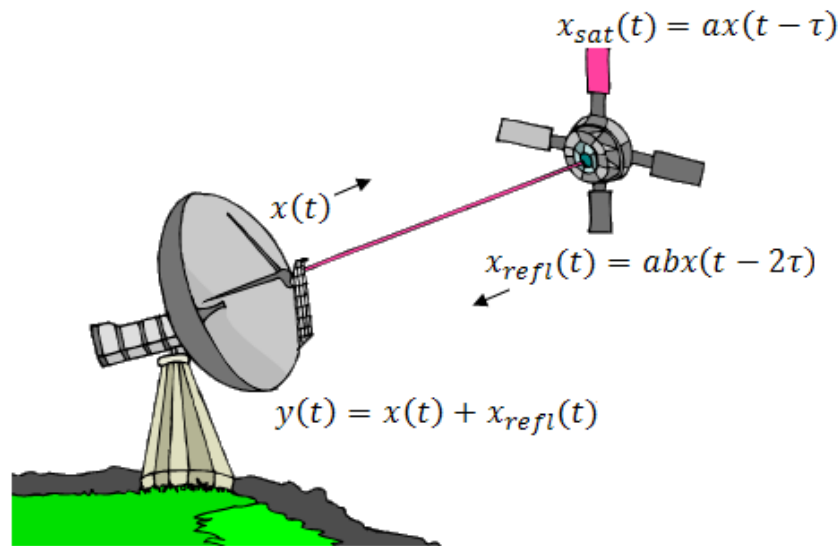

$$x_{sat}(t) = ax(t - \tau)$$
$$x(t)$$
$$x_{refl}(t) = abx(t - 2\tau)$$
$$y(t) = x(t) + x_{refl}(t)$$

Figure 1. A satellite communication model.

As described in[15,16] , let us consider communication between a ground station and a satellite in orbit. Let:
$x(t) = \cos(\omega_0 t)$ be the transmitted signal from the ground transmitter,
$x_{sat}(t) = ax(t - \tau)$ be the signal received by the satellite (amplitude scaling and time shift),
$x_{refl}(t) = abx(t - 2\tau)$ be the reflected signal to the ground station (amplitude scaling and time shift, and echo), and
$y(t) = x(t) + x_{refl}(t)$ be the total signal at the ground station (fading).
Also, let us assume that $0 \leq t \leq T+2\tau$ where *x(t)* is transmitted over [0,T].

The first part of this project was aimed at getting the students to apply the concepts of phasors and Euler identities that they have studied in their previous courses in circuit theory. Using phasors, Euler identities, and trigonometric identities as well as simulation, students were asked to derive the amplitude and phase of $y(t)$ and envelope of $y(t)$ as $\omega_0\tau$ varies. The intent here was to help the students see the different fundamental techniques that they can apply to come to the same solution. Also, students were asked to compute the power of the signals and plot the single and double sided spectra.

1. Plot x vs. t for various values of ω_o.
2. Plot $ab \cos(\omega_0 (t - 2\tau))$ vs. t for various values of ω_o.
3. Plot the figures of question 1 and question 2 on one plot using the **subplot** function of MATLAB.
4. Find the amplitude (envelope) and phase of y using phasor methods. Using the **subplot** function of MATLAB plot the envelope and phase of y vs. $\omega_0\tau$.

Solution:
$$y(t) = \cos(\omega_0 t) + ab \cos(\omega_0(t - 2\tau))$$

$$y(t) = A \cos(\omega_0 t - \theta)$$

$$A = \sqrt{1 + 2ab \cos(2\omega_0\tau) + (ab)^2} \; ; \text{envelope}$$

$$\theta = \tan^{-1}\left[\frac{ab \sin(2\omega_0\tau)}{1 + ab \cos(2\omega_0\tau)}\right]$$

Let $a=1$, $b=0.1$, $\omega_0=1$, the envelope and phase of signal $y(t)$ is shown in Figure 2.
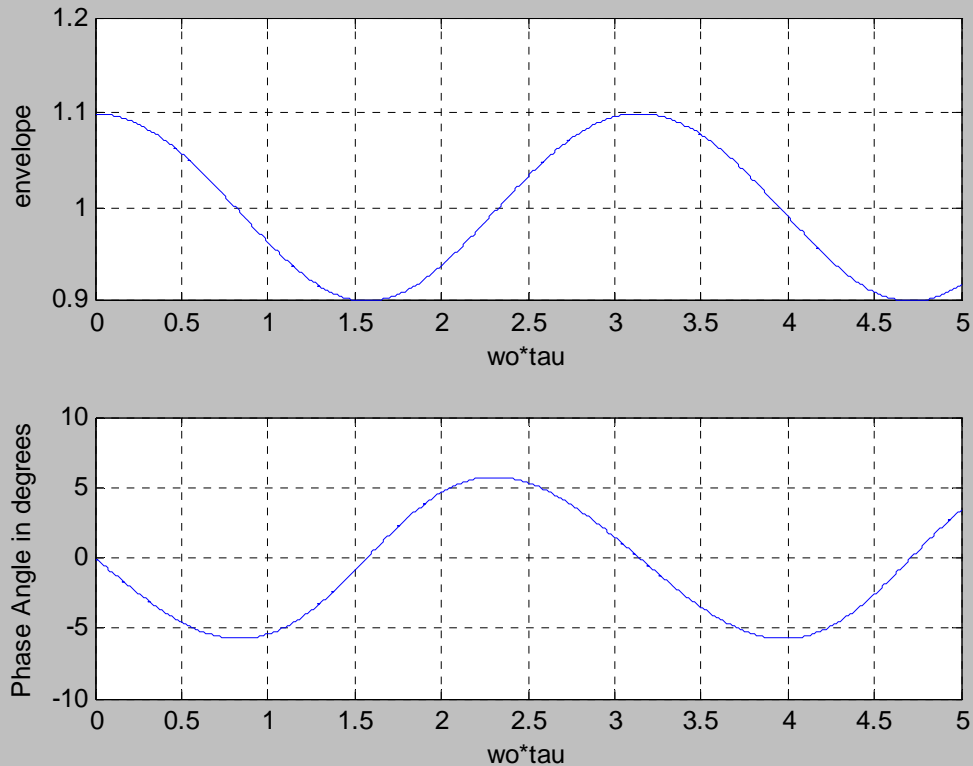

Figure 2. Plot of the envelope and phase of signal at the ground station $y(t)$.

5. What factors determine the values of a, b, and τ?
6. Suppose $y(t)$ exists from $0 \le t \le T + 2\tau$, write a mathematical expression for $y(t)$ using step functions.
7. Find the envelope of y(t) using trigonometric identities.

Hint: $\propto \cos(x) + \beta \sin(x) = \gamma \cos(x - \varphi)$, where $\gamma = \sqrt{(\alpha^2 + \beta^2)}$, $\cos(\varphi) = \alpha/\gamma$ and $\sin(\varphi) = \beta/\gamma$

8. Show that the envelope of *y(t)* is as shown above using Euler's identities for sinusoidal terms. Recall: $e^{j\omega t} = \cos(\omega t) + j \sin(\omega t)$

9. Find the phase of *y(t)*,θ, using Euler's identities. Recall:$\cos(\omega t) = \frac{(e^{j\omega t} + e^{-j\omega t})}{2}$

10. What is the power of *x(t)* and *y(t)?*

11. Plot the **single-sided spectrum** (amplitude and phase) of transmitted signal *x(t)* and the total signal at the ground station y(t).

12. Plot the **double-sided spectrum** (amplitude and phase) of transmitted signal *x(t)* and the total signal at the ground station *y(t)*.

In the second part of the project students were provided with a Simulink model of the satellite communication system.

1. Load and run the Simulink program provided by the instructor.
2. Read your favorite poem into a microphone and experiment with reciting it as you vary a*b and the delay.
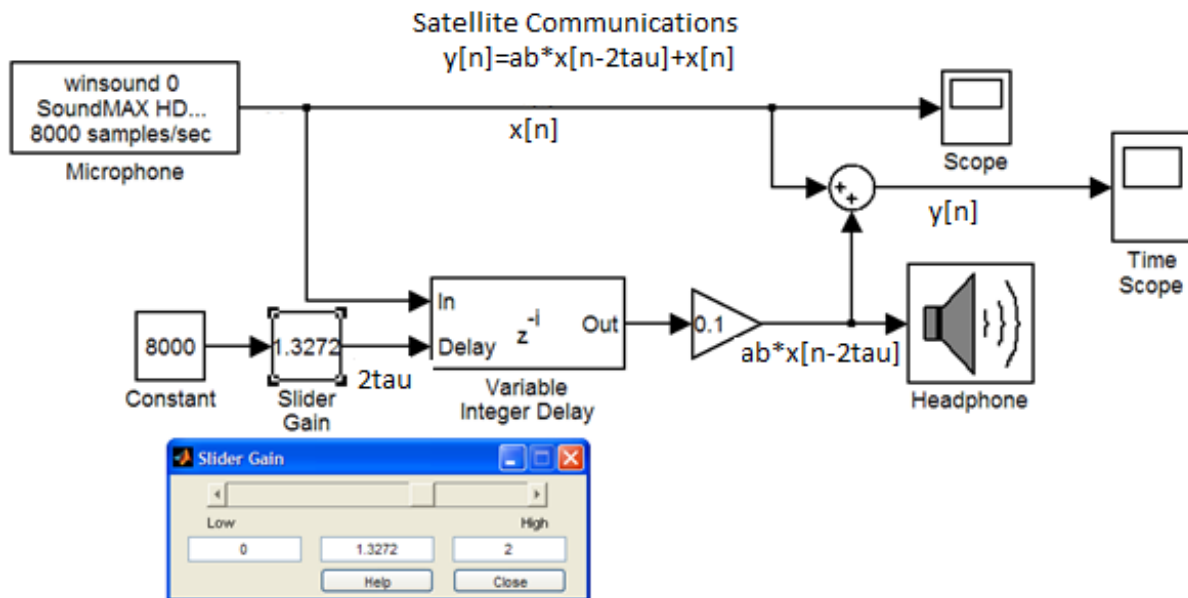3. Describe and discuss your observations.

Figure 3. A Simulink model of a satellite communications system.

The model is shown in Figure 3. The original signal (in this example sound from a microphone) is modeled as *x[n]* and the final signal y[n] is the sum of *x[n]* and *ab*x[n-2tau]*. Students were asked to vary the gain (*ab*) and the number of samples to delay (*2tau*) and observe the effect of these parameters on the final output.

Figure 4 shows a portion of the output *y[n]* observed on the *time scope,* using a sine wave as the microphone input *x[n]*. The output *y[n]* is originally just the signal from the ground station *x[n]*,

with unit amplitude. After a certain number of sample delays (in this case about 1.675seconds), the output shows the effect of the interference of the reflected signal with *ab=0.1*. In this case, since the original signal and the reflected signals are both in phase, the output shows constructive interference.
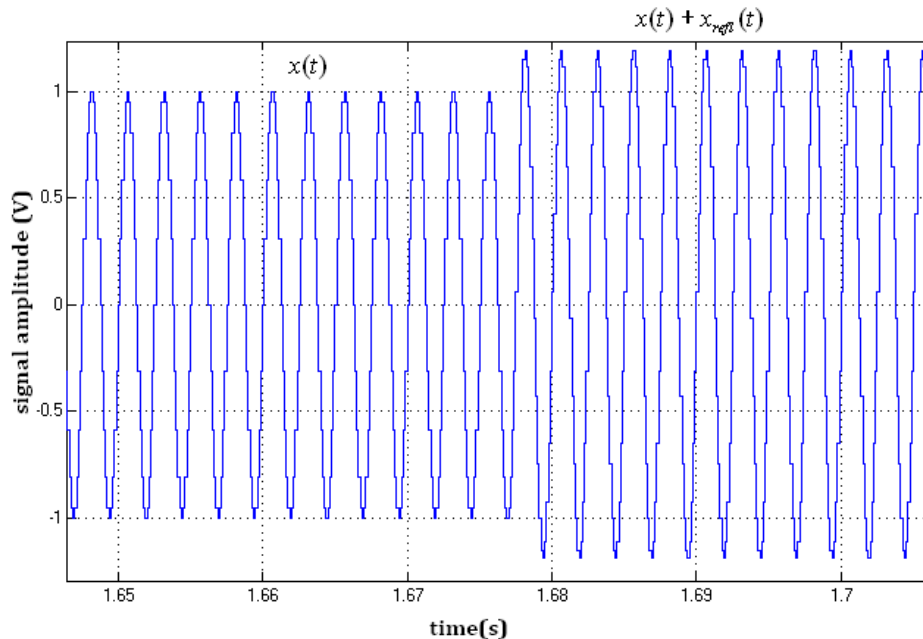

Figure 4. The output at the ground station of the satellite communication system. The plot shows the transition area where the reflected signal interferes with the original transmitted signal.

In the final part, students were asked to reflect on their observations, such as echoes and fading based on what they had just learned from the satellite model.

1. Have you ever experienced delays using your phone?
2. Have you ever experienced echoes when using your phone? Why do echoes occur?
3. Why do we experience fading? Explain why it occurs.
4. Please write a project report that addresses the above questions, using the IEEE Regional Student Paper Contest Guidelines. You are encouraged to expand on these questions and our class discussions and applications.

Data Communications and Fourier Series Project

Using sinusoidal analysis presented in the satellite communication earlier, this project introduces students to Fourier analysis of periodic signals and applications to data communications. In particular, we are interested in determining the harmonic content and the time-response of both the transmitted signal and received signal. We begin with a communication channel with capacity *C* **bits/sec** and data is transmitted over a communication channel with bandwidth *B* **Hz**. For this project, we consider the transmission of an 8-bit ASCII characters (the control signals

are ignored) through our communication channel[1].

The first part of this project required students to display their knowledge and understanding of the key ideas needed for the project. In addition, students were also asked to find the channel capacity and bandwidth of everyday communication platforms, such as digital/analog TV and the telephone line. We asked the students to answer the following questions:

1. In your own words describe the **Fourier series**. What does it tell us? Why are we interested in it?
2. What do the following terms mean: **Harmonic**, **Baud rate**, **Bit rate?**
3. What is a modem?
4. What is the capacity of digital TV in North America?
5. What is the capacity of an analog TV?
6. What is the bandwidth of a telephone line?

In the second part of this project, students were asked to do a Fourier analysis of the ASCII code for "a" passing through a common communication channel, such as the telephone line.

1. Suppose the bit rate is **C** bits/sec (bps), how much time does it take to transmit 8, 16, 32, 64 and 128 bits?

> *Solution:*
> *C bits* pass through the channel in 1 second.
> i.e. *N* bits will pass through the channel in *N/C* seconds.

2. Suppose the bandwidth of a line is 3000 Hz, what is the number of the highest harmonic passed by this line?

> *Solution:*
> Bit rate = *C bits/sec*
> Time required to transmit *N* bits = *N/C seconds*.
>   i.e. Frequency of 1st harmonic = *C/N Hz*.
>   The highest harmonic passed $= \left\lfloor \dfrac{3000}{C/N} \right\rfloor = \left\lfloor \dfrac{3000N}{C} \right\rfloor$

3. Suppose C is 9600 bps, what is the frequency of the first harmonic?
4. Suppose the ASCII "a" signal **[0 1 1 0 0 0 0 1]** is passed through a **3000 Hz** low pass filter. The least significant bit (LSB) is sent first.
    a. What is the time response due to the first harmonic?
    b. What is the time response due to the second harmonic?
    c. What is the time response due to the third harmonic?
    d. What is the time response of the output due to the first three harmonics? What is the average value of the input signal? Can you recognize the original signal? Explain.

    e. How many harmonics do you think will be needed to recover the original signal? Explain.
    f. What can you do to recover the signal at the output of the filter? Explain.

Solution:
Bit rate = *9600 bits/sec.*
i.e. Frequency of 1ˢᵗ harmonic = *9600/8 Hz=1200Hz.*

The highest harmonic number passed within the bandwidth= $\left\lfloor \frac{3000}{1200} \right\rfloor = \lfloor 2.5 \rfloor = 2$. This means that the third harmonic is greater than the bandwidth of the filter.

Figure 5 shows the original ASCII code at the input of the low-pass filter, the approximation of the signal using three harmonics and a stem plot showing the magnitudes of the first 3 harmonics of the signal.
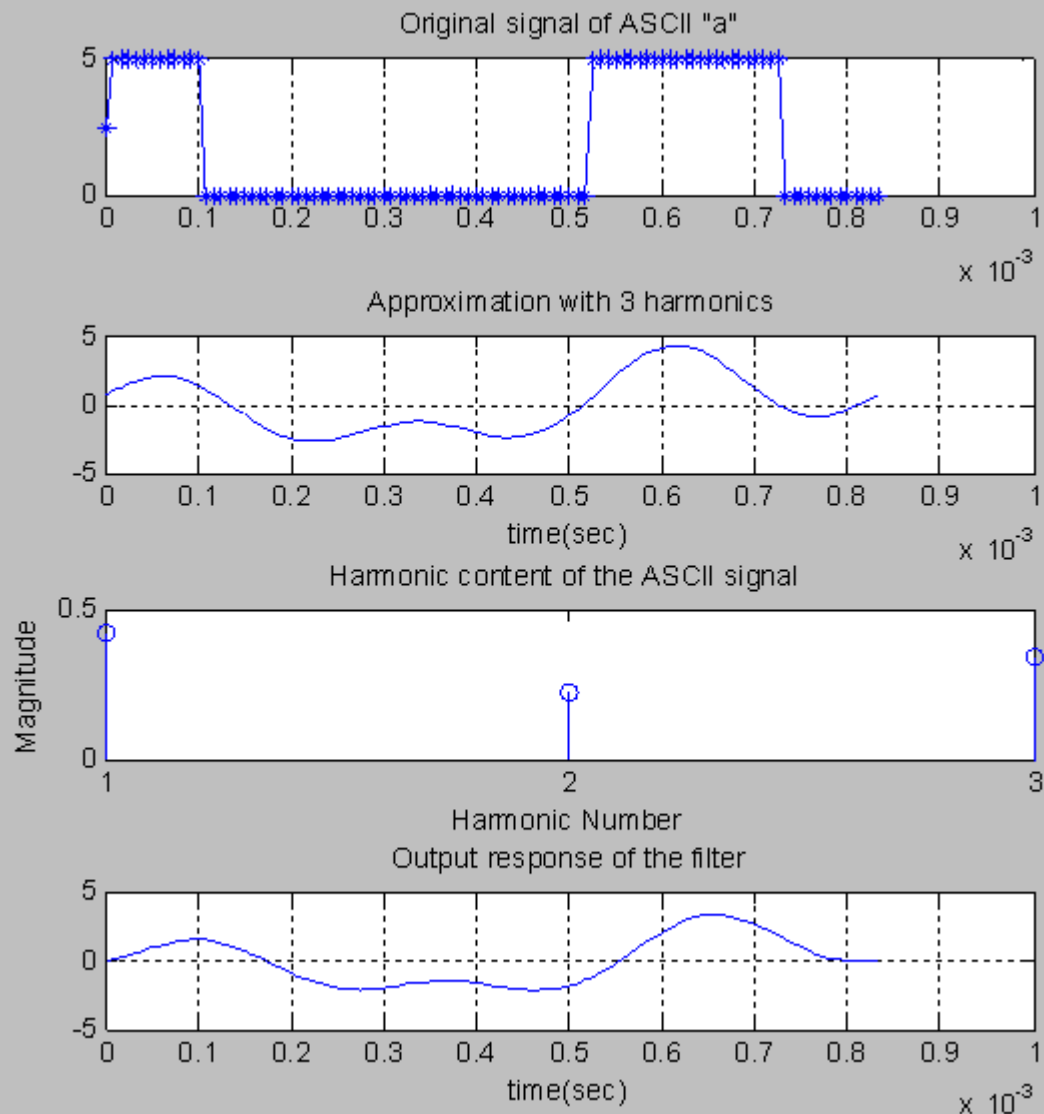

Figure 5. Plot of the original ASCII character, its approximation, the harmonic content and the output response of the filter.

5. What is Nyquist's theorem for maximum date rate using two voltage levels?

> *Solution:*
> *2*Bandwidth*

6. What is Shannon result for a maximum data rate in a noisy channel?

> *Solution:*
> *Data Rate = Bandwidth*log2(1+ S/N)*
> where S/N is the ratio of the signal power to the noise power in decibels(dB).

Now, students were asked to find the ASCII code for the initials of their names and show their understanding of the bit rate and bandwidth of the communication channel by repeating the Fourier analysis on those letters. To generate the ASCII waveform, students programmed the Agilent 33120A Function Generator. Next, they designed a first-order RC low-pass filter with a 3 kHz bandwidth and observed and captured the output response of the filter to the ASCII waveform.

1. Obtain the binary 7-bit ASCII code for the first letter of your first name and last name.
   a. What is the 8-bit code using odd parity? Where did you put the parity bit (MSB or LSB)?
   b. What is the 8-bit code using even parity?

   > *Solution:*
   > 8-bit ASCII code for "a" using odd-parity = [0 1 1 0 0 0 0 1].
   > The parity bit is at the MSB.
   >
   > 8-bit ASCII code for "a" using even-parity = [1 1 1 0 0 0 0 1].
   > The parity bit is at the MSB.

2. Let C= 2400 b/sec and *x (t)* and *y (t)* be the waveforms of your ASCII characters respectively.
   a. Plot the waveforms of *x(t) vs. t* and *y (t) vs. t*.
   b. What voltage levels did you use? Why did you use these levels?
   c. Find the average power of *x (t)*.
   d. What is the fundamental frequency of *x (t)?*
   e. What is the fundamental frequency of *y (t)*?
   f. Find the Fourier series of *x (t)* and *y (t)*.
   g. Plot the first 5 harmonics of *x (t)* vs. *t*. What is the average power of each harmonic?

7. Let *B*= 3 kHz. How many harmonics of **x (t)** can be sent over the channel?   Plot the waveform at the receiver. What did you assume about the channel characteristics?
3. Program the Agilent 33120A Function Generator/ Arbitrary Waveform generator to

produce the periodic waveform *x (t)*. Capture the waveform *x (t)* vs. *t*.

4. Design a low-pass filter with 3 kHz bandwidth and use *x (t)* as your input. Capture the output waveform. Explain your observations.

Solution:

A simple 3000 Hz bandwidth RC low pass-filter was used. The ASCII code for "a" i.e. *x(t)* is the first plot seen in Figure 6. The code was programmed in the Agilent 33120A Function Generator and sent to the filter from the LSB to the MSB. The second plot shows the output response of the filter. Since the highest harmonic number passed within the bandwidth is $\left\lfloor \frac{3000*8}{2400} \right\rfloor = \lfloor 10 \rfloor = 10$, the output of the filter shows a good representation of the input signal.
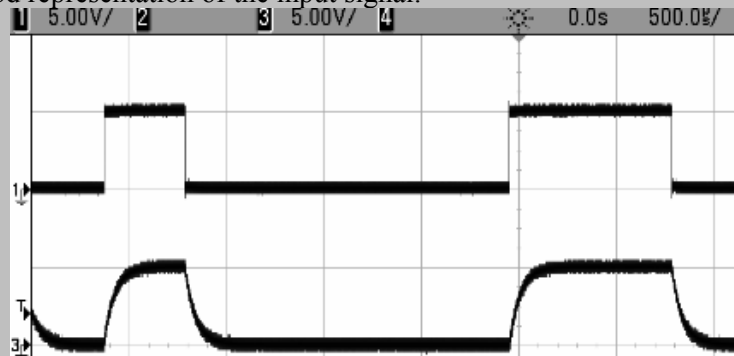

Figure 6. Oscilloscope capture of ASCII code "a" tranmitted over a channel of 3kHz bandwidth at a channel rate of 2400 bps.

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5. Now consider a dial-up modem with C=24 Kbps. Plot the output response of the filter.

Solution:

Since the highest harmonic number passed within the bandwidth is $\left\lfloor \frac{3000*8}{24000} \right\rfloor = \lfloor 1 \rfloor = 1$, the output of the filter, shown in Figure 7, is not a very good representation of the actual input.
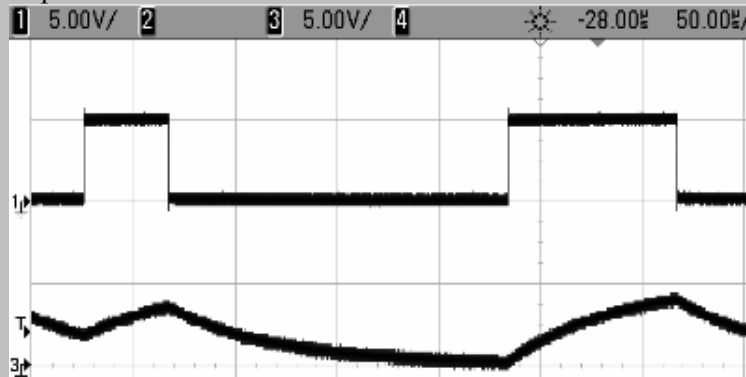

Figure 7. Oscilloscope capture of ASCII code "a" transmitted over a channel of 3kHz bandwidth at a channel rate of 24Kbps.

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6. Consider a T1 transmission line with C= 1.544 Mbps. Now plot the first 5 harmonics of *x (t)* vs. *t*. What is the average power of each harmonic?

Assessment

According to Ma and Nickerson, "although laboratory-based courses play a critical role in scientific education" they observe that "there is no standard criteria to evaluate the effectiveness of labwork[5]." Corter, Nickerson, Esches, and Chassapis measured the educational outcomes using exam and lab grades[2]. Guzelgoz and Arslan surveyed their students and observed that the lab course helped students with the understanding of difficult concepts[4].

Educators have tried to compare the effectiveness of hands-on, simulated, and remote (web) labs**.** The conclusion reached by Corter, Nickerson, Esches, Chassapis, Im and Ma in 2007[3] is that students rated hands-on experiences to be more effective than simulated and/or remote labs**.**

At the end of the semester, we asked students to fill out an anonymous survey regarding the course and the laboratory projects. A total of 24 students responded to the survey and rated each project on a scale of 1 to 5. A rating of 1 indicates that the students *strongly disagreed* with the statement, while a rating of 5 indicates the students *strongly agreed* with the statement. A summary is presented in TABLE I.

TABLE I

Results of the end-of-semester anonymous survey about the laboratory projects.

	1	2	3	4	5	Mean	Median
The laboratory projects were a valuable part of the course.	0	3	1	12	8	4.04	4
The laboratory projects were helpful in developing new skills.	0	2	2	14	6	4	4
The satellite project was very helpful in improving my understanding.	0	3	5	14	2	3.57	4
The data communications project was very helpful in improving my understanding.	0	2	5	10	7	3.92	4

As can be from Table 1, the majority of students, in each of the four statements, gave ratings of 4 or 5, confirming student appreciation for the laboratory project experience in improving student understanding of the critical material.

The satellite communications project, which drew on material presented in previous courses, was the first one presented to the students, and garnered a mean of 3.57. The data communications project came immediately after, was entirely new material, and scored a higher mean of 3.92. We suspect the difference is due to the fact that students already understood the "older" material and did not get the same "boost" in understanding from the laboratory project for the "new" material.

Similarly, we surveyed the students to assess themselves on the course learning goals (a-e) and compared them with the survey from the previous year (2008) as shown in TABLE II. The number of student respondents for 2008 and 2009 were 10 and 24 respectively.

TABLE II

Comparison of Learning Goals.

Learning Goal	2008			2009		
	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
Identify and use signal models	3.1	3	0.99	4.04	4	0.62
Develop models of engineering systems, physical systems, and social systems	2.7	2.5	1.16	3.63	4	0.88
Analyze continuous-time system models by applying Fourier methods, and frequency response methods	3.4	3.5	0.97	3.96	4	0.69
Develop computer models using available software packages for analysis and design	3.2	3	0.79	3.75	4	0.94
Communicate laboratory and project results in written and oral reports	4	4	1.15	4.46	4	0.51

As can be seen in TABLE II, the comparison of the learning goals showed an improvement in 2009 based on the introduction of these two laboratory projects.

Summary

We presented two projects that can be used in linear systems, signal processing, and data communications courses. The satellite communications project built upon earlier material and employed mathematics and simulation. The data communications project focused on Fourier series and relied more upon hands-on lab work. As demonstrated by the student surveys, there was significant improvement in achieving the learning goals for the course as a result of the introduction of the two laboratory projects.

References

1. E. Taslidere, F. S. Cohen, and F. K. Reisman, "Wireless Sensor Networks—A Hands-On Modular Experiments Platform for Enhanced Pedagogical Learning," IEEE Transactions on Education, vol. 54, no. 1, pp.24-33.
2. J.E. Corter, J. V. Nickerson; S. K Esche, and C. Chassapis, "Remote versus hands-on labs: a comparative study," Proceedings of 34th Annual Frontiers in Education (FIE), pp.17-21, Oct. 2004.
3. J. E. Corter, J. V. Nickerson, S. K Esche, C. Chassapis, S. Im, and J. Ma, "Constructing reality: A study of remote, hands-on, and simulated laboratories," ACM Transactions on Computer-Human Interaction, vol. 14, no. 2, Article 7, Aug. 2007.
4. S. Guzelgoz, and H. Arslan, "A Wireless Communications Systems Laboratory Course," IEEE Transactions on Education, vol.53, no.4, pp.532-541, Nov. 2010.
5. J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," ACM Computing Surveys, vol. 38, no. 3, pp. 1-24, Sept. 2006.
6. L. D. Feisel, and A. J. Rosa, "The role of the laboratory in undergraduate engineering education", Journal of Engineering Education, vol. 94, no. 1, pp. 121-130, Jan. 2005.
7. J.E. Greenberg, B. Delgutte, and M.L. Gray, "Hands-on learning in biomedical signal processing," IEEE Engineering in Medicine and Biology Magazine, vol. 22, no. 4, pp. 71- 79, July-Aug. 2003.
8. G. Ferre, A. Giremus and E. Grivel, "Small-group learning projects to make signal processing more appealing: From speech processing to OFDMA synchronization," *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* pp. 2317-2320, 2009.

9. C. H. G. Wright, M. G. Morrow, M. C. Allie, and T. B. Welch, "Enhancing engineering education and outreach using real-time DSP," *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* pp. 2657-2660, 2008.

10. J. Turner and J.P. Hoffbeck, "Putting Theory into Practice with Simulink," *Proceedings of the American Society for Engineering Education Annual Conference & Exposition, 2005.*

11. http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/E001%2010-11%20EAC%20Criteria%201-27-10.pdf. Accessed: January 18, 2011.

12. L. S. Bobrow, *"Fundamentals of Electrical Engineering"*, Oxford University Press, New York, 1996.

13. J.W. Nilsson and S.A. Riedel, "*Electric Circuits* (8th Edition)", by, Prentice-Hall, 2008.

14. *Agilent 33220A 20 MHz Function Generator/ Arbitrary Waveform Generator User's Guide*

15. D. R. Fannin, W. H. Tranter, and R. E. Ziemer, "Signals and Systems: Continuous and Discrete: Fourth Edition," Prentice Hall, 1998.

16. M. J. Roberts, "Fundamentals of Signals & Systems," McGraw Hill, New York, 2008.

17. A. S. Tanenbaum, "Computer Networks (3rd Edition)" Prentice-Hall, 1996, (Chapter 2, pp. 78-81)