A Complete Set of Experiments for Communication Classes

Firas Hassan
Ohio Northern University, Ada, OH 45810
f-hassan@onu.edu

Abstract
In this paper, a set of module based hands-on experiments that cover both analog and digital communication topics are described. The set of experiments can be integrated as a lab component with communication systems classes. The experiments are designed to complement the lecture component and reinforce the student’s understanding of the concepts explained in the class. They cover both analog and digital modulation techniques such as DSB_SC, DSB_C, SSB, NB/WB FM, PCM, ASK, PSK, FSK, MPSK, and QAM. They also cover the effects of band limited noisy channels on the performance of digital baseband communication systems. The experiments were implemented at Ohio Northern University (ONU) in the academic years of 2009 and 2010. Surveys conducted at the end of the classes showed that most of the students found these experiments relevant to the material studied during the course, practically oriented, and aided in their understanding of the course material.

Introduction
The field of communication has gained lot of attention due to the numerous new applications and devices that have been developed, recently. Due to the advances in communication techniques, we can now enjoy video streaming on broadband internet and smart phone devices. Keeping that in mind, fresh graduate electrical engineers need more practical and technical experience in this area. Communication topics usually include: analog and digital modulation techniques, baseband and passband communication systems, performance of communication systems in the presence of noise, tradeoffs associated with various communication systems, and different multi-access schemes. These topics are currently taught in various formats at different schools. For example, Analog and Digital Communication techniques are covered in two separate classes or together as part of a general Communication Theory or Communication Systems class.

Such classes are usually required for electrical engineering majors and can be taken as technical electives for computer engineering majors. Additionally, the classes are mostly offered at the junior or senior level and they are sometimes accepted for credits towards a graduate degree. Many electrical engineering programs around the country cover the communication topics in lecture-based classes without a lab component. While sometimes students are asked to do simulation-based projects to observe the different communication waveforms and report the simulation results, a lab component would enrich the students experience and help in the understanding of the material. An example of a Lab that is totally based on simulation is described in [1]. In addition, [2] and [3] describe a hands-on lab that is similar, in concept, to the work done in this paper. However, [2] concentrates more on electronics and building things from scratch, instead of using plug-in modules, and [3] is targeting mainly wireless communication.
In a previous work [4], the author summarized an effort to address this need through the integration of a few number of experiments with the communication class. Since then, the author has developed a set of twelve different experiments that can demonstrate all the different aspects of the communication systems class. The experiments are scheduled to integrate perfectly with the lecture material on a weekly basis. These experiments are all implemented using a telecommunication instructional modeling system known as tims[5]. The professor can chose between different experiments setup using plug-in modules. It is very well documented and can be easily used at other institutes. The cost of the setup needed to replicate these experiments is only $13,000 for one system with the basic plug-in modules and around $500 for any additional special purpose module.

After the conversion from the quarter to semester system at ONU University, the electrical engineering curriculum committee decided to group the previous Analog and digital communication classes in a communication systems class that covers both topics. The class is four credits with three 50 minutes lectures and one lab period of 180 minutes per week. This gave the author an opportunity to design the syllabus of the class and schedule the lab experiments, accordingly. The text [6] used in the class covers both analog and digital communication techniques. A detailed description of each experiment is given in the following section. The rest of the paper will cover the results of the student surveys from the previous years and give some concluding remarks as well as summarizing the future work.

**Experiment description**

The description of each experiment includes the meeting time, different modules used in the experiment setup, students’ tasks, and the learning objectives. In addition to the tims system and its plug-in modules, each lab bench should include an oscilloscope to measure and observe the different waveforms in the time domain and a spectrum analyzer to check the frequency spectrum of the different signals. The fact that students will be able to see the waveforms in the time and frequency domain at the same time can really help them to grasp the ideas conveyed in this class. Each bench can hold a group of two or three students.

The first lab is done in the second week of class after the instructor has covered double side band suppressed carrier (DSB_SC) modulation technique, the demodulation of this technique using a coherent receiver and some implementation aspects of both the modulator and demodulator. The plug-in modules used in this experiment are an audio oscillator, a voltage controlled oscillator (VCO), two multipliers, and a tunable low pass filter (LPF). Students are supposed to measure the scaling factor and linear region of the multiplier module, check the cutoff frequency of the tunable (LPF), construct a DSB_SC modulator and check its output in the time and frequency domain, construct a coherent receiver using a stolen carrier, that is without generating the carrier locally at the receiver side, and check the different intermediate and output waveforms of the receiver in the time and frequency domain. After performing this lab, students will notice how the modulating signal changes the amplitude of the carrier; understand how the spectrum of the message signal is shifted to the carrier after modulation; and observe that after multiplying the received signal with the carrier and passing it through the tunable LPF, the original message spectrum is shifted back to baseband.
The second lab is done in the third week of class after the instructor has covered double side band with a carrier (DSB_C) modulation technique. At this time, students should appreciate that although this method is less power efficient than the DSB_SC technique, it can be detected through a much simpler noncoherent receiver that does not need a carrier to be generated locally at the receiver side. The plug-in modules used in this experiment are an audio oscillator, a VCO, adder, multiplier, tunable LPF, and a utility module that contains a rectifier, a low order LPF, and an envelope detector (ED). Students will construct DSB_C modulator and demodulate the signal using three different types of noncoherent receivers: a rectifier with a high order LPF, a rectifier with a low order LPF, and an envelope detector. All intermediate and output signals are again observed on the oscilloscope and the spectrum analyzer. After performing this lab, students will understand the difference in the spectrum of DSB_SC and DSB modulated signals; appreciate the fact that with the use of the rectifier and a high order filter the message signal can be reconstructed at the receiver side without any ripples even if the carrier frequency is just ten times the bandwidth of the message signal; and notice that if we are using a low order filter or a cheap ED the carrier should be at least 100 times the baseband signal in order for us to reconstruct the message signal without any ripples.

The third lab is done in the fourth week after the instructor has covered single side band (SSB), as well as, vestigial side band and quadrature DSB modulation methods. All these methods aim at reducing the bandwidth of the modulated signal. In addition, the instructor will cover how to generate the carrier locally at the receiver side and lock it with the phase and frequency of the received signal using a phase locked loop (PLL) or a Costas loop. This experiment is divided into two parts, the first part covers SSB modulation/ demodulation and the second part covers the Costas loop receiver. The plug-in modules used in this experiment are the audio oscillator, quadrature phase shifter, phase shifter, two multipliers, adder, VCO, two tunable LPF, and the utility module. In the first part of the experiment, students should implement a SSB modulator that can transmit at the upper side band (USB) and lower side band (LSB) and demodulate the received signals using a coherent receiver. In the second part of the experiment students should generate a DSB_SC modulated signal and demodulate it using a Costas loop receiver. After implementing this lab, students will understand the difference in the spectrum of the USB and LSB modulated signals and measure the locking region of the Costas loop receiver.

The fourth and fifth labs are done in the fifth and sixth week, respectively. During this period the instructor will introduce different angle modulation techniques such as phase and frequency modulation (FM), explain how to estimate the bandwidth of angle modulation, and demonstrate how to generate narrow band (NB) and wide band (WB) FM modulated signals and demodulate them using an ED or a PLL receiver. While angle modulation techniques generally occupy more bandwidth than the previous amplitude modulation techniques, they offer a good tradeoff between the bandwidth and power of transmitted signal. The plug-in modules used in these two experiments are the audio oscillator, VCO, twin pulse generator, utilities, and multiplier. In these two experiments students will generate an FM signal using the VCO, change the frequency deviation or modulation index ($\beta$) of the FM signals by varying the gain of the VCO or the amplitude of the message signal, and demodulate the signal using a zero crossing receiver, which is a sort of ED, and a PLL receiver. After implementing this experiment, students will understand the difference between NB and WB FM both in the time and frequency domain, verify that the bandwidth estimate of FM modulated signals is correct, and understand that the wider the
frequency deviation the better is the performance of both constructed receivers. Figure 1 below demonstrates, using the output of the spectrum analyzer, how the bandwidth of FM signal varies based on the modulation index, where $\beta$ varies between 5, 4 and 3 for figures 1(a), 1(b) and 1(c), respectively.

![Image](image1.png)

**Figure 1.** Variation of the bandwidth of FM signal based on the modulation index, where $\beta=5$, 4 and 3 for (a), (b) and (c), respectively.

The sixth experiment is done in the seventh week after the instructor has introduced sampling theory and Nyquist rate; explained the role of the anti-aliasing filter before sampling and how to reconstruct the original signal using an interpolation filter; demonstrated the fact that we can use sampling to multiplex signals in the time domain (TDM); described the different quantization techniques, as well as, delta modulation (DM). Sampling and quantization are considered the bridge between analog and digital modulation techniques. The plug-in modules used in this experiment are the analog switch module, twin pulse generator, VCO, and tunable LPF. In this experiment, students will sample an analog signal and reconstruct it using a LPF. They will also multiplex two sampled signals in the time domain and try to de-multiplex them at the receiver side. After implementing this experiment, students will verify that sampling a signal will generate several copies of its spectrum in the frequency domain and hence understand aliasing and Nyquist rate. Students will also start to appreciate the advantage of moving to the digital domain and how easy it is to multiplex signals in the time domain. At the end of the lab, and with the help of two extra special plug-in modules that are not included with the basic package of modules that instructor can demonstrate DM for the students. Figure 2a shows the necessary modules and connection to demonstrate this concept to the students. Figure 2b compares the analog input to the accumulated error signal from the output of the DM. Figure 2c illustrates how the output of the DM is sent as a bit stream of ones and zeros. Figure 2d contrasts the reconstructed signal from the DM output at the receiver side to the original analog signal.
The seventh and eighth experiments are done in the eighth and ninth week, respectively. During these two weeks, the instructor will introduce baseband pulse code modulation (PCM) and the different line codes, describe the effect of band limited channels on the quality of the received signals, explain how to test a channel using the eye diagram, and describe how to reconstruct the PCM codes from the received distorted waveforms using a decision maker. Contrary to the analog domain, baseband digital communication in coaxial cables or optical fiber is still much utilized, nowadays. The plug-in modules used in these two experiments are the audio oscillator, sequence generator, tunable LPF, line code encoder, line code decoder, decision maker, and adder. In these experiments students will check the spectrum and waveform of different line codes, module a band limited channel using a LPF, measure the maximum transmission rate through a band limited channel using the eye pattern diagram, and detect the distorted received waveforms using a decision maker. After implementing this experiment, students will understand the difference between line codes both in the time and frequency domain. In particular, they will be able to measure the bandwidth of the different line codes. Student will also understand how a band limited signal can cause inter symbol interference by distorting the received waveforms and hence induce errors at the receiver side. In addition, students will notice how the decision maker works and appreciate the importance of the sampling position on the performance of the decision maker.

The ninth, tenth and eleventh lab experiments are done in weeks ten, eleven and twelve, respectively. During these three weeks the instructor will introduce different passband digital communication techniques such as amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), and differential phase shift keying. The instructor will also introduce different M-arry passband digital communication techniques such as MPSK, Quadrature amplitude modulation (QAM), and MFSK. MPSK and QAM are used in cases where the rate of transmission is higher than the channel bandwidth. MFSK is used in power limited channels such as satellite communication. Finally, the instructor will explain how to demodulate the passband digitally modulated signals using coherent and noncoherent detectors and how to reconstruct the PCM codes from the demodulated waveforms using the decision maker. The modules used in...
these three experiments are analog switch module, audio oscillator, sequence generator, two multipliers, tunable LPF, VCO, utilities module, adder, tunable Band pass filter (BPF), bit clock regenerator, phase shifter, decision maker, line code encoder, line code decoder, M-level encoder, and M-level decoder. In these three experiments, students should implement ASK modulator and demodulator, PSK modulator and demodulator, FSK modulator and demodulator, DPSK modulator and demodulator, and MPSK/ QAM modulator and demodulation. After implementing these labs students will understand the waveform and spectrum of the different modulation techniques. Students will also verify how to use a PLL to both lock to the carrier frequency of the received signal, as well as, solve the synchronization problem, which is very essential in digital communication. Notice that this is only possible because the master carrier frequency in the times system is an accurate multiple of the master clock that defines the transmission rate. Finally, because students will be able to observe the constellation diagram of both MPSK and QAM on the oscilloscope using the XY mode, they will be able to understand the difference between these two important M-arry techniques.

The twelfth lab is done in week fourteen after the instructor has introduced the fundamentals of probability theory and random processes, as well as autocorrelation and power spectral densities. The instructor will also describe optimum receivers of digital communication systems in the presence of noise such as matched filters and correlators. In addition, the instructor will compare between the performances of the different digital modulation techniques in the presence of noise using the bit error rate (BER) as a figure of merit. The plug-in modules used in this experiment are audio oscillator, two sequence generators, line code encoder, two adders, noise generator, wideband true rms meter, decision maker, line code decoder, and the error counting utilities module. In this experiment, students will implement a baseband transmitter of different line codes, module a noisy band limited channel using a noise generator and a LPF, and check the BER for different noise levels. After implementing this lab, students will be able to plot the BER curves of the different PCM codes at different signal to noise ratios and compare them with the theoretical curves. Students will also be able to study the effect of band limited channels on the performance of digital communication systems in the presence of noise. Figure 3a shows the modules used in this experiment and their interconnections. Figure 3b illustrates a noisy PCM signal at the input of the receiver versus the output of the decision maker. At this level of noise there is a large probability of error (as can be seen from the figure). Figure 3c contrasts the transmitted noise free PCM signal Vs the output of the decision maker at the receiver side. Figure 4d gives an example on counting the number of errors; the figure is showing 164 errors per $10^4$ transmitted bits.

![Image](image1.jpg)  
(a)  
![Image](image2.jpg)  
(b)
Figure 3. (a) modules and interconnections used in the BER experiment, (b) a noisy PCM signal Vs the output of the decision maker with some errors, (c) noise free PCM signal Vs the output of the decision maker, (d) an example on counting the number of errors.

The schedule of each Lab experiments that shows the Lab title, week offered and necessary background lectures is given in Table 1.

<table>
<thead>
<tr>
<th>Lab</th>
<th>Week</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSB_SC mod/demod</td>
<td>Two</td>
<td>Amplitude modulation and demodulation concepts</td>
</tr>
<tr>
<td>DSC_C mod/demod</td>
<td>Three</td>
<td>Non coherent reception of DSB_C signals</td>
</tr>
<tr>
<td>SSB, PLL and Costas Loop</td>
<td>Four</td>
<td>SSB mod and locking to the carrier of the received signal</td>
</tr>
<tr>
<td>FM modulation</td>
<td>Five</td>
<td>Relation between modulation index and bandwidth of FM</td>
</tr>
<tr>
<td>FM demodulation</td>
<td>Six</td>
<td>Zero crossing and PLL receivers of FM signals</td>
</tr>
<tr>
<td>PCM, TDM and DM</td>
<td>Seven</td>
<td>Sampling theory and sigma delta modulators</td>
</tr>
<tr>
<td>Baseband digital signals</td>
<td>Eight</td>
<td>Different line codes and their corresponding bandwidth.</td>
</tr>
<tr>
<td>Baseband digital receiver</td>
<td>Nine</td>
<td>Decision making and intersymbol interference</td>
</tr>
<tr>
<td>ASK and FSK</td>
<td>Ten</td>
<td>Digital passband signals such as ASK and FSK</td>
</tr>
<tr>
<td>PSK and DPSK</td>
<td>Eleven</td>
<td>PSK and noncoherent reception of DPSK</td>
</tr>
<tr>
<td>MPSK, MFSK, and QAM</td>
<td>Twelve</td>
<td>M-arry communication systems</td>
</tr>
<tr>
<td>BER calculation</td>
<td>Fourteen</td>
<td>Noise analysis in digital systems</td>
</tr>
</tbody>
</table>

Assessment
As mentioned before, ONU University has recently transferred from a quarter based system to a semester based system. Hence, this will be the first year of implementing this lab set as a whole. The author is currently offering the communication systems class, and hence there is no official student feedback yet. However, the same lab set was implemented for the previous two years in two different classes. The first six experiments were implemented in the analog communication class and the remaining six experiments were implemented in the digital communication class. At the end of each class students were asked to rate the following statements in their end of term feedback:
1. The laboratory assignments facilitated my learning experience.
2. The laboratory assignments and course material reinforced one another.
3. The laboratory equipment was modern and useful.

Students rate each statement with either strongly disagree (SD), or disagree (D), or undecided (U), or agree (A), or strongly agree (SA). The answers were w between one for SD and five for SA. A total of 13 and 18 students took the class in 2010 and 2011, respectively. As shown in table 2, the mean of the three questions for two different years was between 4.22 and 4.66. Out of the three questions, question two rated the highest in both years. This means that students agree with the fact that the lab can reinforce the lecture material by demonstrating the different theoretical areas covered in class.

**Table 2. Student feedback for the years 2010 and 2011**

<table>
<thead>
<tr>
<th></th>
<th>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>4.30</td>
</tr>
<tr>
<td>Q2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>6</td>
<td>4.46</td>
</tr>
<tr>
<td>Q3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>5</td>
<td>4.38</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>9</td>
<td>4.50</td>
</tr>
<tr>
<td>Q2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>12</td>
<td>4.66</td>
</tr>
<tr>
<td>Q3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>7</td>
<td>4.22</td>
</tr>
</tbody>
</table>

**Conclusion**

In this paper a complete set of lab experiments that can be integrated with communication systems class was introduced. The lab was implemented for three consecutive years at ONU University. Based on the student feedback, experiments helped students in understanding the different concepts of the class. Because the students were able to generate all the different modulation techniques studied in class and check the waveforms both in the time and frequency domain, they were able to better understand the practical aspects of the theory explained in class. In the future, the author is planning on buying more non basic plug-in modules to be able to demonstrate advanced communication topics such as code division multiple access (CDMA) and orthogonal frequency division modulation (OFDM).
References


