Software Defined Radio for Digital Signal Processing Related Courses

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Currently a graduate student at Miami University’s electrical and computer engineering department. My research is in automatic modulation detection. Given a carrier frequency, determine the unknown modulation scheme used to transmit information at that frequency. I also work on creating instructional labs that use LabVIEW and software defined radios such as the NI-USRP 2920 to accompany Miami University’s “Digital Signal Processing” and “Signals and Systems” courses. These courses are very math and theory based, but by adding a lab portion, students will be able to apply fundamental theories covered in class to develop a better understand the topics.

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Abstract

Software-defined radio (SDR) is widely used in undergraduate electrical and computer engineering curricula in the area of communication. It is commonly used as laboratory equipment for students to implement communication systems and verify communication theory learned in class. In this project, supported by a NSF TUES type II grant, Collaborative: TUES: Software Defined Radio Laboratory Platform for Enhancing Undergraduate Communication and Networking Curricula, we explore the possibility of applying the SDR as an education tool to teach fundamental signal processing concepts. To achieve this goal, we developed SDR based laboratory exercises. Although students are still required to develop analog/digital communication systems, the major focuses of these exercises are to illustrate fundamental signal processing concepts such as frequency-shift, spectra of real and complex valued signals, etc. The target students are junior level undergraduate students who have taken “Signals and Systems” but are not necessary enrolled in the class of “Digital Signal Processing (DSP).” Two undergraduate students who have taken the course of “Signals and Systems” but have not yet taken or finished “Digital Signal Processing” were invited to test laboratory exercises developed in this project. The goal of this project is to develop laboratory exercises to demonstrate theories covered in fundamental signal processing courses. Such courses are mathematically orientated and students often feel challenged in these classes. We believe that experimental exercises with real-life application examples can motivate students and help them to develop a better understanding of signal processing theories.

Introduction

One of major issues an electrical engineering undergraduate student encounters when he/she starts to learn the concepts of signal processing like the Fourier transform, in a class such as “Signals and Systems”, is the difficulty of comprehending the concept of frequency domain and related operations. It is not unusual for a student in this kind of class to try to memorize important Fourier transform pairs and properties to earn an acceptable grade without understanding the implications and applications of signal processing techniques. In many cases, it is not until students take subsequent courses such as “Communication Systems” or “Digital Signal Processing” that they begin to appreciate the applications of signal processing techniques. However, it is too often that many students do not perform well in these courses because of the weak foundation laid in the course in which they are exposed to basic signal processing concepts for the first time.

One way to motivate engineering students to learn complicated and sometimes abstract engineering concepts is to complement theory with appropriate laboratory exercises. One of the major application areas of signal processing is communications. The rapid advance of software-defined radio (SDR) in recent years made communication system experiments much easier to conduct than ever and students do not have to invest a significant amount of time to master the operation of equipment before conducting experiments. In this paper, we will present our SDR laboratory course designed to help junior-level students to get a better understanding of basic signal processing techniques. The focus of this course is fundamental signal processing concepts rather than sophisticated communication theories for which many SDR based textbooks have been written1-3.
Comparison between Conventional and Proposed Pedagogy

Use the course of “Signals and Systems” in which most students learn the concept of frequency domain operations systematically for the first time as an example. The instructor of this course frequently covers the basic signal operations such as time-shift followed by the definition of linear time-invariant system that allows the instructor to introduce the concept of convolution. The continuous time Fourier transform and its related operations are then covered. If time permits, sampling theory and some discrete time operations may be introduced⁴. Some instructors might employ simulation assignments using software such as Matlab® to facilitate students’ learning. One issue with this approach would be that simulation software such as Matlab® is designed to handle discrete-time signals and students need to use the software to learn continuous-time signal processing. The other issue is that it is difficult to conduct nontrivial signal processing tasks in this kind of assignments due to students’ limited knowledge about signal processing. For example, it will be difficult to assign a Matlab® assignment that requires students in the class of “Signal and Systems” to design a lowpass filter. On the other hand, asking students to plot the convolution of two signals using a computer program might not excite them.

To solve the issues mentioned before, we would like to develop a laboratory course that helps students to comprehend the fundamental theory of signal processing. The laboratory exercise for this course needs to (1) be directly related to real-world applications (2) allow students to process continuous-time signals (3) allow students to start working on laboratory exercises with limited signal processing background and gain more insights about signal processing theory throughout the course. One of the major applications of signal processing is wireless communications and the rapid advance of SDR, both hardware and software, significantly reduces the complexity of building a SDR project. Therefore, it is a natural choice to develop this laboratory course using SDR as a platform. The selection of SDR platform will be discussed next.

SDR Platform Choice

One hardware kit widely used in the teaching of digital signal processing techniques is Texas Instruments’ Digital Signal Processing Starter Kit (DSK)⁵-⁶. The popular model is TI-DSK-6713. This kit is designed to process audio signals and needs a daughter card to up-convert signals to the radio frequency. This kit is widely used in a senior/graduate-level course such as “Real-Time DSP” whose usual prerequisite is “Digital Signal Processing.” This DSK can be programmed via Texas Instruments’ Code Composer Studio⁷. Students typically need to possess a solid understanding about digital signal processing to conduct signal processing experiments with a DSK. Therefore, it might not fit our need to teach junior-level students fundamental signal processing techniques.

Another tool, RTL-SDR, has received a significant amount of attention in recent years⁸-¹⁰. This very inexpensive SDR kit (can be purchased for less than $20) allows students to receive a radio signal and process it using software such as Matlab® and GNU radio. Many RTL-SDR projects can be found on the Internet¹¹. Its affordability allows individual student to purchase one unit and avoid going to the schools’ laboratory at assigned lab hours to conduct experiments. However, because this kit can only be used as a receiver, students need to use signals of opportunity for experiments and the instructors usually do not have control over the signals for students to process. For example, the frequency range of the RTL-SDR is 24 MHz – 1766 MHz and the commercial AM radio frequency range is 535-1605 kHz. As the results, students will not be able to use the RTL-SDR to conduct AM radio experiments unless the instructor set up an AM radio station in
the laboratory. Additionally, students will not be able to build a transmitter with this kit. We would like to develop a laboratory course in which students design both a transmitter and receiver. To this end, we will need to use a different SDR kit.

![Figure 1. The National Instruments’ NI-USRP-2920](image)

The SDR kit we propose to use in this proposed course is National Instruments’ NI-USRP-2920. It is a newer version of USRP developed by Ettus Research originally. This SDR kit can be programmed via LabVIEW which is also used in some required laboratory courses at Miami University. Using LabVIEW’s inherent functions, students can easily build a radio transmitter and receiver and focus on signal processing concepts rather than detailed hardware settings. Due to this functionality, students can use the same kits in a higher-level course to conduct more complicated communication experiments. The picture of NI-USRP-2920 is shown in Figure 1.

**Related SDR Lab Courses**

As mentioned in the previous section, many SDR laboratory courses have been developed on different platforms such as Texas Instruments’ DSK and RTL-SDR. Some SDR laboratory courses were developed using the NI-USRP-2920, the same platform used in this project. The major focuses of these courses are communication systems rather than fundamental signal processing concepts and the prerequisite of these courses are most likely to be Digital Signal Processing. Therefore, a significant portion of these courses are dedicated on subjects such as synchronization and equalizations or students are required to design digital filters in early lab exercises. On the other hand, this project is aimed to prepare students for the course of Digital Signal Processing; therefore, the focuses of the course developed in this project are fundamental signal processing concepts such as the difference between real-valued and complex-valued signals, frequency-shifting property, etc. We rely on LabVIEW’s functions to implement complicated signal processing tasks thus allowing students to build SDR projects. Students are only required to understand these functions’ working principles rather than their implementation details. With this approach, we can focus on basic signal processing concepts and students can gain insights.
about signal processing concepts and be motivated by implementing working radio transmitter/receiver and digital communication systems.

Developed Lab Exercises

A two-credit hour course named “Introduction to Software Defined Radio” is created in this curriculum development project. This course has fifty minutes of lecture time and one hundred and ten minutes of lab time per week for 14 instructional weeks. The prerequisites of this course is “Signals and Systems” and a basic programming course. This course has seven laboratory exercises based on the NI-USRP-2920 followed by a final project. These laboratory exercises are described in the following.

Lab 1: Introduction to NI-USRP and LabVIEW

The first lab exercise is designed to help students to become familiar with LabVIEW and learn how to control the NI-USRP-2920 using LabVIEW. Students learn how to generate sinusoidal and square waves and plot signal waveforms on the computer screen. Through conducting this experiment, student will acquire the basic concept of graphical programming language such as LabVIEW.

Lab 2: Spectrum Analysis

This lab exercise is designed to help students to learn how to conduct Fourier analysis of a signal. Students learn how to generate a square wave and plot its spectrum. Students can multiply the signals with different window functions such as a Hanning or Hamming window to observe the different spectra of these window functions. Students are also requested to sense a given frequency range in which a commercial FM signal can be found. The FM signal is identified by observing the FFT magnitude spectrum.

Lab 3: Amplitude Modulation (AM)

In this lab exercise, students build a double sideband AM transmitter and receiver and analyze signal’s spectrum. By observing the modulated signal’s spectrum, students can witness that by multiplying a signal with a sinusoidal signal, the original spectrum is shifted to the carrier frequency. Through conducting this experiment, student can acquire a deeper understanding of Fourier transform’s frequency shift property.

Lab 4 Single Sideband Amplitude Modulation

In this lab exercise, students build a single sideband AM transmitter and receiver and analyze the signals’ spectrum. This lab is designed to demonstrate the symmetric spectra of real-valued signals. By conducting this lab, student can see how the Euler’s formula is applied in real-life applications. One of the issues instructors encounter when teaching digital signal processing concepts are complex-valued signals. This lab can prepare students for later lab projects dealing with complex-valued signals such as Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) signals.

Lab 5 Frequency Modulation (FM)
In this lab exercise, students build a FM transmitter and receiver. Since most students have been listening to AM and FM radio since their childhood, the FM radio project is a good lab project after the AM radio project. Additionally, due to the frequency range of the NI-USRP-2920, this kit cannot receive commercial AM radio signals but it can receive commercial FM radio signals. This lab is used to demonstrate the concept of instantaneous frequency and concept of chirp signals.

After accomplishing the first five laboratory exercises listed above, students will be required to generate sophisticated digital communication signals such as phase-shifted keying (PSK) and quadrature amplitude modulation (QAM). They are the subjects of Lab 6 and Lab 7. The instructor can choose to implement one or both of them depending on the time limitation.

Lab 6 Phase Shift Keying (PSK)

In this lab exercise, students build a PSK transmitter and receiver. This lab project shows students how to generate complex-valued signals and demonstrate the importance of synchronization in digital communications. Some other factors such as match filter and pulse shaping filter are also considered in this project.

Lab 7 Quadrature Amplitude Modulation (QAM)

In this lab exercise, students build a QAM transmitter and receiver. This lab project provides students another opportunity to learn complexed-valued signals. If the instructor would like to allow students more time for the final project, he/she might choose cover only Lab 6 or Lab 7.

Final Project

Students are expected to finish one regular lab exercise per week and work on a final project after finishing all regular lab exercises. Some regular lab exercises like Lab 6 or Lab 7 might be a two-week project. Students will apply the knowledge they acquired from regular lab projects to the final project. The final project meant to be an open-end project. Interested students might choose to continue their final project after finishing this course and use it as a senior capstone project to pick in their senior year.

The undergraduate students participating in this curriculum project chose to investigate the co-existence of a FM radio station and a digital communication system in the same spectrum. This project allows students to learn the basic concepts of code-division multiple access (CDMA) and the relation between the bit error rate and noise level. One faculty member reviewing our curriculum proposal recommended an orthogonal frequency division multiplexing (OFDM) lab exercise as an optional lab exercise or a potential final project topic to help students get a deeper understanding about Fourier transform.

LabVIEW is a graphical programming language and it provides plenty of communications related functions; therefore, the programming tasks can be significantly simplified to allow students to focus on signal processing concepts rather than programming. Furthermore, due to LabVIEW’s user-friendly programming environment and the capability of NI-USRP-2920, students will be able to conduct more complicated lab exercises. Each LabVIEW program consists of two parts: a block diagram and a front panel. The front panel can be considered as the graphical user interface and the block diagram is the execution portion of the program. The block diagrams and front panel of a LabVIEW PSK transmitter developed in Lab 6 are shown in Figure 2 and Figure 3, respectively. The block diagrams and front panel of a LabVIEW PSK receiver developed in Lab 6 are shown in Figure 4 and Figure 5, respectively.
Figure 2. The LabVIEW Block Diagram of a PSK Transmitter Program

Figure 3. The LabVIEW Front Panel of a PSK Transmitter Program
Figure 4. The LabVIEW Block Diagram of a PSK Receiver Program

Figure 5. The LabVIEW Front Panel of a PSK Receiver
Assessment Method and Feedbacks

We discussed this course proposal with faculty members who have taught fundamental signal processing courses in the past and received very positive feedbacks. Two undergraduate students were invited to conduct the lab exercises and evaluate the lab manuals and they showed great interest in the lab materials. One participant is taking Digital Signal Processing and we have observed a significant improvement in this student’s class performance. Based on the feedback from participants, the lab exercises help students to visualize the difference between different signals. However, some lecture time spent on reviewing basic signal processing concepts can help students to build a coherent connection between time-domain and frequency-domain operations in addition to being very beneficial.

To systematically assess the effectiveness of this proposed pedagogy, we intend to compare the scores of students who take this laboratory course and who do not take this laboratory course in the courses of “Digital Signal Processing” and “Communication Systems” in a larger scale. Such a comparison can provide more measurable assessment results. We intend to seek assistance from statisticians when analyzing this data.

Conclusion

A SDR based laboratory course is developed to teach junior-level students fundamental signal processing concepts. Compared with other approaches, the proposed approach allows students to comprehend the implication of signal processing theory via real-life communications system examples with little difficulty.

References

2. Black, Bruce A., Introduction to Communications – Lab Based Learning with NI USRP and LabVIEW Communications, National Instruments, 2014.


