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Undergraduate Research: Adaptation and Evaluation of Software-defined Radio-based Laboratories

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Undergraduate Research: Adaptation and Evaluation of Software Defined Radio Based Laboratories

Abstract

Funded by a collaborative NSF TUES type II project, a novel suite of affordable and evolvable Software Defined Radio (SDR) based laboratories was implemented and institutionalized at three institutions (Wright State University, Miami University and Central State University) to demonstrate its capability and adaptability. As a participating institution, Central State University worked closely with the other two institutions and successfully adapted the laboratory modules. Further, we developed and updated our own laboratory modules to improve undergraduate students' understanding and learning. The latest modules include **Starting out with SDR**, **GNU Radio Companion**, **SDR with Python Programming**, **USRP Implementation** (e.g. FM receiver) and **Advanced USRP Implementation** (e.g. Digital modulation constellation). The modules have been integrated into two undergraduate level courses for three years. The students' learning outcomes were internally evaluated by the PI at the institution and a reviewer from the leading institution, Wright State University; and externally evaluated by a reviewer who was neither from the participating institutions nor directly involved with the project. The achieved goals and discovered issues were reported and discussed. Overall, the results demonstrated a positive example of integrating modern technology and research into minority undergraduate education, thereby enhancing the minority undergraduate Computer Science curricula.

1. Introduction

The explosion of the modern wireless technology[1] has made it an intriguing topic in higher education. Many talented students in the Science, Technology, Engineering, and Mathematics (STEM) programs are eager for hands-on experience to discover how wireless communication works. However, wireless networking laboratories are usually offered only at the graduate level. Few institutions can offer a real laboratory in their networking courses at the undergraduate level, simply because the traditional approach of conducting networking laboratories is too expensive. For example, the Telecommunications Instructional Modeling System (TIMS) communication laboratory equipment[2] used by Auburn University[3] and Georgia Tech[4] costs $100,000 for one basic setup, and upgrading the hardware for different laboratory modules would cost even more. Thus, a more affordable solution to conduct networking laboratories is desired, and it should be made evolvable so that it can be easily adapted to different educational programs.

SDR[5] is a radio communication system where most traditional hardware components are implemented by means of computer software. A basic SDR system may only consist of a personal computer equipped with a Radio-frequency (RF) hardware frontend, such as the Universal Software Radio Peripheral (USRP)[6] designed by Ettus Research™. As for the software solution, although there is a $5,500 teaching bundle offered by National Instruments Corporation[7], a preferable choice is GNU Radio[8], a free and open-source software development toolkit that can create various signal processing blocks and can be combined with external RF frontend to create SDR, or work alone in a simulation-like environment. Because most signal processing tasks are handled by the computer's CPU, the SDR system is cost effective and flexible enough to setup various networking laboratories without the use of expensive specific hardware such as RF signal generator, spectrum analyzers, or modulators/demodulators.

Funded by a collaborative NSF TUES type II project, a novel suite of affordable and evolvable Software Defined Radio (SDR) based laboratories was implemented and institutionalized at three institutions to demonstrate its capability and adaptability. Compared to the other two institutions, our university is a relatively small institution with a large diverse population of students. SDR based laboratory had never been introduced to the students before, which made us a suitable subject to test the suite's adaptability. In order to help the undergraduate students to comprehend the concept and implementation of SDR, we re-designed five lab modules that provides step-by-step guidelines and instructions that can improve the students' learning outcome. The lab modules had been continuously updated from 2014 to 2017 based on the students' feedback.

2. Laboratory Setup

2.1. System Setup

In this work, we used USRP1 motherboad ($700) from Ettus Research™ as the hardware frontend. Each USRP1 consists of a motherboard that provides up to four 12-bit analog-to-digital converters (ADC) at 64M samples/sec, four 14-bit digital-to-analog converters (DCA) at 128M samples/sec, a million gate-field programmable gate array (FPGA) and a programmable USB 2.0 controller (see Figure 1). ADCs and DACs are the bridge between the continuous analog signals and the discrete digital samples. All the ADCs and DACs are connected to the FPGA. The functionality of FPGA is to perform the high-speed general purpose operations, such as digital-up conversion and digital-down conversion, decimation, and interpolation, and to reduce the data rate feeding to USB2.0. FPGA connects to a USB2.0 interface chip. The waveform-specific processing are performed on the host CPU. Each fully populated USRP motherboard can support up to two transmit daughter boards and two receive daughter boards. Radio frequency (RF) front-end is implemented on the daughterboard. In ours case, we use one RFX400 daughter board ($275) for each motherboard, which has 2 quadrature frontends for transmitting and receiving, and the bandwidth is 40MHz for both frontends.

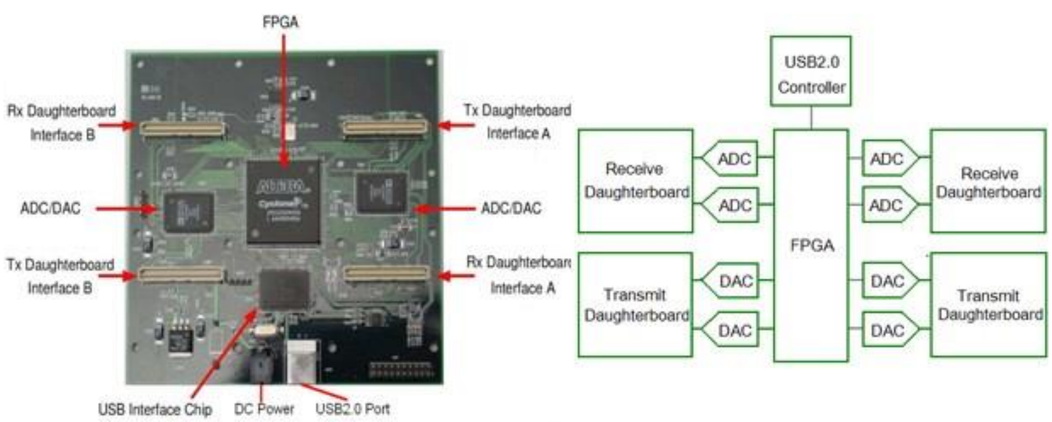

Figure 1: USRP1 Motherboard

2.2. Laboratory Modules

In order to improve undergraduate students' understanding and learning, the following step-by-step laboratory modules are updated based on our previous modules in 2016[9] and the students' feedback in 2016 and 2017:

I) **Starting out with SDR:** GNU Radio is only officially supported by Linux operating system, but some undergraduate students are not familiar with Linux at the first place. This module provides a complete guide on how to install Ubuntu[9], a Debian-based Linux operating system, as a guest operating system on Microsoft Windows using Oracle VirtualBox[10]. As an alternative solution, this module also provides a guide on how to install Ubuntu/Windows Dual system for academically advanced students. This module also provides a complete guide on how to install GNU Radio and the USRP Hardware Driver (UHD) on Ubuntu, using the build-in script provided by Marcus Leech[8]. In previous study[9], we also provide a guide on how to manually install GNU Radio and UHD from the source, and the students who explore this approach can acquire the latest version of GNU Radio components and make changes to the GNU Radio core. But the students' feedback suggested this method could be rather challenging at the undergraduate level. Thus we only provided related links for independent study.

II) **GNU Radio Companion**. The objective of this module is to introduce GNU Radio Companion (GRC), a graphical tool included in GNU Radio that can create signal flow graphs with signal processing blocks. When the blocks are connected correctly, a flow graph will be created. The corresponding Python code will be automatically generated and can be saved in a *.py* file. The students can change the properties of the blocks in GRC or edit the source code directly. This module is especially suitable for students with little to no Python programming background.

III) **SDR with Python Programming**. The objective of this module is to teach students how to edit and run Python source code that calls the GRC blocks. Incomplete source code is provided and the students need to finish and test the code by themselves. USRP front is not required in these laboratories. They can be implemented just using the computer's sound card. Preliminary programming background is recommended.

IV) **USRP Implementation**. This module is a collection of laboratories that require USRP support. These laboratories were mostly developed and maintained by the student research assistants (RAs), and designed for average students who are interested in working on Software-hardware interface. For example, in one laboratory the students need to create an application with GNU radio and USRP to receive local FM radio signals (e.g. 105.7MHz) using the following blocks:

- UHD USRP Source
- Low-Pass Filter
- WX GUI FFT Sink
- WBFM Receiver/Demodulator
- Audio Sink

And the expected graph is showed in Figure 2:

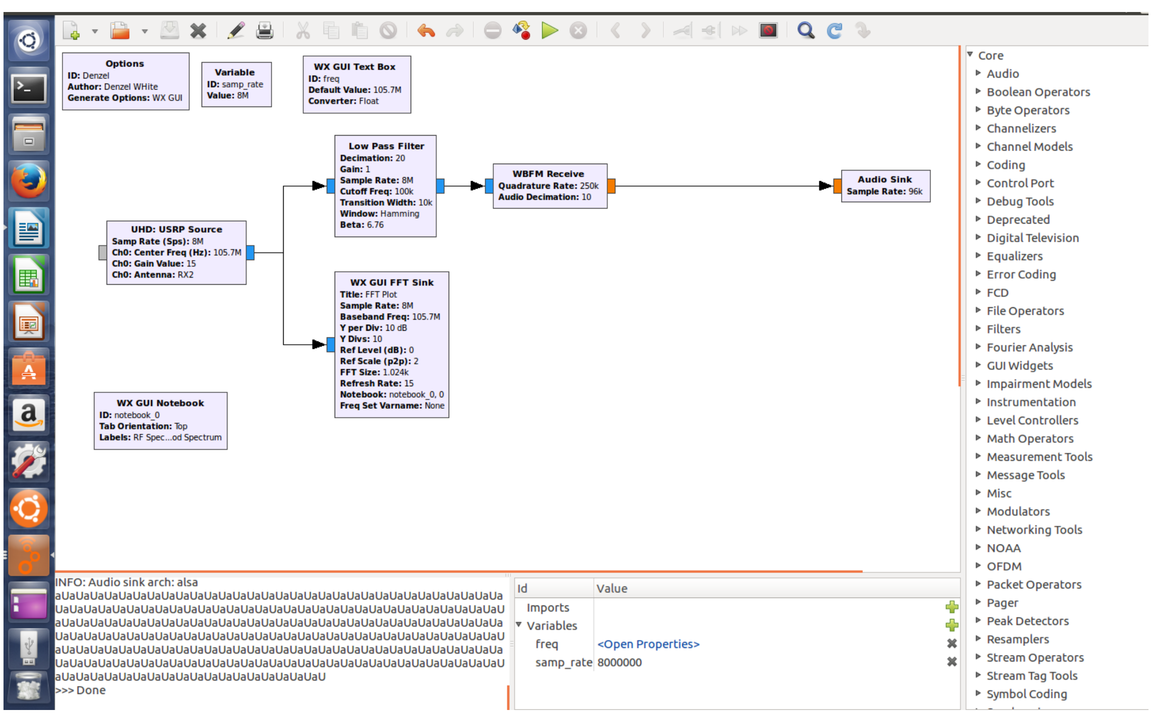

Figure 2: FM Recevier Created using USRP1 and GNU Radio

V) **Advanced USRP Implementation**. Based on the undergraduate student's feedback from our institution, this module is reserved for advanced students who have strong background in Python programming and USRP frontend. It contains a collection of more comprehensive laboratories that require higher level of understanding of digital signal processing and programming, and extra knowledge background such as MATLAB and Labview. These laboratories were mostly developed at Wright State University, such as the digital modulation/demodulation platforms[12].

The redesigned module I-V shall provide adequate guidelines and examples that allow an institution to build SDR based laboratories from scratch. The complete Python code for each laboratory is provided, so that the instructors will be able to edit the code as needed, and the students can benefit from different ways of exploring GNU SDR library.

2.3. Course and Undergraduate Research Setup

The SDR lab modules were integrated as elective laboratories into two courses for STEM majors: CPS3316 - Computer Networks and CPS4895 - Senior Project from 2014 to 2017. Starting from fall 2015, SDR was also introduced to other students who were not registered for CPS3316 and CPS4895 via colloquium talks. By the end of 2017, SDR based laboratories were introduced to more than 50 students across the campus, and 28 students completed at least one laboratory report or SDR based project report. 10 students who showed sufficient understanding and strong interest in developing SDR based laboratories were awarded as research assistants (RAs). RAs were trained to carry out research work according to the project schedule, such as system environment maintenance, module debugging and developing new modules. We expected the RAs could improve their understanding in wireless communication and networking area and gain valuable research experiences that would help them to be graduate school ready.

3. Evaluation and Assessment

3.1. Assessment Methods

Student Feedback: The students' learning outcomes were evaluated and assessed with quantitative and qualitative metrics. The students' academic performance was recorded based on their laboratory reports and project reports. Anonymous questionnaires were collected from participating students to assess the impact of SDR based laboratories. Comprehensive face-to-face interviews were conducted for RAs for training purposes.

Internal Evaluation: An independent internal evaluation was conducted by Dr. Brian Rigling, the chair of the PI at Wright State University, who is not directly involved with this project.

External Evaluation: The project was independently assessed by an external review committee member, Dr. David Mycue at Brown University, who is not directly involved with this project from each participating institution.

3.2. Assessment Results

The course assessment results were summarized in Table 1.

Total surveyed students (2014-2017)	**28**
Students who demonstrated adequate knowledge and skills to complete a satisfactory lab report, or project report with SDR related topic (received more than 70% credits)	**89.3%**
Individual Level: Students who agreed that they gained unique knowledge and enhanced their scientific and/or technological understanding in individual laboratory sessions.	**100%**
Individual Level: Students who agreed that the course with SDR-based laboratory sessions progressively deepened and broadened their skills.	**100%**

Course Level: Students who agreed that adding SDR-based laboratory sessions to the course made it more interesting.	**96.4%**
Program Level: Students who agreed that they were better motivated and engaged to stay in the Computer Science program after SDR based laboratories were offered.	**85.7%**

Table 1: Course Assessment Summary

From undergraduate research perspective, the collaborative project exposed participating undergraduate students to the possibilities of graduate study and encouraged them to choose a career path involving research. We observed that the students developed more intellectual confidence as they were awarded as research assistants. They benefited greatly when collaborating with other students who share their commitment to science, mathematics, and engineering. The project also advanced the research skills of the undergraduate students and enhanced the research and employment opportunities for these students. Shortly after joined this project, two RAs were offered NASA student research fellowship, one RA was offered another NSF research assistantship at Wright State University, and one RA was recruited by an IT company before graduation because his research background.

The progress of the project was recognized and approved by the internal reviewer. The external reviewer was also impressed by the various SDR modules developed by the three institutions and endorsed the overall project.

4. Conclusion

In this work we adapted and assessed a novel suite of affordable and evolvable Software Defined Radio (SDR) based laboratory modules at a minority institution. The assessment results suggested that the laboratory modules can benefit a diverse population of students by motivating, engaging, and enhancing their learning and understanding. We also received positive reviews from internal and external reviewers. The results demonstrated a positive example of integrating modern technology and research into minority undergraduate STEM education.

With three institutions participating, the overall collaborative project had an immediate local impact. The hardware solution for the project is inexpensive, and the software we employed to develop the laboratories is open source, with a large supporting community. The proposed laboratory suite is therefore affordable and evolvable, and can be easily adapted by other institutions. We will continue to develop the suite in order to lead a national model of SDR laboratory based wireless communication and networking courses.

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