Integration of Software-Defined Radios into Undergraduate Communications System Courses for Minority Students

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Abstract- Software-defined radios (SDR) are reconfigurable communications systems whose functionality can be redefined by software on a computer or embedded system. In this paper, we describe the integration of the SDR laboratory developed and tested at Auburn University into the communications system curriculum in the Department of Electrical Engineering of Tuskegee University, a historically black college and university (HBCU). The main purpose of this effort is to improve the abstract thinking ability and hands-on skills and to keep abreast with state-of-the-art technologies among the minority students at Tuskegee University. Assessment results and student feedbacks will be used to further improve the laboratory design to a fully-fledged laboratory course.

Keywords: Software-defined radio, communications system engineering, wireless engineering, curriculum development.

INTRODUCTION

Although the concept of software-defined radio (SDR) dates back to the 1970's, the term was first used in an IEEE publication in 1992 [Mitola, 9]. Because of their flexibility and cost efficiency, SDRs allow the implementation of radio communication systems that are interoperable among different standards, protocols, frequency bands, user requirements and functionalities and thus bring profound impact to the evolution of communications systems. It is expected that, in the near future, SDRs are to become the dominant radio communications technology.

Given the importance of the SDR technology and the need for SDR expertise by the industry, government and academia, it was found that SDR courses were only offered mostly to graduate students [Reed, 11][Heath, 3]. To fill in this gap, Mao et al. at Auburn University made an effort to develop and introduce SDR courses into their ABET-accredited Bachelor of Wireless Engineering program [Mao, 8]. In [Mao, 8], the authors described their hands-on approach of teaching wireless communications and networking based on SDRs.

Through their many years of experience in undergraduate education, the authors noticed that the lack of hands-on capabilities among the students at Auburn University was so severe that it was not only jeopardizing students' engineering career, but causing damage to the department's recruiting and retention records as well. In addition, the authors also found that the introductory level courses in communications systems can be so mathematical and abstract that the students struggle with even the very basic concepts. In an attempt to address these incumbent problems, and motivated by the situated learning theory [Anderson, 1][Lave, 7], the authors designed and integrated SDR term projects and lab experiments and senior design projects with traditional curriculum in wireless

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engineering and communications systems. These projects and experiments give the student the opportunities and platforms to actually apply and experiment with the theory and principles of wireless communications they learned in classrooms, to handily observe the entire process of signal processing throughout a communications system and to create and test their own ideas. The authors believed that their approach has the potential to enhance student learning outcomes, improve hands-on and practical skills of students and strengthen the aptitude of teamwork among students. The authors offered the projects and experiments in the summer and fall semesters of 2012 and received highly positive feedbacks from the students through online survey. The authors thus intended to promote their teaching model to institutions other than Auburn University.

It is believed that, to protect and keep the competitive edge of the United States, improving our science, technology, engineering and mathematics (STEM) education of underrepresented minority students has become a critical issue. According to figures published by the U.S. Census Bureau in 2008, ethnic minorities currently consist of a third of the U.S. population and, by the year 2042, they will comprise more than half of the population in the U.S. [United States Census Bureau, 14]. Actually, by the year 2023, less than ten years from now, more than half of all children will be minorities. This demographic change indicates that, not too far from now, we are going to see a steady increase in the percentage of minority students in our STEM talent pool.

As one of the most prestigious historically black colleges and universities (HBCU) in the U.S., Tuskegee University has always been a top provider of African-American engineers in the nation and thus situates at the forefront of providing STEM education to minority students. Within the Electrical Engineering Department of Tuskegee University, communications engineering is one of the most emphasized components. From years of teaching at Tuskegee University, similar difficulties and problems as mentioned above were observed among the students in the teaching of communications systems by the authors. This observation in turn led the authors to the idea of adopting the well-received SDR teaching models at Tuskegee University.

The remainder of this paper will be organized as follows. We start with a brief description of SDRs. This is followed by a discussion on the current courses offered in the Electrical Engineering Department at Tuskegee University and how SDRs can help improve the teaching and learning in these courses. We then introduce the SDR term projects and lab developed and offered at Auburn University and the test offering of these projects to the minority students at Tuskegee University. The assessment data and survey results from Tuskegee students involved in the projects will be presented. Conclusions will be made and future work stated in the last section.

SOFTWARE-DEFINED RADIO: A PRIMER

According to the SDR forum, an SDR is a radio in which some or all of the physical layer functions are software defined [SDR Forum, 12]. The underlying concept of an SDR is to make the radio reconfigurable simply by means of software change so that a generic hardware platform can be used for multiple purposes. SDRs are especially attractive in operations in which communications across various standards and/or protocols are needed. They are also highly valuable in systems that are often upgraded and expanded to accommodate new services and tasks. It is believed that, due to their adaptability, cost and time efficiency, SDRs will find widespread applications in mainstream telecommunications markets.

A simplified block diagram of an SDR is shown in Figure 1. For RF reception, the analog signal from the antenna is first passed through a front-end low-noise amplifier to improve signal-to-noise ratio (SNR). The signal is then converted into digital by the analog-to-digital (ADC) converter and then processed by the baseband processor. For RF transmission, digital signals from the baseband processor are converted into analog by the digital-to-analog (DAC) converter and then a power amplifier (PA) is used to amplify the signals before transmission. Throughout both reception and transmission, the baseband processor, implemented using programmable processing devices including field programmable gate array (FPGA), programmable system on chip (SoC) and general purpose processors (GPP), performs all the physical layer functions such as filtering, up/down conversion, modulation/demodulation and other baseband signal processing.

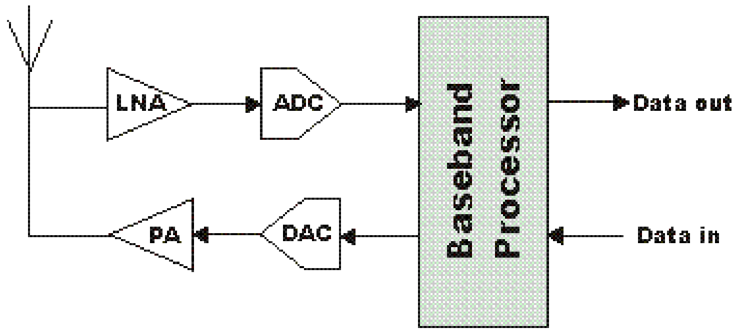

Figure 1: Block diagram of an SDR.

UNDERGRADUATE WIRELESS ENGINEERING CURRICULUM AT TUSKEGEE UNIVERSITY

Established in 1881 by the prominent educator Booker T. Washington, Tuskegee University plays a central role in the education of African-Americans in the United States. Because of its value in the history of African-American higher education, the university is the only Historically Black College and University (HBCU) to be named as a national historic site. Among the five colleges at Tuskegee University, the College of Engineering is one of the top producers of African-American engineers throughout the nation. It is one of the only ten HBCU colleges that offer ABET-accredited engineering programs.

Of all the four departments in the College of Engineering, the Electrical Engineering Department is the largest both in terms of the number of students and faculty members, and is the only one that has an ABET-accredited graduate program. During the 2007-2008 academic year, a total of 93% of the undergraduate students that were enrolled in the Electrical Engineering Department were African-American, among which 21% of them are female.

As was noted by Dr. Warren Washington, chair of the National Science Board,

"It is vital to our national security that we harness the nation's human resource talent. Presently, the nation's diverse human resources are underutilized. As an increasing number of underrepresented groups of Americans are seeking to obtain undergraduate and graduate degrees, it is essential to also encourage them to consider science and engineering fields of study."

Given the leading role of the department in the education and training of African-American electrical engineers, the department is a critical player in reaching the goal as described by Dr. Washington.

One of the necessary basic skills an electrical engineer should gain from his/her college education is the hands-on experience on practical engineering systems. However, through their years of teaching, the authors noted that the students are in lack of such kind of experience by a significant measure. Not only is this lack of experience seriously jeopardizing the career prospects of the students, it hurts the recruitment and retention of students in the departments as well. In an effort to make up for this shortfall in our departments, the authors decided to collaborate in establishing a software-defined radio laboratory that will provide students with the necessary equipment and environment to develop their much-needed practical skills.

The Electrical Engineering Department at Tuskegee University and the Department of Electrical Engineering at Auburn University both offer a series of classes on communications which teach the fundamental theory and practice of analog, digital and wireless communications and networking. In the analog part of these courses, students are required to build an FM transmitter that is able to transmit message signals over a certain distance with reasonably good signal quality. Although students may improve their practical skills through this project, they are not getting in touch with the state-of-the-art technology given the fact that FM transmission has been around for a long period of time. Meanwhile, in the digital part, students are to simulate and evaluate the performance of digital communication systems using computers. Be it that computer simulation of real-life systems is a great way to study and analyze digital communications, the students still do not have a complete feel of the real system. An excellent way to address these disadvantages in our curriculum is to develop a laboratory course that allows students to implement real analog and digital communication systems or components. This leads naturally to our proposed project - radio communication systems that can be handily built using software and FPGA boards.

Based on the proposed SDR laboratory ad hands-on projects, the wireless engineering courses at Tuskegee University can be improved as follows.

Random Variables and Stochastic Processes: This three credit hour course offered is fundamental for the students to understand the theory and practice of telecommunications. A major part of communication engineering is built upon the theory of random variables and processes. Thorough and profound understanding is critical for the students to carry on and through our programs and even further to their careers. Due to the mathematical nature of these courses, it is not surprising to find students frequently lost in all the equations and abstractions put on the board.

The proposed SDR laboratory can help in this respect in that it can handily generate random signals graphically so that the students can not only see the random signals or noise physically, but analyze them using the mathematical tools such as density functions, Fourier analysis, etc. taught in the classrooms. Using the graphic functionality of the SDR components, the results of these analysis can be easily explained and thus improving the learning outcome.

Figure 2: An electrical engineering student at Tuskegee University is trying to pick up signals from his FM transmitter on a radio receiver.

Communication Theory I – Analog Communications: This is an introductory course taught at Tuskegee University in the area of communications. It serves as the starting point for students who are interested in communications. It covers mainly the traditional analog communication techniques such as amplitude modulation (AM) and frequency modulation (FM) transmitting and receiving systems. The course can be very theoretical since a thorough understanding of these systems requires familiarity of Fourier analysis. Students need to be very proficient with the conversion between time- and frequency-domain representations of signals. When talking about the frequency spectra of all the differently modulated signals, the most frequently asked question by the students is how the abstract mathematical equations look like in real life. In addition, the students have a strong curiosity on how the modulation/demodulation and frequency translation process really works. To address this problem among Tuskegee Students, they are required to build an FM transmitter whose signal can be received at a certain distance on any radio receiver. The students reacted to this project very positively since they not only improved their hands-on skills, but obtained a better idea of how communication systems work as well.

Although the FM transmitter project is a success, an important component the course is lacking is an accompanying lab course through which students can obtain hands-on experience and in-depth understanding of the theory systematically. To make up for this disadvantage, the course will be redesigned to incorporate several projects involving analysis and construction of transmitters and receivers, making use of the SDR lab environment. Upon completion of these projects, in addition to be exposed to a different set of hands-on experiments with practical communication systems, the students can see for themselves how the signals are modulated and demodulated, and what happens in the time and frequency domain at different stages of the process. Consequently, their understanding of the theory and practice of telecommunications will be greatly enhanced.

Communication Theory II – Digital Communications: Based on their knowledge on the traditional analog communication techniques, students will learn about the theory and practice of digital communication systems in this three- hour course. From our experience with the students, these classes can be even more abstract to the students because of the increased complexity of digital communications systems compared with analog ones and all the different mathematical theories upon which the systems are based. Usually, to help students establish a clear idea of the systems, computer simulation projects are assigned. Computer simulation of real digital communication systems is an important tool to improve learning. However, for sake of simplicity, a lot of digital-signal processing is omitted and many system functions are abstracted into simpler modules in a computer simulation. These simulations do serve the purpose of evaluating the performance of a digital communication system, but fail to provide the students the technical details of how the real system works. Students are dealing with the mathematical models of the system instead of the system itself. To address this problem, these courses will be supplemented with lab projects from the proposed SDR laboratory. Using the SDR lab, the students will be able to build all the components of a digital communication system, observe the signal waveforms and constellations at different stages, study the effect of noise and interference on the waveforms and the overall system performance. Through these projects, the student will gain first-hand knowledge and practical skills on digital communication systems.

Wireless Communications: This is a three credit hour course that covers the theory, characteristics and system design considerations of cellular wireless communication systems. For now, there are no labs or projects associated with these courses. A significant part of these courses is devoted to the explanation of signal fading in wireless channels which is the biggest challenge for the design of wireless communication systems and the diversity techniques that were developed to cope with this severe channel condition. Because of the lack of lab component in these courses, the fading effect can only be taught mathematically and oftentimes students are found confused about the different wireless channel models. The proposed SDR laboratory can address these problems our students currently have. Making use of the wireless radios, different wireless channel conditions will be assessed and different diversity techniques will be implemented and evaluated.

SDR PROJECT AND LAB DEVELOPMENT AT AUBURN UNIVERSITY

In the Spring semester of 2010, Mao et al. at Auburn University sponsored a senior design project based on SDRs. A team of eight students from different related engineering departments designed an SDR system that can receive signals from FM radio, Municipal Radio and broadcast TV bands [Mao, 8]. Upon the successful completion of this senior design project, Mao et al. proceeded to offer SDR-based term projects to students in their Communications Systems classes in Summer and Fall 2012. These SDR term projects are based on the Open Source Communications Architecture (SCA) Implementation for Embedded-Systems (OSSIE) kit developed at Virginia Tech [OSSIE, 10]. In order to test the effectiveness of these term projects, two students were first hired to try out the OSSIE lab experiments in Fall 2011 independently. Four fully-fledged term projects were then offered to students registered for the Communications Systems classes in Summer and Fall 2012. Anonymous survey results after the offerings showed that these projects did help in enhancing classroom teaching [Mao, 8].

Encouraged by the progress made and positive feedback from the students, Mao at al. took it further to develop an SDR laboratory course for undergraduate students and test offered it in Spring 2013. The SDR Lab course is based on GNU Radio, a free & open-source SDR development toolkit [GNU Radio, 2]. It consists of nine experiments, ranging from analog/digital communications to wireless local area networks (WLAN) [Huang, 4][Huang, 5][Huang, 6] and cellular networks. Unlike the existing SDR lab at the graduate level [Heath, 3], this lab course is tailored for undergraduate students. The lab course was test offered at Auburn University in Spring 2013 with 6 students, and was well received.

SDR COURSE DEVELOPMENT AT TUSKEGEE UNIVERSITY

With SDR projects and labs fully developed at Auburn University and seeing the benefits they bring to student learning outcomes, the authors decided to cooperate to incorporate them into the communications curriculum of Tuskegee University as described in previous sections. As a start-up step, three students in the course "Communications Theory I – Analog Communications" were selected to test and fine-tune the term projects in Fall 2012. These students were first trained on the PC-based OSSIE and GNURadio platforms. These platforms allow students to simulate communication systems and analyze every stage of signal-processing without any SDR device. This is particularly convenient since the students can install them on their own computers and practice with them anytime they want. Then the students learned how to interface the software with SDR devices. We used the Universal Software Radio Peripheral (USRP) developed by Ettus Research (now acquired by National Instruments) as our hardware platform. Figure 3 shows a software defined radio system used by the students.

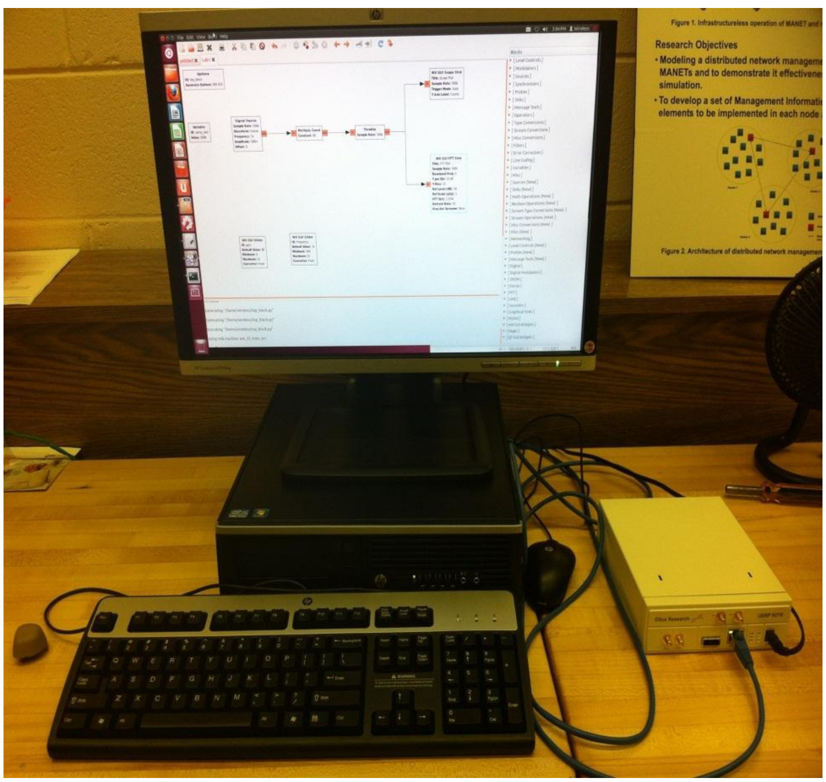

Figure 3: A software defined radio system under development by the students in the Electrical Engineering Department, Tuskegee University. The hardware device is USRP N210 from Ettus Research.

After the three students finished their training in this introductory phase, a team of seven selected students with various academic backgrounds was formed to carry the program further and to test the effect of the SDR projects in a larger scale. Figure 4 shows some of the team members posing with one of the authors in the Communications Laboratory at Tuskegee University. The students started out on a preliminary project that familiarizes them with the

Figure 4: Dr. Fan Jiang and some of his SDR project team members worked in the Communications Laboratory at Tuskegee University to test and develop SDR projects.

Linux environment, GNU Radio, USRP and the GNU Radio Companion. Then, they moved on to implement and experiment with amplitude modulation inside the GNU Radio Companion environment. In this second project, the students learned how to build the amplitude modulation and demodulation blocks to simulate the entire system from transmitter to receiver. They were able to observe every stage of the signal processing and the effect of random noise on signals both in time and frequency domain and thus relate to the abstract theory they learned in classes. Being able to see the actual signals throughout the system in real life turned out to help the students understand the theory of communications profoundly. Students were asked to build both an AM transmitter and receiver using the USRP platforms in the third project. Using these radios, they would be able to transmit and receive any signals they want. Not only did they enjoy the fun of implementing actual working radios, they obtain hands-on experience how to configure the USRP platforms through specialized software. Upon completion of the third project, students took one step further to implement FM or PM transmitter and receivers. In short, through these carefully designed projects, the participating students not only obtained deeper understanding of the communication theory through the hands-on experiments, but also gained valuable experience with SDR and the programmable platform. Such experience will certainly make them more competitive in the job market.

STUDENT FEEDBACK AND SSESSMENT

In order to assess the effectiveness of our SDR projects on student learning and to determine possible further improvements that can be made, all the students took part in the projects were asked to take an anonymous online survey to assess their learning experience and express their opinions. We used the Student Assessment of Learning Gains (SALG) website [SALG, 13] to gather learning-focused feedback from students. Since the online survey was modified to fit the unique features of our SDR projects, it provides us with a complete and accurate measurement of learning gains due to the projects.

The survey was made up of 10 sets of multiple-choice questions with 60 questions in total. Besides answering the questions, students can write their own comments on the projects in the survey. Results from this survey showed the SDR projects were highly appraised by the students. Listed below are excerpts from students' comments:

"It's easier to see the immediate impact of changes to a system which is hard to visualize in most academic courses."

"It helped my understanding develop more by actually seeing modulation interacting with the channel and noise rather than just seeing equations."

"The hands-on approach is great. I can try different amplifier values and see how they affect the output. This gave me a greater understanding of the material overall."

"After working on this project, I have a new interest in communications. The technology we are working on still has much potential to grow and there are still new discoveries to be made. This excites me."

"Working hands-on with this project helped me to grasp the concept a lot faster."

For the 60 multiple-choice questions, students can choose from the following responses: no gain (1), a little gain (2), moderate gain (3), good gain (4) or great gain (5), where the numbers in the bracket are scores associated with each response. A summary of survey scores on a selected set of eight questions that measure the effectiveness of SDR projects in helping students understand class contents is plotted in Figure 4. The questions asked are:

As a result of your work in this project, what gains did you make in your understanding of each of the following?

(1.1) The main concepts explored in this class.

(1.2) The relationships between the main concepts.

(1.3.1) The following concept that has been explored in this class: Modulation of analog signals.

(1.3.2) The following concept that has been explored in this class: Transform an analog signal to digital.

(1.3.3) The following concept that has been explored in this class: Transmission of digital signals.

(1.4) How ideas from this class related to ideas encountered in other classes within this subject area.

(1.5) How ideas from this class relate to ideas encountered in classes outside of this subject area.

(1.6) How studying this subject area helps people address real world issues.

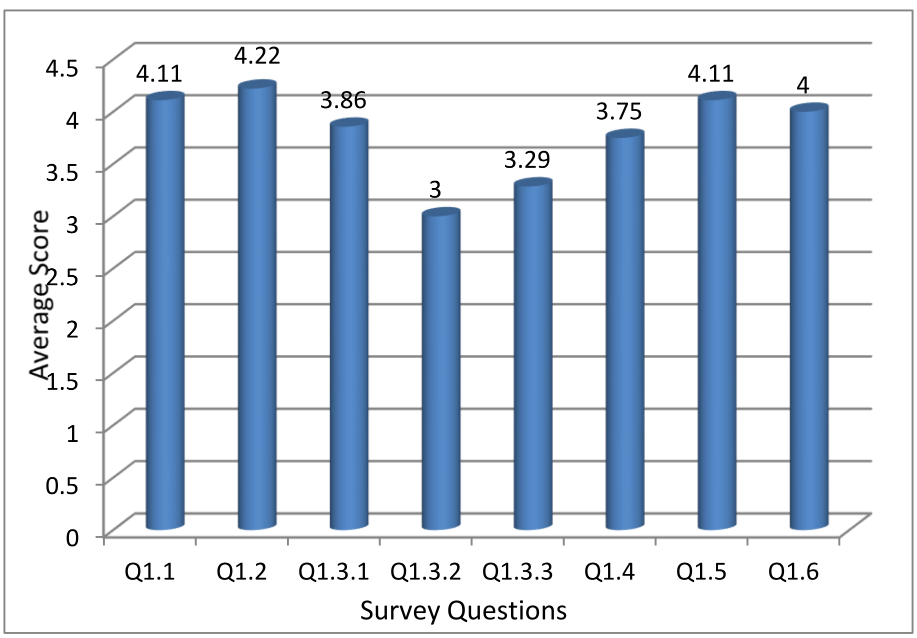

Figure 5: Average scores of students' responses to selected questions on the effectiveness of SDR projects in helping classroom learning and teaching.

As can be observed, all questions scored an average of 3.0 or higher with six of them are greater than or equal to 3.75 and three of them scored above 4.0. This indicates the learning gain is at least moderate and more of the gains are close to or even above “good”. Specifically, Questions 1.1, 1.2, 1.5 and 1.6 have average scores of 4.0 or above. This tells that there is a good gain or better among students in understanding the main concepts taught inside the area, relating the main concepts taught inside and outside the area and the addressing of real world issues after completing the SDR projects.

From these anonymous responses and comments by the students, we can see that the SDR projects are effective in enhancing student learning and understanding of abstract theories and concepts of communications engineering and improving their ability of relating theory with practical issues in the real world.

CONCLUSIONS

With the mindset of promoting STEM education of under-represented minority students, the initial effort of incorporating SDR term projects developed at Auburn University into the communications systems courses in the Electrical Engineering Department at Tuskegee University was described in this paper. The projects were well-received by the minority students in the department. The benefits of this hands-on approach to the teaching and learning of abstract concepts in communications theory were manifested by assessment data and feedback from the students exposed to the projects. Encouraged by the positive turnout of the projects, the authors will develop a complete SDR laboratory course to go along with the existing theory-dominated courses on communications systems. Upon successful implementation of this lab course, the authors also plan to advocate adoption of it by other institutions.

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