Introducing Software Defined Radio into Undergraduate Wireless Engineering Curriculum through a Hands-on Approach

Prof. Shiwen Mao, Auburn University

Dr. Shiwen Mao received a Ph.D. in Electrical and Computer Engineering from Polytechnic Institute of New York University in 2004. Currently, he is the McWane Associate Professor in the Department of Electrical and Computer Engineering at Auburn University in Auburn, AL. Dr. Mao's research interests include performance analysis, optimization, and algorithms for wireless networks. He was awarded the McWane Endowed Professorship in the Samuel Ginn College of Engineering for the Department of Electrical and Computer Engineering at Auburn University in 2012. He received Auburn Alumni Council Research Awards for Excellence—Junior Award and two Auburn Author Awards in 2011. He received NSF Faculty Early Career Development (CAREER) Award in 2010. He is a co-recipient of the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems and the Best Paper Runner-up Award of QShine 2008. He is on the Editorial Board of IEEE Transactions on Wireless Communications, IEEE Communications Surveys & Tutorials, Elsevier Ad Hoc Networks Journal, Wiley International Journal of Communication Systems, and ICST Transactions on Mobile Communications and Applications.

Mr. Yingsong Huang, Department of Electrical and Computer Engineering, Auburn University

Yingsong Huang received the M.S. degrees in Control Theory and Control Engineering and the B.S. in Automation, both from Chongqing University at Chongqing, China. Since 2007, he has been pursuing his Ph.D. in the Department of Electrical and Computer Engineering, Auburn University, Auburn, AL. His research interests include modeling, control and optimization in computer networks and multimedia communication.

Dr. Yihan Li, Auburn University

Dr. Yihan Li received her B.E. and M.E. degrees from Tsinghua University at Beijing, P.R. China in Electrical Engineering in 1993 and 1997, respectively. She also received her M.S. in System Engineering in 2000 and the Ph.D. degree in Electrical and Computer Engineering in 2004 from Polytechnic University (now Polytechnic Institute of New York University) at Brooklyn, NY, in 2000. Currently, she is a visiting assistant professor in the Department of Electrical and Computer Engineering at Auburn University in Auburn, AL. She was a research scientist in the Department of Electrical and Computer Engineering at Polytechnic University from 2004 to 2006, and a postdoctoral fellow in the Department of Electrical and Computer Engineering at Auburn University from 2006 to 2009. Dr. Li's research interests include scheduling in-wired and wireless networks, wireless ad hoc networks, and high-speed packet switching. She is a member of Tau Beta Pi.

Prof. Prathima Agrawal, Auburn University

Dr. Prathima Agrawal is the Sam Ginn Distinguished professor of Electrical Engineering and the director of the Wireless Engineering Research and Education Center at Auburn University. Before arriving at Auburn University in 2003, from 1978 to 1998, she worked at AT&T Bell Laboratories at Murray Hill, NJ in various capacities. There she created and became the head of the new Networked Computing Research Department. From 1998 to 2003, she was assistant vice president of the Internet Architecture Research Laboratory and executive director of the Networking research department at Bellcore (Telcordia), at Morristown, NJ. Dr. Agrawal is widely published in the fields of mobile computing, computer architecture and VLSI design. She holds 51 US patents. She is a fellow of IEEE. Dr. Agrawal received the B.E. and M.E. degrees in Electrical Communication Engineering from the Indian Institute of Science at Bangalore, India. She received her Ph.D. degree in Electrical Engineering from the University of Southern California at Los Angeles, CA.

Prof. Jitendra K Tugnait, Auburn University

Jitendra Tugnait received the B.Sc. (Hons.) degree in Electronics and Electrical Communication Engineering from the Punjab Engineering College in Chandigarh, India in 1971; the M.S. and the E.E. degrees from Syracuse University in Syracuse, NY; and the Ph.D. degree from the University of Illinois-Urbana-Champaign in 1973, 1974, and 1978, respectively, all in Electrical Engineering. From 1978 to 1982, he was an assistant professor of Electrical and Computer Engineering at the University of Iowa at Iowa City, IA. Tugnait was with the Long Range Research Division of the Exxon Production Research Company at Houston, TX, from June 1982 to Sept. 1989. He joined the Department of Electrical and Computer Engineering at Auburn University in Auburn, AL, in September 1989 as a professor. He currently holds the title of James B. Davis Professor. His current research interests are in statistical signal processing, wireless and wireline digital communications, cognitive radio, multiple sensor multiple target tracking and stochastic systems analysis. Dr. Tugnait is a past associate editor of the IEEE Transactions on Automatic Control, the IEEE Transactions on Signal Processing, IEEE Signal Processing Letters, and the IEEE Transactions on Wireless Communications. He is currently an associate editor and an area editor of the IEEE Transactions on Signal Processing, and a Senior Editor of IEEE Wireless Communications Letters.

Introducing Software Defined Radio into Undergraduate Wireless Engineering Curriculum through a Hands-on Approach

Shiwen Mao[1], Yingsong Huang[2], Yihan Li[3], Prathima Agrawal[4], Jitendra Tugnait[5]

Abstract – A software defined radio (SDR) is a modern radio communication system that can be reconfigured on-the-fly. In this paper, we describe a project on introducing SDR to the Bachelor of Wireless Engineering (BWE) curriculum at Auburn University. Our efforts consist of three intertwined thrusts: (i) We offer well-defined SDR senior design projects, as well as research projects for students supported by the NSF Research Experience for Undergraduate (REU) program; (ii) We also use SDR-related experiments as term projects to enhance the existing wireless engineering courses at Auburn; (iii) We are developing an SDR laboratory course based on the experience and feedback from the SDR projects, and will test-offer the lab course in the near future.

Keywords: Software defined radio, situated learning theory, undergraduate laboratory course, wireless communications and networking, wireless engineering.

INTRODUCTION

The concept "Software Defined Radio" (SDR) was coined by Joseph Mitola in 1992[1]. SDR is an emerging technology that is profoundly changing radio system engineering[2]. In traditional wireless communications, different wireless devices cannot communicate with each other due to their different hardwired radio systems. In the SDR paradigm, many radio system components are implemented in software and can be reconfigured on-the-fly, thus allowing a single piece of hardware for multi-standard, multi-band and multi-functional wireless systems. Such a paradigm change has far-reaching impact on the evolution of future wireless communications and networking systems.

Recently, considerable advances have been made in SDR research and development. In addition to better understandings and theory, a notable advance is the availability of programmable wireless platforms that allow researchers to create software radios, such as Ettus Research LLC's Universal Software Radio Peripheral (USRP) (acquired by National Instruments Corporation in Feb. 2010), Rice University's Wireless Open-Access Research Platform (WARP), and other commercial platforms.

---

[1] Department of Electrical and Computer Engineering, Auburn University, 200 Broun Hall, Auburn University, Auburn AL 36849-5201, smao@ieee.org

[2] Department of Electrical and Computer Engineering, Auburn University, 200 Broun Hall, Auburn University, Auburn AL 36849-5201, yzh0002@tigermail.auburn.edu

[3] Department of Electrical and Computer Engineering, Auburn University, 200 Broun Hall, Auburn University, Auburn AL 36849-5201, yli@auburn.edu

[4] Department of Electrical and Computer Engineering, Auburn University, 200 Broun Hall, Auburn University, Auburn AL 36849-5201, agrawpr@auburn.edu

[5] Department of Electrical and Computer Engineering, Auburn University, 200 Broun Hall, Auburn University, Auburn AL 36849-5201, tugnajk@eng.auburn.edu

Although there is a compelling need for SDR expertise in the wireless industry, SDR has been regarded as a highly advanced topic and, to the best of our knowledge, only offered as graduate level courses at a few schools[2,3]. Motivated by this need, we propose to introduce SDR into the undergraduate wireless engineering curriculum with a hands-on approach. The existing programmable wireless platforms are the enablers for the proposed hands-on approach. In additional to allowing create software radios on-the-fly, the platforms also provide full access to the physical (PHY) and medium access control (MAC) layers, which was not possible previously. Therefore, what can only be studied through abstract theory and computer simulations, are now becoming tangible and reconfigurable to students. Such full access to the entire protocol stack can potentially transform the traditional lecture-based wireless engineering education. The specific objectives of this project are as follows.

- To develop wireless communications experiments and projects, by exploiting the full access to the PHY and MAC as enabled by the programmable wireless platforms.
- To integrate the SDR experiments and projects with traditional wireless communications courses to enhance teaching and student learning.
- To develop a new SDR laboratory course for junior and senior level wireless engineering students. The objective is to expose undergraduate students to the advanced SDR technology with a hands-on approach, and to train the future wireless workforce with the much needed SDR expertise.

The proposed project will enhance student learning and improve the quality of our undergraduate education, specifically, enhancing Auburn University's ABET-accredited Bachelor of Wireless Engineering (BWE) program, first-of-its-kind in the nation. The SDR lab course will prepare our students for the compelling need of SDR expertise from the wireless and defense industry. Well defined components from the lab experiments will also be used for demonstration, final projects, and senior design projects. The hands-on approach has the potential of transforming traditional classroom-based wireless engineering education.

In the reminder of this paper, we first introduce the preliminaries of SDR and its advantages for undergraduate wireless engineering education. We then report our experience with the SDR projects and the development of the SDR lab course. This paper is concluded with a discussion of future work.

BACKGROUND AND MOTIVATION

Software Defined Radio (SDR)

An SDR is a radio communication system where components that have typically been implemented in hardware, such as mixers, filters, amplifiers, modulators, demodulators, and detectors, are instead implemented in software. As a result, such radios can provide software control of a variety of modulation techniques, wideband or narrowband operations, security mechanisms, and waveform requirements of current and evolving wireless standards over a broad frequency range[1,2].

An ideal SDR is illustrated in Fig. 1. In the ideal SDR, the antenna connects directly to the Low Noise Amplifier (LNA) and analog-to-digital converter (ADC) for the reception path, or the Power Amplifier (PA) and digital-to-analog converter (DAC) for the transmission path. The processor handles all radio functions, such as filtering, up/downconversion, modulation and demodulation, and the digital baseband. This is a paradigm change from traditional radio engineering. As illustrated in Fig. 2, in order to support four different standards (i.e., UMTS, CDMA, Wi-Fi, and Bluetooth), a hardware radio approach needs to incorporate four chipsets, one for each of the standards. With SDR, the standards are implemented in software, to be loaded and executed in a common hardware platform consisting of FPGA and DSP chips. If there is a need to support a new standard, one simply needs to load the code, which implements the new protocol, into the hardware platform and execute the code there.

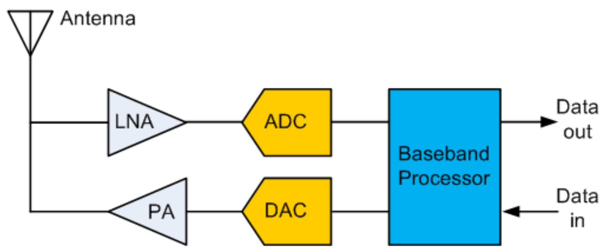

Fig. 1 Diagram of an ideal SDR.

Such an SDR paradigm has many advantages. As discussed, now a single piece of hardware can support multi-standard, multi-band, and multi-functional wireless systems. Diverse needs for different systems can now be satisfied with a single generic hardware, thus achieving great interoperability among various wireless networks. Upgrading a wireless system with add-on functionalities is reduced to downloading a new driver. Prototyping new radio technology is greatly simplified and time-to-market can be significantly reduced.

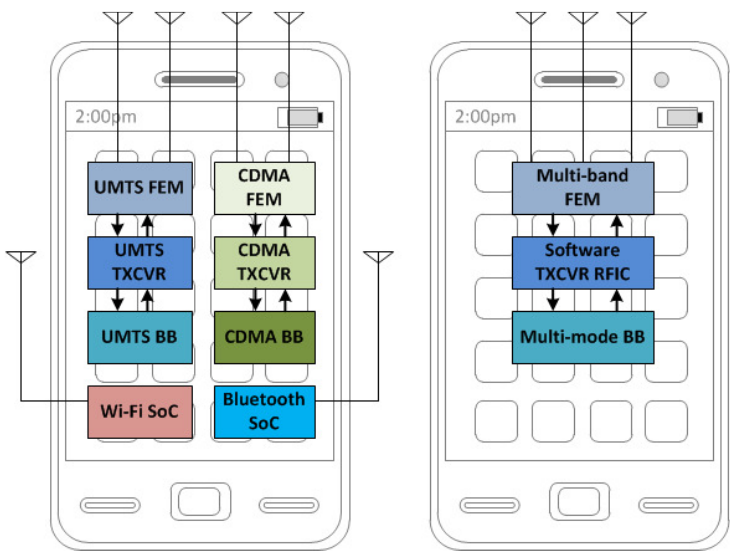

Fig. 2 Comparison of SDR with traditional hardware radios. UMTS: universal mobile telecommunications system; CDMA: code division multiple access; Wi-Fi: wireless fidelity; FEM: front end module; TXCVR: transceiver; BB: baseband; RFIC: radio frequency integrated circuits; SoC: system on chip.

The potential of SDR is maximized when combined with spectrum sensing and the so-called cognitive engine[4]. The combination, termed cognitive radio (CR), is a frequency-agile wireless communication device that enables dynamic spectrum access[5,6]. CR capitalizes on recent advances in spectrum regulation policy that allow share licensed bands with unlicensed users[7]. The idea of dynamic spectrum access was largely motivated by FCC's finding of serious underutilization of allocated spectrum[8], which is in drastic contrast with the common belief of spectrum depletion. Such discrepancy calls for an overhaul of the spectrum regulation policy. A CR can sense the spectrum to detect unused frequency bands as well as its radio environment, and make decisions on how to reconfigure the SDR to achieve improved performance. The SDR radio module is capable of reconfiguring RF and can be programmed to tune to a wide spectrum range and operate on any frequency bands within the range. CR has attracted tremendous interest from industry, government, and academia alike. The SDR/CR concept is changing the way how wireless systems are designed, and driving the next generation of radio devices and wireless standards to enable a variety of new applications.

SDR for Undergraduate Curriculum

In the conventional system partition for wireless protocol implementation (e.g., Wi-Fi), RF and baseband processing are mainly handled by the 802.11 chipset, while the MAC protocol is mostly implemented in the firmware as microcode stored in onboard memory and executed at a micro-controller on the card[9]. The driver in the operating system kernel manages the network interface card and provides an interface for upper layer applications. Several open-source Linux drivers are available, such as MadWiFi and HostAP. By extending these device drivers, we can modify a certain part of the MAC layer and, to some extent, develop new MAC protocols. However, the PHY is generally hardwired and not accessible for developers. It is very hard and costly to test a new PHY technology. As a result, most researchers resort to simulation to validate their ideas. With the SDR platforms, both the MAC and PHY layers are now accessible. Testing and prototyping new MAC/PHY ideas boil down to writing software codes and executing the code on the platform. This opens a new dimension of opportunities for teaching wireless courses with a hands-on approach, which can make abstract theory tangible, and motivating student learning by building real, working wireless systems.

SDR has a broad spectrum of applications for both military and civilian wireless networks, many of which may require supporting a wide variety of evolving wireless protocols in real time. SDR represents a modern approach to radio engineering and will certainly have significant impacts in our society. We believe there is a compelling need to expose our undergraduate students to this important technology. The benefit will be considerable: (i) we will train a new generation of wireless engineers with the advanced SDR expertise to meet the demand from both industry and government (e.g., regulation and military), and (ii) we can also fully exploit the high potential of the SDR systems, such as the reconfigurability and visualization capability, for enhancing traditional wireless engineering courses.

We believe a hands-on approach would be a perfect match for teaching SDR. One of the indispensable, essential skills an electrical engineer should gain from his/her college education is the hands-on experience on practical engineering systems. However, through our own teaching experience, we found that the students are in lack of such kind of experience by a considerable measure. This lack of experience is not only seriously jeopardizing the career prospects of the students, but also hurting the recruitment and retention of students in the department as well. In an effort to make up for this shortfall, the proposed lab course will provide students with the necessary equipment, environment, and instructions to develop their much-needed practical skills.

The proposed approach is also motivated by the Situated Learning Theory[10,11], the core of which is "learning by doing." The hands-on approach has many advantages and will help to enhance the existing wireless engineering courses. It has been proven through educational research that students will have a vivid and lasting understanding of what they do much more than what they only hear or see. Working on a project will sharpen a student's creative skills. Persevering through a project and seeing it to completion give them a great sense of accomplishment. Last but not least, students will work together on some projects, which help to develop their team-building and teamwork skills, important qualities for their future career development and success.

SDR PROJECTS

SDR Senior Design Project

In the Spring 2010 semester, we sponsored a senior design project based on SDR. The senior design team consists of eight students from our wireless engineering, electrical engineering, computer engineering, and software engineering programs. The students are divided into three groups, each focusing on the RF design, embedded system design and software design aspects of the SDR system, respectively. The RF design team built and tested an antenna that receives in the FM radio, Municipal Radio, and broadcast TV bands. The embedded system team designed an internal power supply for USRP1/USRP2, and an LCD front panel for configuration and information display. The software team developed the Graphical User Interface (GUI) for USRP control.

The integrated system was demonstrated at the senior design fair in May 2010, to successfully receive from several FM radio stations. In fact, this project is more challenging than the FM radio lab that will be described in the next Section, since it also involves antenna design and embedded system design. The team completed the project independently and the demonstration at the May 2010 senior design fair was quite successful. This senior design project clearly tested the feasibility of the proposed SDR lab and other SDR-related curriculum enhancements for undergraduate students.

SDR Term Projects for ELEC 3400—Communication Systems

In addition to exposing undergraduate students to the modern radio engineering approach, the proposed SDR experiments can also be used to enhance our existing wireless engineering courses. For this purpose, components of the SDR lab (to be introduced in the next section) can be adopted for classroom demos, final projects, and senior design projects. Based on the proposed SDR lab, the wireless engineering-related courses offered in our department can be enhanced.

In the Summer 2012 and Fall 2012 semesters, we offered SDR-based term projects to students in the ELEC 3400—Communication Systems classes. This is an introductory course in the area of communications. It covers mainly the traditional analog communication techniques, such as amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM), and digital communication techniques, such as sampling and digitizing analogue signals, baseband transmissions, and modulated transmissions. The course can be very theoretical since a thorough understanding of these systems requires familiarity with Fourier analysis, probability and stochastic processes. 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 different 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 process works in a real system. To address this problem, optional MATLAB exercises were typically assigned to students to compute and plot various signals.

Although the MATLAB exercises are helpful, an important component the course is lacking is an accompanying lab course through which students can systematically obtain hands-on experience and in-depth understanding of the theory. To make up for this shortfall, the course was enhanced to incorporate several projects involving analysis and construction of modulators/demodulators. Upon completion of these projects, students could gain deep understanding of practical communication systems and 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. With the projects, students could also be able to build various components of a digital communication system, observe the signal waveforms and constellations at different stages, and study the effect of noise and interference on the waveforms and the overall system performance. Through these projects, students could gain first-hand knowledge and practical skills on analog and digital communication systems. Consequently, their understanding of the theory and practice of telecommunications would also be greatly enhanced.

The SDR term projects are based on the Open Source Software Communications Architecture (SCA) Implementation for Embedded-Systems (OSSIE) kit developed at Virginia Tech (available at: http://ossie.wireless.vt.edu/). SCA is promoted for commercial use by the SDR Forum. It addresses important tasks including waveform acquisition, interoperability, operation and deployment on CR devices, API, and common component information, while the SCA middleware makes an abstraction of the underlying hardware from interoperable and programmable waveforms. OSSIE is one of the first open source C++ implementations of the SCA Core Framework (CF).

The Virginia Tech team has offered a set of OSSIE experiments at the OSSIE website. In particular, we find the first four OSSIE labs quite suitable for the term projects. First, the coverage and levels of these labs are good match for the undergraduate course. Second, these labs are based on computer simulations; there is no need for the use of an SDR device (such as a USRP). The latter is important, since students can thus work on their own computer without needing to go to a laboratory to try the experiments. We took a two-step approach to incorporating the OSSIE projects with the Communication Systems course. First, we hired two undergraduate students, using funds from the NSF REU program, to try out the four OSSIE labs in Fall 2011. The students tested the experiments independently, and fine-tuned the contents and instructions of the labs to make them better suitable for our students. Second, we offer the four labs as term projects to the Summer 2012 and Fall 2012 Communication System classes. After an introduction and demo lecture, students were provided with the revised lab instructions and a DVDROM, which is self-contained with OSSIE and other dependent software. Students were required to complete the four OSSIE labs during the semester, with help from experienced graduate students, and to complete a survey to provide feedback by the end of the semester.

Assessment and Student Feedback

We employed the Student Assessment of Learning Gains (SALG) facility at http://www.salgsite.org to collect feedback from students, which is an on-line survey that measures student perceptions of their learning gains due to any components within a course. We modified the standard template provided at SALG to match the unique features of the SDR term projects, and had our students take the survey by the end of the semesters. When the data was returned, we analyzed the raw data to reveal the effectiveness of our effort and to identify potential problems for further improvement.

The anonymous survey consists of 10 sets of questions (totally 60 questions, in addition to comments). We find the SDR term projects very well received by the students. Some example student comments are given below:

> "*The project has really helped me in the understanding because it provided me with real hands-on experience*."

> "*The hands-on approach really gave the true picture of the project. It has taught me how to get a picture of whatever I am learning*."

> "*Things that used to be abstract to me can now be felt real or practical*."

Selected student survey scores for the effectiveness of the SDR term projects from the Fall 2012 ELEC 34000—Communication Systems class are plotted in Fig. 3. The corresponding questions 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) The following concept that has been explored in this class: Modulation of analog signals.

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

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

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

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

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

The optional scores for each problem are: 1: no gains; 2: a little gain; 3: moderate gain; 4: good gain; 5: great gain. The average score for the 32 students in the class are plotted in Fig. 3. It can be seen that the average scores are all between 3 and 4 (i.e., moderate to good gain). The highest average score is for Question 1.1, which is 4.0. The students felt that the OSSIE labs provided good gain for them to understand the main concepts covered in this course. The lowest average score is for Question 1.8, which is 3.59. Thus it would be helpful to relate the course material to more real world issues in future classes. From the survey, we find the SDR term projects did help to enhance classroom teaching and student learning of the abstract communications theory.

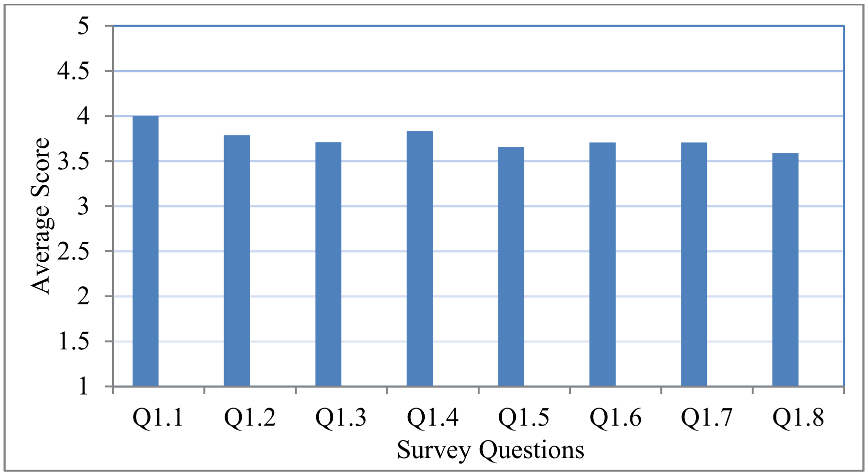

Fig. 3 Selected student survey statistics about the effectiveness of the SDR term projects from the Fall 2012 ELEC3400—Communication Systems class.

SDR LABORATORY COURSE DEVELOPMENT

The SDR projects offered in our undergraduate classes provide valuable experience and test the feasibility of introducing SDR into our undergraduate wireless engineering curriculum. Encouraged by the progress made and positive feedback from students, we plan to develop an SDR laboratory course for undergraduate students.

SDR Platform

For the SDR lab course, we plan to use both simulations (as in the four OSSIE labs we offered) and hardware experiments using a wireless programmable platform. Several SDR development platforms are available[12]. Such platforms provide the flexibility of modifying and optimizing the PHY layer and integration with the MAC and higher layers, where FPGAs are used for handling the high data rates from the analog-to-digital (A/D) and digital-to-analog (D/A) converters and for symbol rate processing.

After evaluating various options, we decide to use USRP and GNU Radio for the SDR experiments. USRP is a popular SDR platform from Ettus (see Fig. 4). GNU Radio is an open-source software toolkit for building software radios, generally independent of the hardware. Programming with GNU Radio/USRP is relatively easy, and the relatively lower price makes it suitable for classroom use. The open-source software also reduces the cost of the lab, and makes it easier for inter-operability and adoption at other universities once this lab is fully developed.

SDR Lab Course Structure

There are already some well-designed lab experiments available for both OSSIE (from Virginia Tech) and WARP (from Rice University), which were very helpful to us in constructing our own SDR lab course. The SDR lab will cover basic communications technologies and typical wireless networks, consisting of the following components: (i) preliminaries and introduction to SDR, Linux, GNU Radio, and USRP; (ii) analogy communication modulation and systems, (iii) digital communication systems, (iv) wireless network systems including wireless local area networks (WLAN) and cellular networks.

Fig. 4 The USRP kit connected to a laptop computer, which is configured to operate as a wireless node[13,14].

We have developed the lab instructions and set up the lab, and will test offer it in Spring 2013 to a group of six students as ELEC 4970—Special Topics in Electrical Engineering: Software Defined Radio Lab. We plan to firstly provide one or more lecture notes to prepare students with SDR preliminaries and basic operation of the programmable platforms. Once the students are well prepared, they can start working on the hands-on lab experiments, which will take about ten to twelve weeks. Lab reports will be designed to include a set of instructions on collecting and analyzing data and a set of questions/problems. Final grades will be given based on both lab performance and lab report grades.

Based on this test offering and feedback from the students, we will revisit and update the lab experiments in the summer. Some fundamental questions to be answered are, are these labs suitable for senior students? What are the prerequisites? Does our current curriculum cover the sufficient background? We also plan to find ways to incorporate our research outcomes on SDR and CR with the lab, to show students how to leverage and capitalize the SDR potential to achieve network-wide performance improvements. These will also be organized into advanced labs for students who are interested to study more on this topic.

CONCLUSIONS

In this paper, we propose to introduce SDR into Auburn University's undergraduate Wireless Engineering Curriculum. Our efforts consists of three thrusts: (i) introducing SDR experiments for senior design and REU projects; (ii) using SDR experiments as term projects to enhance the existing courses; and (iii) developing a new SDR lab course. We report our experience with these efforts in this paper. In the near future, we will fully develop the SDR lab course and offer it to our wireless engineering students. We will also work on promoting adoption of the SDR lab at other institutions once it is fully developed and tested.

ACKNOWLEDGMENTS

This work is supported in part by the US National Science Foundation (NSF) under Grants DUE-1044021 and CNS-0953513, and through the NSF Broadband Wireless Access and Application center (BWAC) Site at Auburn University. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Foundation.

References

[1] J. Mitola, "The software radio," in *Proc. IEEE National Telesystems Conference*, pp.15–23, Washington, DC, May 1992.

[2] J. H. Reed, *Software Radio: A Modern Approach to Radio Engineering*, Prentice Hall PTR, Upper Saddle River, NJ, 2002.

[3] R. W. Heath, Jr., *Digital Wireless Communication: Physical Layer Exploration Lab Using the NI USRP*, National Technology and Science Press, Allendale, NJ, 2012.

[4] Y. Zhao, S. Mao, J.H. Reed, and Y. Huang, "Utility function selection for streaming videos with a cognitive engine testbed," *ACM/Springer Mobile Networks and Applications Journal* (MONET), vol.15, no.3, pp.446–460, June 2010.

[5] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol.23, no.2, pp.201–220, Feb. 2005.

[6] Y. Zhao, S. Mao, J. Neel, and J.H. Reed, "Performance evaluation of cognitive radios: metrics, utility functions, and methodologies," *Proceedings of the IEEE*, vol.97, no.4, pp.642–659, Apr. 2009.

[7] Federal Communications Commission (FCC), "Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies," *Notice of Proposed Rule Making and Order*, FCC 03–322, Dec. 2003.

[8] FCC Spectrum Policy Task Force, "Report of the spectrum efficiency working group," Nov. 2002. [online] Available: *http://www.fcc.gov/sptf/reports.html*.

[9] J. Corbet, A. Rubini, G. Kroah-Hartman, *Linux Device Drivers*, 3rd Edition. O'Reilly Media, Inc., Sebastopol, CA, 2005.

[10] J. R. Anderson, L. M. Reder and H. A. Simon, "Situated learning and education," *Educational Researcher*, vol.25, no.4, pp.5–11, May 1996.

[11] J. Lave, *Cognition in Practice: Mind, Mathematics and Culture in Every Life*, Cambridge University Press, Cambridge, UK, 1988.

[12] G.J. Minden, J.B. Evans, L.S. Searl, D. Depardo, R. Rajbanshi, J. Guffey, Q. Chen, T.R. Newman, V.R. Petty, F. Weidling, M. Peck, B. Cordill, D. Datla, B. Barker, and A. Agah, "An agile radio for wireless innovation," *IEEE Communications Magazine*, vol.45, no.5, pp.114–121, May 2007.

[13] Y. Huang, P. Walsh, Y. Li, and S. Mao, "A GNU Radio testbed for distributed polling service-based medium access control," in *Proc. IEEE MILCOM 2011*, pp.519–524, Baltimore, MD, Nov. 2011.

[14] Y. Huang, P. Walsh, Y. Li, and S. Mao, "A distributed polling service-based medium access control protocol testbed," Chapter 2 in *Mobile Ad-Hoc Networks*, pp.23–51, H. Zhou (editor), InTech, Shanghai, China, Dec. 2012.