AC 2010-1115: SOFTWARE RADIO BASED WIRELESS LABORATORY DESIGN AND IMPLEMENTATION FOR ENHANCING UNDERGRADUATE WIRELESS ENGINEERING EDUCATION

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Software Radio Based Wireless Laboratory Design and Implementation for Enhancing Undergraduate Wireless Engineering Education

Abstract

Wireless communication and networking have revolutionized the way people communicate. The past decades have witnessed two trends: miniaturization of wireless devices, and scarcity of radio resources. Miniaturization results in more devices being deployed. As more devices go wireless, they have to share a finite yet increasingly crowded radio spectrum. As devices become smaller and the airwaves become more crowded, more efficient ways are needed to allow them to communicate and share the spectrum.

Software defined radio offers one solution. With careful planning and design, devices are taught using software to figure out which frequency bands are quiet, negotiate with other devices in their vicinity, and pick one or more bands over which to transmit and receive data. *Cross-layer networking design* offers another solution, which integrates the lower layer knowledge of the wireless medium with higher protocol layers, to devise efficient methods of network resource sharing and to make applications adaptive to radio channel and network conditions. These potentials make cross-layer design an increasingly important area for future network engineers to grasp. Therefore, future engineers will need to be trained with fundamental principles as well as emerging technologies across protocol layers. The evolution of wireless communication and networking presents such a need and a unique opportunity to integrate undergraduate education across the Electrical Engineering and Computer Science curricula, which trains future engineers with a deeper and holistic understanding of and skills for current and emerging wireless communication and networking technologies.

In this paper, we report the development of an easily replicable model of evolvable, low cost, *software defined radio* (SDR)-based wireless communication and networking laboratories as well as associated teaching and learning materials that can be adopted or adapted to impact national engineering education practices. The SDR-based laboratories are tailored to the need of individual courses, yet serve as a catalyst for the integration of core courses. The outcomes include a set of pilot wireless course laboratories based on the Universal Software Radio Peripheral (USRP) boards that employ GNU software radio, lab development user manuals, lab teaching manuals, proven methods of effective lab instruction, and evaluation & assessment materials. The labs will create a space where students can learn by working with tangible signals, wireless channels, and communication systems, which reinforces mathematics and simulation examples, and helps integrate concepts by building a working system. The initial effectiveness of enhancing student learning and skills has been demonstrated.

Introduction

Wireless communication and networking have revolutionized the way people communicate. Currently, there are more than two billion cellular phone subscribers worldwide. Wireless local area networks have become a necessity in many parts of the globe. Along with the technological advances, the past decades have witnessed two trends: miniaturization of wireless devices, and scarcity of radio resources. Miniaturization results in more devices being deployed. As more devices go wireless, such as laptops, cell phones, wireless sensors, and radio frequency ID tags, they have to share a finite yet increasingly crowded radio spectrum[1]. As devices become smaller and the airwaves become more crowded, more efficient ways are needed to allow them to communicate and share the spectrum.

Software defined radio offers one solution, where, with careful planning and design, devices are taught using software to figure out which frequency bands are quiet, negotiate with other devices in their vicinity, and pick one or more bands over which to transmit and receive data[1]. *Cross-layer networking design* offers another solution, where the lower layer knowledge of the wireless medium is integrated with higher protocol layers, to devise efficient methods of network resource sharing and to make applications adaptive to radio channel and network conditions, which makes cross-layer design an increasingly important area for future network engineers to grasp. Therefore, future engineers will need to be trained with fundamental principles as well as emerging technologies across protocol layers. The evolution of wireless communication and networking presents such a need and a unique opportunity to integrate undergraduate education across the Electrical Engineering and Computer Science curricula, which trains future engineers with a deeper and holistic understanding of and skills for current and emerging wireless communication and networking technologies.

In response to this recognized need and as part of its development priority, the College of Engineering & Computer Science at Wright State University has developed undergraduate wireless engineering options in the department of electrical engineering, and the department of computer science & engineering, which will be developed into a full-fledged wireless engineering undergraduate program across both departments. This is a collective effort by faculty from both departments who also have had fruitful research collaboration. Wright State University has a large population of non-traditional engineering students who are working professionals with diverse background. This laboratory fits well with their work experiences and background by providing a learning experience with a curriculum that balances, mature with emerging technologies, theory with innovative real-work environment laboratories, and emphasizes student success and achievements.

Current State of Wireless Communication Course Laboratories

There have been on-going activities to improve the wireless communication and networking undergraduate education. Currently, most undergraduate (wireless) communication courses are taught without a laboratory. Students study and learn theoretical techniques via equations, derivations, and computer simulations. Although computer simulations and tools do help students a great deal, they do not engage students as much as hands-on laboratories[2], where students learn better by working with tangible signals, wireless channels, and communication systems, which reinforces mathematics and simulation examples, and helps integrate concepts by building a working system.

Wireless engineering is being adopted as a new undergraduate program or a certificate program in a few universities[3,4,5,6]. Some universities offer communication laboratory and/or wireless communication laboratory courses. For example, Auburn University's wireless engineering program[3] offers a required ELEC 3060 Wireless Design Laboratory course for undergraduate wireless engineering students. This course uses Emona Instruments' TIMS (Telecommunication Instructional Modeling System) tool to carry out communication experiments. TIMS is a hardware based laboratory trainer which consists of a fixed lower rack hardware module, and 12-slot upper rack for plug-in modules. By plugging different modules in the upper rack of the equipment, different communication experiments can be performed. A few other universities are also using TIMS equipment for their undergraduate communication laboratory courses, e.g., Georgia Tech ECE department is using TIMS in its ECE 4602 Communication Systems Lab course.

While TIMS does offer students more hands-on experiences by playing with the hardware setup and connecting different modules together, it is more or less a "cook-book" type of equipment: Students follow the procedure and see the expected results on the scope, therefore the equipment offers only limited insight on the underlying theory or how the modules are actually designed, built, and implemented. More importantly, TIMS is not an evolvable system, which offers little flexibility for students to design and perform new or advanced experiments, except by purchasing new modules, or building customized modules from Emona Instruments. TIMS is also pricey ($100,000 for one basic setup), especially considering that more modules will be needed to support a series of core courses in a wireless engineering curriculum.

The transition of instruction from traditional wireless transmission to software radio transmission has already been noticed and is being pursued by institutions of higher education. For example, Professor C. Richard Johnson of Cornell University and Professor William A. Sethares of University of Wisconsin-Madison have written a new communication textbook entitled *Telecommunication Breakdown: Concepts of Communication Transmitted via Software-Defined Radio*, in which they teach communication theory via building a software radio based receiver using *Matlab simulations*. We would like to take the educational concept one step further to enable students to experiment and build SDR based working systems in their coursework and training.

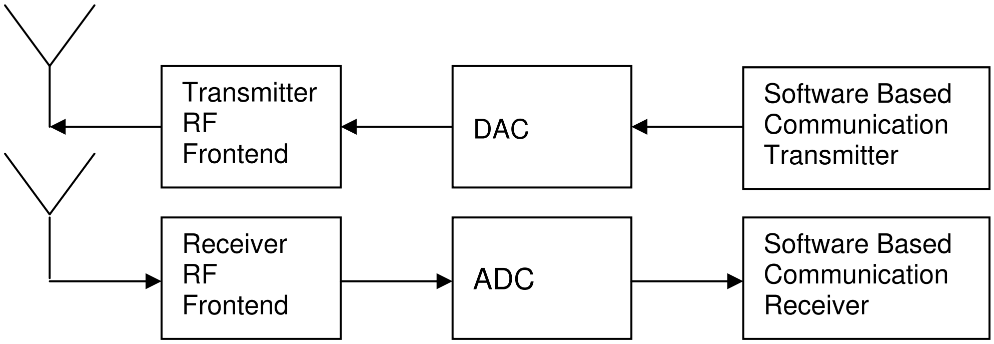

Figure 1. Typical software radio block diagram.

Preliminary Course Laboratories based on Software Defined Radio

Software Defined Radio (SDR) has emerged in recent years as a powerful concept for current and future wireless communication system design. In SDR, key components of the radio are implemented in software. Figure 1 shows a typical diagram of SDR, in which the received RF signal goes through the RF frontend and feeds to an analog to digital converter (ADC), then the output of ADC, the digital signal, goes into, and will be processed by, the software based communication receiver. In SDR, no complicated and expensive analog circuitry is needed to perform the transmission. On the contrary, software defines the transmitted waveforms and demodulates the received waveforms. Software radio has led the trend in the wireless communication arena to design and build wireless communication systems using reconfigurable software rather than fixed hardware. We see this as an opportunity for STEM education innovation by bringing in this new technology within a limited budget.

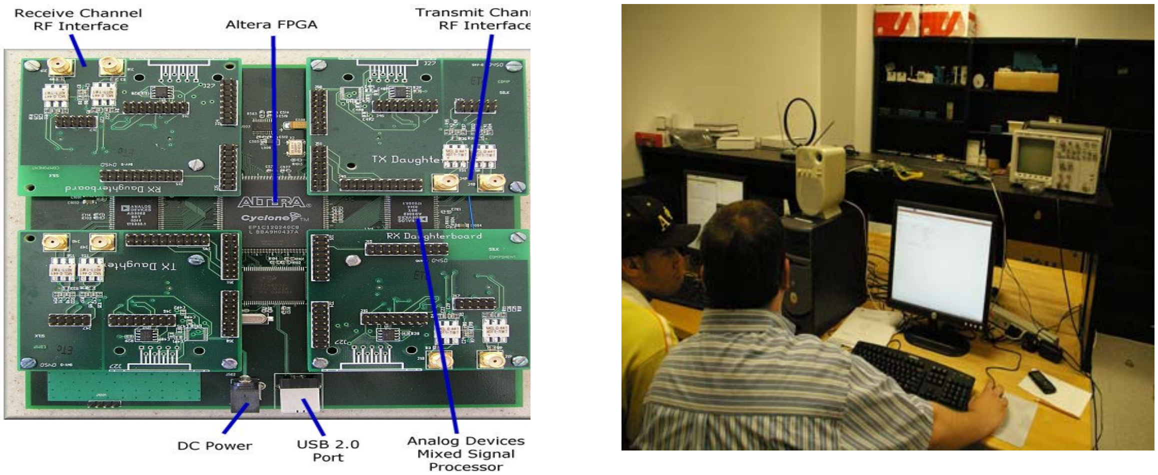

Figure 2. (a) USRP software radio board; (b) Current teaching lab setup.

At Wright State University, in the past several years, we have experimented in our undergraduate wireless communication course (EE421) with off-the-shelf Universal Software Radio Peripheral (USRP) boards[7] that support GNU software radio[8] for course laboratories. Figure 2(a) shows a picture of a USRP board. USRP boards are designed to allow general purpose computers to function as high bandwidth software radios. Primary development is done on Linux; however, USRP boards can also run FreeBSD, NetBSD, Windows, or Mac OS X. A USRP consists of a small motherboard containing up to four 12-bit 64M sample/sec ADCs, four 14-bit, 128M sample/sec DACs, a million-gate field programmable gate array (FPGA), and a programmable USB 2.0 controller. Each fully populated USRP motherboard supports four daughterboards: two for receiving and two for transmitting. RF frontends are implemented on the daughterboards, which are designed to allow easy prototyping in order to facilitate experimentation. Current USRP transceiver daughterboards provide frequency up to 2.4GHz with bandwidth of 20 MHz and 14-bit resolution.

The development of free GNU software radio is sponsored by the Free Software Foundation[8]. GNU radio provides a library of signal processing and communication blocks implemented in C++. By using these blocks, modifying these blocks, or implementing new blocks, users can easily develop SDR based wireless communication systems. GNU software radio not only can provide the capability to develop new technologies, but also can improve the traditional wireless communication by utilizing the advanced algorithms available in GNU radio to enhance the signal quality.

Preliminary Laboratory Design

Figure 2(b) shows our current teaching lab setup. We have 4 USRP boards which cost about $550 each, with each USRP board having 4 daughterboards (about $50 each). With the equipment, we designed and implemented several exciting course laboratories.

One lab is to design and build a tunable AM/FM transmitter and receiver using SDR. Speakers are connected to the USRP board so that students can play their favorite radio stations. With a microphone connected to the transmitter, the laboratory setup is essentially a radio station. A successfully executed lab allows students to talk via the microphone, and broadcast through the SDR transmitter. They can then receive via the SDR receiver, and hear their own broadcast from the speakers in another room. The students were very excited about the lab as they could relate to it easily. The students also felt a sense of real accomplishment and pride when they overcame all the challenges during the design and implementation, and made it work.

Another lab is to design a wireless text messaging system like cellular text messaging. Figure 3 shows a diagram of current lab setup and Figure 4 shows the GUI that students have developed for the wireless text radio transmitter. As can be seen in the GUI, different carrier frequencies, modulation schemes, and pulse shapes can be chosen to transmit the text or a file wirelessly. Figure 5 shows a “software based spectrum analyzer” at the receiver side. Students can observe not only the time characteristics of the signal, but also the frequency characteristics, even without an expensive spectrum analyzer. A successfully executed lab allows students to do real-time text messaging between standalone laptops (i.e., with no network access), or transmit digital files from one standalone laptop to another via the USRP software radio enabled wireless link.

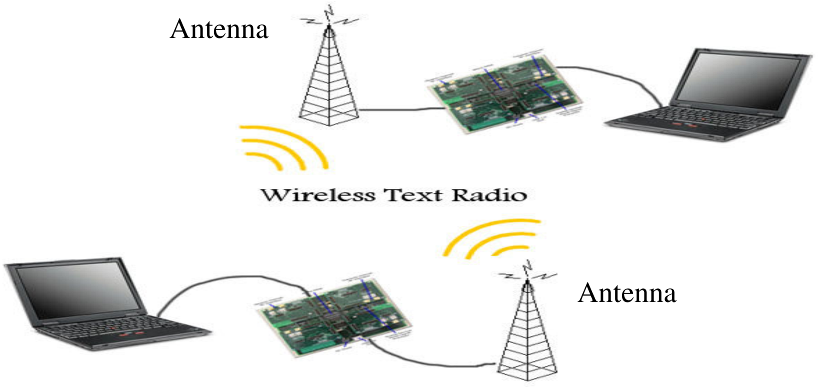

Figure 3. Wireless communication laboratory: wireless text radio.

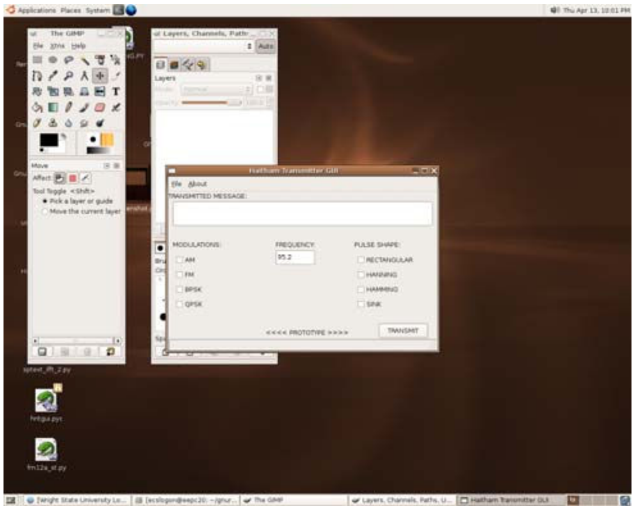

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Figure 4. GUI of wireless text radio lab project.

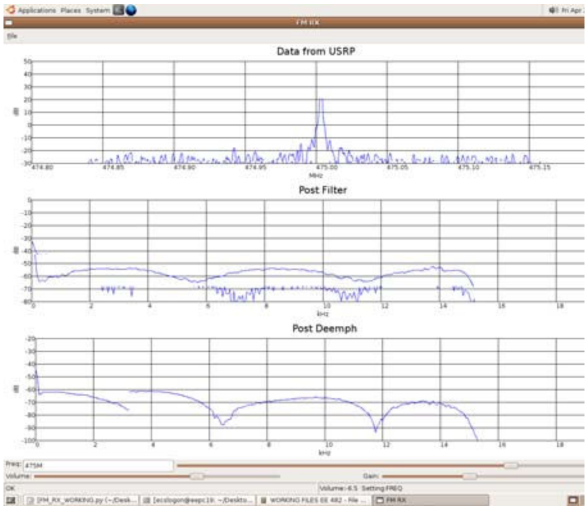

Figure 5. Software spectrum analyzer at USRP receiver.

Development of Evolvable SDR based Wireless Communication and Networking Laboratories: an Example

Based on our successful experiences, lessons learned, and student feedback, we believe that the SDR approach that employs USRP boards is powerful and flexible enough to build an effective teaching and learning platform, and therefore deserves further development into a set of laboratories by integrating with other wireless networking components, such as wireless sensor networks. Motivated by this belief, we have conducted extensive discussions with undergraduate student focus groups and sought their input in lab design for several core wireless communication and networking courses. We therefore propose to develop evolvable SDR based wireless communication and networking laboratories and associated user manuals, lab manuals, GNU radio design libraries, and to demonstrate the effectiveness of enhancing student learning and skills in some existing undergraduate courses.

Design Rationale and Consideration

According to R. M. Felder and R. Brent, "*Creating a course to achieve specified outcomes requires effort in* ***three domains****:* ***planning*** *(identifying course content and defining measurable learning objectives for it);* ***instruction*** *(selecting and implementing the methods that will be used to deliver the specified content and facilitate student achievement of the objectives); and* ***assessment and evaluation*** *(selecting and implementing the methods that will be used to determine whether and how well the objectives have been achieved and interpreting the results).*[9]" Although courses can be designed and taught to achieve various objectives, designing and teaching courses to satisfy the ABET engineering criteria appear to be an obvious choice and goal. Here we focus on course planning and instruction of laboratories, and on how to formulate learning objectives[10,11], and develop instructional techniques to help achieve the ABET outcomes 3a-3k[9] better.

Although we do not expect that a single course with labs addresses all of the ABET outcomes, we believe that the three courses enhanced by our proposed laboratories will address many aspects of the ABET outcomes. We realize that addressing an outcome and satisfying it are not synonymous. During course and lab planning, additional efforts will be taken on the part of the instructors, graduate assistant, and graduate teaching assistants to offer help, tutorials, tutoring, and other useful materials that help students learn more effectively.

One of ABET's criterion 3 outcomes, 3b, is an ability to design and conduct experiments, as well as analyze and interpret data. The labs offered in many current courses across Electrical Engineering and Computer Science disciplines are *prescribed labs*, in which the labs are designed basically with step-by-step instructions on how to operate individual instruments, how to perform the steps to see the expected phenomenon and/or to obtain the expected measurements, and how to process the data obtained and draw conclusions. Students who have successfully executed the expected steps can be claimed to have conducted the experiments. Arguably, they can also be claimed to have analyzed and interpreted data by writing and submitting a report. However, prescribed labs obscure students' abilities, so that the answers to whether they actually are able to understand and perform the experiments or if they have been involved in the design of an experiment become subjective. We believe that prescribed labs do serve as necessary stepping-stones to allow students an easy entry to the subject matter. However, as students mature, it is also necessary to equip them with the ability to explore the unknown via problem identification, problem formulation, experiment design, and data analysis and interpretation. Therefore, our labs will *strike a balance between prescribed labs and open-ended exploratory labs*, depending on subject matter and students' progress through a series of courses. By having an open-ended laboratory, students will be directly involved in their own lab/experiment design. They will be trained to be more independent, to recognize the need of, and to foster a habit of, engaging in lifelong learning[9].

To motivate adult learners, labs are designed to show relevance because adults are not very patient with material for which they cannot see an immediate use[12,13]. Students will work in teams, because teamwork affords them the chance to learn from one another and share ideas and experiences. This approach enhances learning and helps participants form connections with others by promoting cooperation and collaboration[14,15,16,17]. Meanwhile, to accommodate students with different learning styles, interactive web modules/courseware will be developed that will give students background information, e.g., reviews of technical background, an introduction of the schematic organization of the USRP boards, development environment, sample small scale projects, statistical data analysis, sample project reports, and so on. The Web enhanced modules will have a balance of concrete, real world examples (for sensing learners) and unifying principles (for intuitive learners). Interactive and attractive, colorful visuals can be easily incorporated in the modules (for visual learners); verbal narrative and explanations (for verbal learners) may also be an integrated part. Small online quizzes and questions posed will provide opportunities for active participation (for active learners) and time for individual thinking (for reflective learners).

Lab Development Supporting Wireless Communication

Lab one: *Analog modulation and demodulation*
In this lab, students will experiment different analog modulation and demodulation techniques including AM, FM, SSB, DSBSC in the prescribed part. They will then build AM and FM receivers which can tune to AM and FM radio stations. Advanced students will build AM and FM transmitters and receivers to create their own AM and FM radio stations.

Lab two: *Baseband transmission*
In this lab, students will perform experiments in baseband transmission of digital data. They will study the time domain and frequency domain characteristics of different baseband transmission techniques, such as pulse shape, eye patterns, PAM.

Lab three: *Digital modulation and demodulation*
In this lab, students perform experiments in digital modulation and demodulation techniques, including BPSK, QPSK, QAM, FSK, PCM and BER calculation.

Lab four: *Multiple access and spreading spectrum*
In this lab, students will perform experiments that deal with different multiple access techniques including TDMA, FDMA and CDMA. Different spreading spectrum techniques will also be studied such as Direct Sequence Spreading Spectrum and Frequency Hopping Spreading Spectrum.

Lab five: *An open-ended lab project on wireless text radio*
In this open-ended lab project, students will be guided to combine together what they have learned in the classroom and in previous lab experiments to build a complete wireless digital transmission system. In this system, students can input text from a GUI at the transmitter side and transmit it wirelessly, and the receiver should receive and reproduce the text on the screen of computer monitor. All parameters of the system, such as carrier frequency, modulation scheme, pulse shape, and so on, should be variable and tunable.

By conducting these labs, students will be able to gain hands-on experiences and deeper insights into wireless analog and digital data transmission. And they will be able to design key components of a wireless transceiver, and integrate them together. The prescribed labs also prepare the students for the design challenge in the follow-up courses, e.g., mobile computing and wireless sensor networks. Because SDR is *flexible and evolvable*, new experiments, modulation schemes, advanced techniques (such as OFDM, MC-CDMA), can be easily added into the laboratory curriculum by designing and implementing new software, without constantly upgrading and/or buying new hardware modules.

Lab Instruction

The design of SDR based laboratories gives us the opportunity to re-think lab instruction in a wireless curriculum in order to enhance students' learning and their capability of analyzing and solving real-life problems. We believe that an integral design, with both prescribed labs and problem-solving open-ended labs[18,19,20], can be a viable solution. This mixture of lab styles poses a challenge to lab facilities, students, and instructors as well. We believe that the proposed SDR

USRP platform, lab design, and suitable pedagogy may provide a right recipe for student success.

Specifically, the SDR based USRP boards has been demonstrated as a low-cost, flexible platform for a series of prescribed and open-ended labs, which provides a consistent facility with which students can get familiar and build their design experiences progressively. Instructors can accommodate a series of lab designs of increasing technical demands and complexity, beginning with prescribed labs and culminating in individual or group-based problem solving labs.

Our lab offerings in wireless communication have found that the use of this progressive instruction method has successfully helped the learning of students and have better addressed desired learning outcomes. Take the wireless text messaging lab project as an example, we provide students with the challenge of integrating and creating a complete digital wireless radio system after a series of four prescribed labs as described previously. We believe that this hands-on experience of making one complete system is better as a learning tool compared with studying various components of a system without integrating them together. In particular, students will attain the skills to design a complete system.

For many students, this is their first attempt on wireless communication system design. In order to help students get through the process effectively and smoothly, we advise them to follow a few common system design steps. Specifically, student working groups are guided to:

1. *Write a clear problem definition statement.* Students explain the big picture of how all the components they have studied and experimented in the prescribed labs are pieced together as a complete system.
2. *Identify the knowledge they already possess and what they need to acquire to successfully carry out this project.* Students regularly update this list as they progress.
3. *Prioritize learning needs, set learning goals and objectives, and allocate resources and team members' responsibilities.* Students then use the "divide and conquer" method to decompose what they need to learn into different components and allocate them within the group. One student may study channel coding method and decide which coding scheme is the best "fit" for the project's needs, another student may study synchronization techniques and find out a solution that offers the best tradeoff in complexity and performance, etc. Each will be responsible for teaching and explaining to other students about their choice and rationale.
4. *Carry out the necessary research and analysis and generate possible solutions.* Students are reminded by the instructor "not to aim too high" at this stage. It is essential to make the core of the project working before adding on optional packages. Time limit of the laboratory usually prevents students from creating a very comprehensive system. They need to learn to generate reasonably good solutions within a deadline

We also encourage and promote cooperative learning[15,16,17] by involving students working in teams to accomplish a common goal. Specifically, student groups are formed to conduct labs. Each group has a leader and two or three team members. Early on in the lab design stage, a brain-storming gathering of the group and instructors is arranged because it provides an opportunity not only for discussing imaginative designs of the system, but also for the team members to understand each other's working styles. Team members meet at least twice a week to discuss their progress and work together. During the meetings, group members give each other feedbacks, challenge one another's conclusions and reasoning, and also encourage one another when the project is not moving along smoothly. The team leader takes charge of the entire process and is responsible for allocating subtasks to team members with guidance from the instructor. It is obvious that students need to maintain *positive interdependence*[15,16]: students need to rely on each other to complete the project and nobody can do this alone. This teaches them the necessity of being a team player and the needs to keep learning from colleagues in their future careers. If students know they are going to be held individually accountable, they would make a serious effort to learn and contribute.

As instructors, we have attempted to integrate an *assessment driven learning* approach to ensure students' progress. Assessment is built into the lab execution. For example, with the assistance of GTAs, students in a team are randomly picked to report progress, and explain design choices and decisions. Comprehensive short quizzes can also be administered. In addition, the roles of students or the tasks assigned to students may be switched regularly. Team members conduct self-assessment on their performance as a group regularly, and identify what they do well as a team, what they need to improve, and how to make the collaboration more effectively in the future. A healthy competition is encouraged among different teams to motivate and provide incentives to students to learn and to cooperate among team members.

Preliminary Evaluation and Outcomes

Our evaluation plan focus on three aspects: (1) effectiveness of SDR based lab design for individual courses; and (2) impact of labs on student learning and skills enhancement, and their success. Our preliminary evaluations were carried out using self-administered questionnaires. As an example, the evaluation for EE421 Wireless Communication posed 6 questions:

1. Is the software defined radio (SDR) based teaching laboratory useful in improving your understanding of communication theory? On a scale of 1 to 5, how much has the SDR based teaching labs helped your learning?
2. Did you use spectrum analyzer to observe the spectrum of a RF signal before this class? On a scale of 1 to 5, how much has the hands-on experience and observation of the RF signal and RF signal's spectrum increased your interest and kept you in the class?
3. Has the SDR based teaching laboratory and the hands-on experience helped you in deepening your understanding of some prerequisite courses such as linear system?
4. Will you take other communication and wireless engineering courses after EE421? Has the SDR based teaching laboratory increased your interest in taking such courses? On a scale of 1 to 5, how much has it helped?
5. Do you have any suggestions on the SDR based teaching laboratory of EE421 in the future?
6. What do you expect in the SDR based teaching laboratory of future communication and wireless engineering courses?

The student feedback has been overwhelmingly positive to all the questions posed. Students have been quite enthusiastic about how labs have been conducted. Some student comments are quoted as follows:

> *"On scale 1 to 5, I scale to 4, because it created interest in me to learn more about how communication is made possible."*
> *"It has helped in the way of creating interest in communication. I will surely take courses after completing this course."*
> *"Yes, 5 it really gave me an interest in communication aspects."*
> *"Yes, the lab gave me a visual application of the theory we talked about in class."*
> *"Yes. I was shady on some of the prerequisites but the lab helped in my understanding of spectrums."*
> *"4, yes it does help me in improving my understanding & gave me clear idea about different modulation technique."*
> *"I think I will. I had zero interest prior to this course, but the projects and the laboratory have allowed me to consider taking another course."*
> *"5. It's very good by learning with hands on experience & by using devices rather than theoretically learning."*
> *"The laboratory teaching gave a good practical experience about the subject."*
> *"Yes this lab has helped in refreshing EE concepts."*

The outcomes of this laboratory development may serve as an example for adaptation and/or adoption. Some of the outcomes so far include (1) a set of pilot wireless course laboratories based on the USRP boards employing GNU software radio and related teaching and evaluation materials. (2) a pilot test for evaluating the developed labs that demonstrates the effectiveness of motivating, engaging, and enhancing student learning and skills as prescribed by the ABET.

Conclusions

Future engineers will need to be trained with fundamental principles as well as emerging technologies. The evolution of wireless communication and networking presents such a need and a unique opportunity to integrate undergraduate education across the Electrical Engineering and Computer Science curricula.

We have developed an easily replicated model of evolvable, low cost, *software defined radio* (SDR)-based wireless communication and networking laboratories and associated teaching and learning materials that can be duplicated to impact national engineering education practices. Furthermore, we have demonstrated the effectiveness of enhancing student learning and skills in an undergraduate course, wireless communication.

This work will benefit a diverse population of students by motivating, engaging, enhancing their learning and skills as prescribed by the ABET. Therefore, the laboratory development is directly aligned with the departmental and institutional priority of development, and has had an immediate local impact. The technology on which the lab development is based is cutting edge, demonstrating a viable example of adopting new technology and research to enhance undergraduate STEM education. The platform employed for development, USRP boards, is low cost; and the software used, GNU software radio, is free and has a large supporting community that provides unlimited innovation. Therefore, the lab environment can be easily portable to even the most cash-starved institution. No expensive testing equipment is needed, which provides a very low entry point for adaptation and/or adoption nationwide. The one time investment can also withstand the trial of time because the platform is as evolvable as the GNU software radio. All the materials developed are available publication dissemination. The initial success of this laboratory development has prompted us to conduct further evaluation and assessment and to pursue a full scale implementation for a national model of SDR lab-based wireless communication and networking courses.

Bibliography

1. DARPA XG working group RFC, "The XG Vision." available from http://www.darpa.mil/ato/programs/XG/rfcvision.pdf
2. R. M. Felder, R. Brent, "Learning by doing." *Chemical Engineering Education*, 37(4), 282-283,2003.
3. Auburn University Wireless Engineering Undergraduate Program, http://www.eng.auburn. edu/wireless/
4. Tufts University, Microwave and wireless engineering certificate program: http://ase.tufts.edu /gradstudy/programCertMicroWirelessEng.htm
5. University of South Florida, Wireless and microwave research and instruction program: http://ee.eng.usf.edu/certificate/
6. Bradley University Microwave and wireless engineering program, http://www.bradley.edu/ hilltopics/wireless/
7. Universal Software Radio Peripheral Board, Ettus Research LLC, http://www.ettus.com/
8. GNU Radio—The GNU Software Radio, http://www.gnu.org/software/gnuradio/
9. R. M. Felder, R. Brent, "Designing and teaching courses to satisfy the ABET engineering criteria." *Journal of Engineering Education*, 92(1), 7-25, 2003.
10. B. S. Bloom, D. R. Krathwohl. "Taxonomy of educational objectives, Handbook 1. Cognitive domain." New York: Addison-Wesley, 1984.
11. D. R. Krathwohl, B. S. Bloom, B. B. Massia, "Taxonomy of education objectives, Handbook 2. Affective domain." New York: Addison-Wesley, 1984.
12. R. J. Wlodkowski. "Enhancing adult motivation to learn." San Francisco: Jossey-Bass, 1993.
13. J. Vella. "Learning to listen, learning to teach." San Francisco: Jossey-Bass, 1994.
14. L. D. Fink, "Creating significant learning experiences." San Francisco: Jossey-Bass, 2003.
15. R. M. Felder, R. Brent, "Effective strategies for cooperative learning." *Journal of Cooperation and Collaboration in College Teaching*, 10(2), 69-75, 2001.
16. D. B. Kaufman, R. M. Felder, H. Fuller, "Accounting for individual effort in cooperative learning teams." *Journal of Engineering Education*, 89(2), 133-140, 2000.
17. B. Oakley, R. M. Felder, R. Brent, I. Elhajj, "Turning student groups into effective teams." *Journal of Student Centered Learning*, 2(1), 9-34, 2004.
18. K. M. Edens. "Preparing problem solvers for the 21st century through problem-based learning," *College Teaching*. 48(2): 55-60, 2000.
19. Maricopa Center for Learning and Instruction. "Problem-based Learning." http://www.mcli. dist.maricopa.edu/pbl/problem.html
20. McMaster University. "Problem-based Learning," http://www.chemeng.mcmaster.ca/pbl/pbl.htm.