Software Defined Radio Laboratory Platform for Enhancing Undergraduate Communication and Networking Curricula

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Abstract: The advances of communication and networking have changed the world fundamentally. Communication and networking courses, especially wireless communication and networking courses, have become an integral part of the Electrical Engineering, Computer Science, and Computer Engineering curricula. However, most of these courses are taught at many institutions without a laboratory. For those courses associated with labs, often special hardware based experiment systems are used. These experiment systems are expensive so most schools cannot afford them. More importantly, such systems lack the flexibility to evolve over time and adapt to different environments. In our previous NSF funded CCLI project "Evolvable wireless laboratory design and implementation for enhancing undergraduate wireless engineering education", we have developed and demonstrated the first nationwide example of evolvable software defined radio (SDR) based laboratories for three existing undergraduate courses. These laboratories have been well received by the students, and have significantly improved the learning outcomes of such courses. Furthermore, these labs have attracted students to these courses: the enrollment of these courses has increased drastically after the introduction of these labs. Based on our success of this project, we are developing a suite of experiments and laboratories into a sequence of courses (ranging from freshmen year introductory course to senior year elective courses and capstone design projects) that vertically integrates the SDR based experiment approach in this NSF TUES type II project. We are also equipped with hardware based experiment systems to evaluate and compare the teaching effectiveness of the novel SDR approach to that of traditional hardware equipment approach. The novel SDR approach and laboratory suite will be implemented, transferred and institutionalized at three participating institutions (Wright State University, Miami University (a mostly undergraduate serving institution), and Central State University (an HBCU)) to demonstrate the capability of enhancing student learning and easy adaptability by other institutions.

1. Introduction

Need & Motivation: Wireless communication and networking has tremendously changed our everyday life in the past two decades. Currently there are 292.8 million wireless subscribers in the US, representing 93% of the total population [1]. The wireless industry generates $155.8 billion dollars in avenue annually and is still growing [1]. WiFi networks [2] enable the creation of a mobile workforce. In addition to wireless notebooks, the use of cell phones and other wireless devices has become the norm rather than the exception. In today's ever-growing mobile environment, it is essential for every mobile worker to use wireless technology.

This explosion of wireless technology poses a unique and promising opportunity to attract new talent into the Science, Technology, Engineering, and Mathematics (STEM) programs and to revolutionize our undergraduate education. At career days, we have met numerous young high school seniors who eagerly expressed their interest in becoming an engineer or a computer scientist because they were so intrigued to know how iPhone or the Internet works. The newly established Wireless Engineering option at Wright State University [3] has been seeing ever increasing enrollment since it started a few years ago.

However, we feel that we have not provided the undergraduate students with the necessary learning environment they are entitled to. Electrical engineering and computer science are practical disciplines, and students learn by doing. Hands-on experience is an integral part of their learning. Students learn from equations and homework; they learn from computer simulations through Matlab and Labview; but nothing beats a real laboratory where they can get their hands dirty. However, based on our study, very few universities offer laboratories in their communication and networking courses. There is a simple reason behind this: many schools **cannot afford** such laboratories.

The traditional approach of conducting communication and networking laboratories is using RF equipment such as radio frequency signal generators and spectrum analyzers, or custom-made/special laboratory equipment. Radio frequency equipment is often expensive, and it may not be feasible to purchase multiple sets of such equipment to accommodate an undergraduate teaching lab. For example, a pair of RF signal generator and spectrum analyzer cost tens of thousands of dollars. The TIMS (Telecommunications Instructional Modeling System) communication laboratory equipment [4] used by most of the few universities (e.g., Auburn University [5] and Georgia Tech [6]) offering laboratories in their curricula costs $100,000 for one basic setup. Recently, National Instruments has developed a software defined radio (SDR) based digital communications teaching bundle to serve the digital communication course [7]. This bundle consists of two SDR boards, the connecting cable and the courseware and costs $6399 per set [7]. Although the price is much lower than other systems, it is considerably higher than the cost of the SDR boards themselves. More importantly, such special laboratory equipment (including the NI's SDR based digital communication teaching bundle) is **not evolvable** and offers limited flexibility for designing and performing new or advanced experiments, except by purchasing new modules, or building customized modules from the manufacturer.

Hence, it is our belief that it is urgent and highly desirable to create a revolutionary approach for conducting communication and networking laboratories. Our goal is an affordable, evolvable, and expandable laboratory suite that can be easily transferred to different institutions to allow them to offer laboratories for communication and networking courses in their curricula and to leverage such laboratories to recruit, retain, and better educate STEM students.

2. Software Defined Radio Platform

Software Defined Radio has emerged in recent years as a powerful and working concept for current and future wireless communication system design [8]-[11]. In SDR, key components of the radio are implemented in software. Figure 1(a) shows a typical diagram of SDR. Take the receiver in Figure 1(a) as an example, 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 is 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.

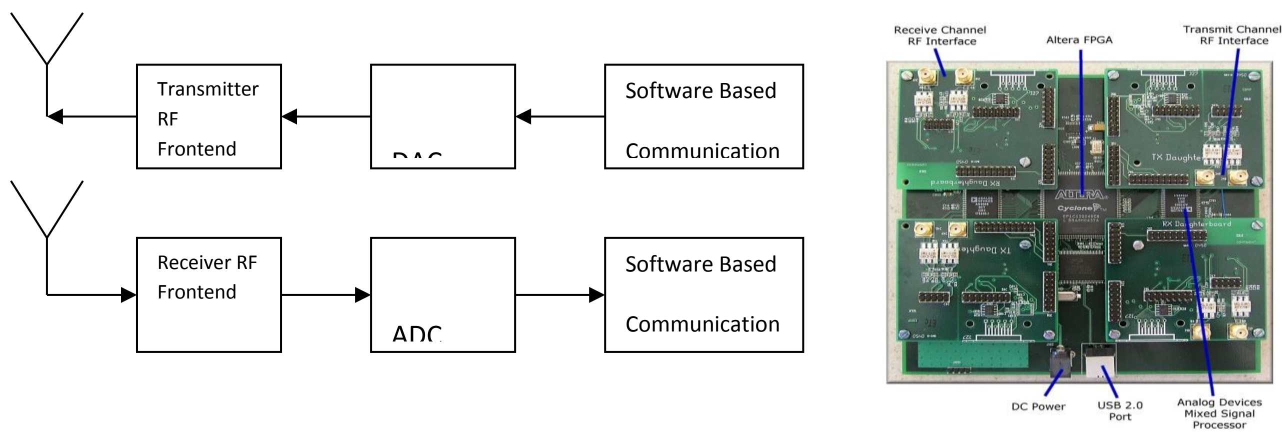

Figure 1. SDR (a) A typical SDR diagram; (b) A USRP board.

We have chosen the Universal Software Radio Peripheral (USRP) developing boards [12] and associated GNU radio software [13] for this project. The USRP is designed to allow general purpose computers to function as high bandwidth software radios. Figure 1(b) is a picture of the USRP developing board. The 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 the receiver and two for the transmitter. RF front ends are implemented on the daughterboards. Daughterboards are designed to be easy to prototype in order to facilitate experimentation.

There are a few features that make USRP boards ideal for our purpose: (1) **Affordability**: The USRP boards are inexpensive and affordable by all institutions. Each USRP motherboard costs only $750. The daughterboards' prices range from $50 to a few hundred dollars. A basic setup of two USRP motherboards and daughterboards costs less than $2,000, only a fraction of the special hardware-based approach's cost. (2) **Flexibility:** The USRP boards' operating frequency can be easily changed from DC to 5GHz by attaching different daughterboards, allowing great flexibility in designing labs for different courses and topics such as Wireless LAN [2], Wireless Sensor Network [14], etc. Additionally, the software nature of SDR enables the labs designed on USRP to easily change all parameters such as carrier frequency, symbol rate, modulation type, routing schemes, network protocols, etc. (3) **Evolability:** Since the communication and networking components reside on the general purpose computers operating the USRP boards, the laboratory is totally evolvable. Designing new components and new labs is easy and is not limited by the hardware platform. (4) **Portability and transferability:** The USRP board is light and small: it weighs only 130 grams and measures 16 cm long, 12 cm wide and 6 cm thick. It is smaller and lighter than a book. It is contained in a nice metal package, making it safe to carry and move. The GNU radio software associated with the USRP is open source software sponsored by the Free Software Foundation (FSF). GNU Radio provides a library of signal processing and communication blocks implemented in C++. This allows universities to easily share and transfer the laboratory modules.

3. Type I Project Results

Our NSF CCLI type I project entitled "*Evolvable wireless laboratory design and implementation for enhancing undergraduate wireless engineering education*" (grant 0737297, $150K, February 2008 - January 2012) funded the purchase of 20 USRP motherboards that cost about $750 each, with each USRP board having 6 daughterboards. Using these 20 boards, we created 10 lab setups that accommodate 20 students in one lab session. We then designed and implemented laboratories for three existing undergraduate courses: *wireless communications*, *wireless sensor networks*, and *mobile computing*, which form a part of an integral wireless engineering curriculum.

3.1 Intellectual Merit of Type I Project

Lab Development Supporting Wireless Communication: The senior level wireless communication course has been offered twice a year and enrolled more than 40 students. We have designed a series of labs to cover a wide range of topics in wireless communication. These topics include: (1) Analog modulation and demodulation; (2) Digital baseband transmission; (3) Digital modulation and demodulation; (4) Multiple access and spreading spectrum; (5) An open-ended lab project on wireless text radio.

Lab Development Supporting Mobile Computing: This junior/senior level course has been offered twice a year and enrolled more than 30 students. We have designed a series of SDR-based labs for this course. These labs include *wireless TCP protocol, TCP performance over heterogeneous wired-to-wireless networks, Dynamic Source Routing, etc.* As an example, in one project we have developed a *"Mobile TV"* that cuts across application, transport, network, and physical layers, which helped the students to understand the heterogeneity between the wired Internet and the emerging wireless Internet.

Lab Development Supporting Wireless Sensor Networks: This senior level course has been offered twice a year and enrolled more than 20 students. Wireless sensor network is a rapidly expanding application area whose recent research has been phenomenal. As a course, *wireless sensor networks* has been offered mainly at the graduate level in various institutions. With the help of the SDR labs we have designed for this course, we were able to offer this course at the undergraduate level and attracted a good number of students.

Learning Outcome Improvement: We have employed a number of different methods to evaluate the effectiveness of the labs to improve the learning of the students in these courses. In each course, we have gathered pre-course questionnaires and post-course questionnaires. We have also designed and gathered anonymous questionnaires specifically on the labs in these courses with quantitative and qualitative metrics. We have conducted exit interviews with graduating students for their responses to these labs. We have received student feedback in and out of classroom on these labs. We have presented some of these labs to high school students as part of the recruiting effort. We have surveyed employers of our graduates. We have studied the enrollment data of the wireless engineering option before and after the introduction of these labs. The outcome from all of these methods is consistently positive. As an example, the enrollment of the wireless engineering option has increased by 30% since the introduction of these labs.
We have presented our findings of this project in two papers at the 2010 ASEE conference [15][16].

4. Development of Evolvable SDR based Communication & Networking Laboratory Platform

Based on our successful experiences and lessons learned in the type I project, we plan to extend and expand our CCLI type I project to create an affordable and evolvable SDR-based Communication & Networking Laboratory Platform which will serve a large number of courses ranging from freshman year to senior year and will be portable and transferable to other institutions. Some courses may not require a full-scale laboratory, but a few SDR-based projects will benefit the students tremendously. The software nature of the SDR-based laboratory platform makes it possible to build the laboratories in modules, and different courses can choose and integrate these modules from the pool for their own purposes. The portability of the SDR boards makes it easy for the laboratories to be transferred among three participating institutions.

To support this effort, we have acquired 20 desktop computers with 30 monitors and additional 60 USRP daughter boards from Wright State University technology fee, and integrated the SDR setups with an existing wireless sensor network testbed supported by NSF CRI Award #0454170 at WSU. This combined facility will then be used for our lab development. As part of the support from the College of Engineering & Computer Science to this project, we have been provided with a new dedicated teaching lab at the Russ Engineering Center Room 152B with more than 1,200 square feet of space, specifically for this project. Figure 4(a) shows the current SDR setup at the new lab.

Additionally, we have obtained funding from the State of Ohio to purchase hardware based laboratory equipment including 10 sets of Tektronix AFG3252 Arbitrary Function Generator and 10 sets of Tektronix DPO3014 Digital Oscilloscopes. The DPO also operates as a spectrum analyzer.

Furthermore, we have built a thorough wireless communication network testing system to serve this project. With approximately 1 million dollars from NSF, AFOSR, AFRL and the State of Ohio, this wireless communication network testbed consists of Vector Signal Generator, Vector Spectrum Analyzer, Arbitrary Waveform Generator, Digital Phosphor Oscilloscope, Vector Network Analyzer, and Wireless Channel Emulator. With such a wireless communication network testing system, we can easily validate new laboratories proposed in this project before we implement them on the SDR platform, significantly increasing the speed of the project development. Figure 3(b) is the instructor’s setup in the dedicated lab, besides the SDR lab setup and the Arbitrary Function Generator and DPO, we have placed the Tektronix AWG7062B and Tektronix DPO7254 for this purpose.

We have already developed a comprehensive teaching manual and a user manual for the three courses supported by the CCLI type I project. In this project, with the assistance of a few graduate students and undergraduate students across all three participating universities, we will develop comprehensive teaching manuals, user manuals, video recordings of the instruction, and other teaching materials for all the laboratories serving multiple courses. A series of GNU software radio blocks not available in current GNU library will also be designed and implemented.

Conclusions

Based on our success of a NSF CCLI type I project, we are developing a suite of experiments and laboratories into a sequence of courses (ranging from freshmen year introductory course to senior year elective courses and capstone design projects) that vertically integrates the SDR based experiment approach in this NSF TUES type II project. We are also equipped with hardware based experiment systems to evaluate and compare the teaching effectiveness of the novel SDR approach to that of traditional hardware equipment approach. The novel SDR approach and laboratory suite will be implemented, transferred and institutionalized at three participating institutions to demonstrate the capability of enhancing student learning and easy adaptability by other institutions.

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