Enhancements to Software Defined Radio Design Engineering Education

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Abstract - *Software defined radio (SDR) combines aspects of computer science with communications, computer, software, and systems engineering. SDR instruction 1) integrates students' prior knowledge of enabling technologies and disciplines; 2) diversifies students' skill sets to enhance their ability to advance SDR and other multidisciplinary areas of engineering; and 3) meets a need for engineers familiar with SDR and related technologies. SDR courses must both survey and integrate relevant topics, and introduce students to challenges that are characteristic of SDR and typical of multidisciplinary engineering. This paper describes implementation and outcomes of enhancements to SDR graduate courses at the Naval Postgraduate School and at Virginia Tech. Recent modifications include development of hands on laboratory exercises and their increasing integration into the courses, use of block oriented modeling software and open source SDR software and rapid prototyping tools to bridge the gap from theory to prototyping of SDR waveform applications, and integration of industry and government examples and case studies. Course structure and recently introduced approaches are described and outcomes characterized based on observation and numerical and qualitative student reporting. Finally, plans for refining and synthesizing reported approaches and incorporating further enhancements are described.*

Keywords: software defined radio, Software Communications Architecture, communications, interdisciplinary

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INTRODUCTION

An SDR is a radio in which most of the signal processing is done in software running on a computer or on an embedded computing device. The SDR usually has an antenna, an amplifier, and a downconverter like traditional hardware radios, but the rest of the radio functionality is accomplished by an analog to digital and/or digital to analog converter and software running on a computing device. Thus the modulation and demodulation are defined in software, which motivates the term software defined radio. The idea for software defined radio is not new [Mitola, 10], but advances in analog and digital electronics, as well as investment by the American military are making SDRs practical and increasingly attractive for many applications. SDRs are particularly attractive when it is desired that the radio be multimode or easy to upgrade. This is important to the military where it is hard to predict how a radio will be used over its lifetime and important to the mobile phone industry where it is desirable to be able to upgrade basestations via software updates. Indeed, both the military and the mobile phone industry are designing and deploying software defined radios. The ease of design, simulation, and test for a software defined radio suggests that the trend of increasing reliance upon software defined radios will continue.

The increasing importance of SDR is matched by an increasing need for engineers skilled in SDR design in industry and government. While SDR design is increasingly represented in engineering curricula [Arslan, 1, Bilen, 2, Goodmann, 4, Hoffbeck, 5, Kang, 6, Schelle, 14] most engineering universities still do not teach this important technology, resulting in substantial shortages in engineers ready to design SDRs. Virginia Tech (VT) and the Naval Postgraduate School (NPS) are among those universities that recognize the need for SDR-savvy engineers and the need for the corresponding educational opportunities. As a direct consequence, Virginia Tech and the Naval Postgraduate School each include a course in Software Defined Radio design in their electrical engineering graduate curricula.

Virginia Tech and the Naval Postgraduate School have been actively collaborating in this area since 2005. [Kragh, 7] describes these courses as they existed in 2007, and this paper describes subsequent substantial enhancements to those courses.

BACKGROUND ON VT AND NPS COURSES

Virginia Tech introduced a graduate level course in software radio in 1999. This 15 week semester course is taught each fall. In addition to an overview of SDR concepts, the course includes an SDR-focused survey of enabling technologies including software engineering and architectures, radio frequency (RF) and digital hardware, analog-to-digital and digital-to-analog converters, direct digital synthesis, and multirate signal processing. The course also addresses SDR applications such as smart antennas, multiple-input multiple-output (MIMO) systems, and cognitive radio. The course is project oriented, with semester-long or shorter projects making up the bulk of the coursework and grade. Projects were initially primarily literature reviews, theoretical, or simulation studies, but projects that involve SDR implementation are now also feasible due to availability of low cost SDR hardware and improved software. Since 2002, the course has used a textbook [Reed, 11], which was developed with input from students who took the course in previous years. The second edition of the textbook is expected to be published in 2010. Since 2006, the class has included hands-on laboratory exercises that use OSSIE, the open source SCA-based SDR software from Virginia Tech. Development of these exercises, now available on the OSSIE web site [OSSIE, 12], was initiated by NPS and now is a collaborative effort that involves both institutions.

NPS has offered a graduate lecture and laboratory course in software defined radio design annually since 2006. This course was modeled after the Virginia Tech course and uses the same textbook and laboratory exercises. However, the NPS course is different due to its shorter duration and military perspective. The NPS course is only eleven weeks in duration which implies that it does not cover some of the advanced topics such as smart antennas, MIMO systems, and cognitive radio. The military perspective implies a substantial emphasis on the Software Communications Architecture (SCA), due to the importance of the Joint Tactical Radio System (JTRS) in the American military and the requirement for all JTRS radios to be compliant with the SCA. Emphasis in the course is given to SDR design, simulation, and implementation.

RECENT MODIFICATIONS TO COURSES

Coordination of Lectures with Hands-on Exercises

The wide range of technologies that enable SDR could be covered in nearly any order, so the order can be varied, for example, to accommodate guest lecturers. Introduction of the hands-on laboratory exercises provides another consideration when scheduling the lectures. From 2006 through 2008, the hands-on lab exercises were introduced into Virginia Tech's SDR class following lecture material on software issues in SDR, which was presented in the middle of the semester. As the software matured and its use in projects became more feasible, it became desirable to familiarize students with the software earlier in the course so that they would be prepared to use it in semester-long projects if desired. In 2009, the first hands-on exercises were introduced in the second week of the semester, conforming to the schedule in the NPS course. At both schools, this requires moving the lecture material on SDR software issues immediately after the initial overview of SDR. Since several additional exercises were available for 2009, an effort was also made to coordinate scheduling of the remaining labs with coverage of related topics in the lectures.

Ordering of Enabling Technologies, Case Studies, and Project Presentations

In 2009, Virginia Tech's course was also modified to cover enabling technologies early in order to better equip students to complete semester projects. The final 2 ½ weeks of the course lectures consist of SDR case studies, which are better understood in light of the previous material on enabling technologies and applications. Two of the final three lecture periods are devoted to student presentations of semester projects, which included project overviews and preliminary results.

Also in 2009, lectures in synchronization and a discrete-time approach to receiver design were added to the NPS course following the presentation found in [Rice, 13]. It was recognized that these topics are essential to proper design of digital communications receivers, which is a critical course objective. Exercises were assigned in the design, simulation, and test of binary phase shift keying transmitters and receivers including phase and symbol timing synchronization. Students were given the performance criteria (data rate, pulse shape, range of frequency and symbol timing jitter, etc.) and a signal recording including carrier frequency errors and symbol timing jitter. Success in demodulating the signal determined assignment grades.

OUTCOMES

The success of the two courses can be measured in several ways. One way to measure the success of the learning process is in terms of the projects produced by the students. In both courses, students were able to produce software defined radio designs and simulations of substantial complexity, typically using the OSSIE SCA-based design environment, a computer, and the universal software radio peripheral (USRP) [Ettus, 3]. Successful team projects have included a software defined oscilloscope, and SDR implementations of an AM receiver, an FM receiver, an FM transceiver, a binary phase shift keying receiver, a software defined spectrum analyzer, and others. Another way to measure the success of the course is in terms of student opinions regarding the course content, the textbook, and the laboratories. As can be seen in Tables 1 and 2, which show the results of student surveys, the average ratings for the course, textbook, and labs were excellent at NPS and VT students seemed to agree with that appraisal.

A major enhancement to the course has involved the laboratory assignments and their improved coordination with the lecture material. These improvements have been detailed in a separate paper [Kragh, 8]. Therefore, it is noteworthy that the laboratory ratings in Table 1 include these substantial improvements only in 2009. The 2009 courses included the laboratory exercises currently posted on the OSSIE website. The average NPS 2009 respondent rated the laboratories 4.33, which is a better evaluation of the current state of the laboratories and the design environment software. This is the only rating that showed a change of greater than 10% in 2009 ratings relative to the corresponding 2006-2009 rating average.

Table 1. End of course evaluation of NPS's SDR course, 2006-2009 cumulative (42 respondents)
1=poor (lowest 10%), 2= fair, 3=average (middle 40%), 4=excellent, 5=outstanding (top 10%)

Item	**Mean**
Overall, I would rate this course:	4.17
Overall, I would rate the textbook:	3.96
Overall, I would rate the laboratories:	3.60*

*2009 laboratory rating is **4.33** (20.3% above four-year mean)

Table 2. Midterm Evaluation of VT's SDR course, Fall 2009, Week 9 (10 respondents)
1=disagree, 2=tend to disagree, 3=tend to agree, 4=agree, 5=n/a (not included in mean)

Item	**Mean**
course encourages critical/original thinking	3.5
textbook is a good resource for class	3.5
overall, the course at this point is satisfactory	3.7

FUTURE ENHANCEMENTS

In feedback during week 5 of VT's fall 2009 course, some students indicated a desire to see more industry examples throughout the course. Although the case studies in the latter part of the class partially address this, we plan to review the notes and include additional examples from industry projects throughout the lectures where feasible.

Both schools plan on building on past successful student products to include design and implementation of a binary phase shift keying digital radio transmitter and receiver as a new laboratory exercise. This exercise will reinforce the students' skills in discrete time implementation of receiver signal processing including phase, frequency, and symbol timing synchronization. Successful completion of this planned laboratory exercise will prepare the students to design more advanced digital transceivers including more advanced modulation schemes, forward error control coding, or inclusion of multiple access protocols for wireless networking.

Updates to labs

In 2009, Virginia Tech's class has integrated hands-on exercises to a greater degree than previously, with a total of 10 exercises. In the process, we have identified potential refinements to the labs for future years. Improvements in the OSSIE Waveform Workshop rapid prototyping tools have gradually reduced the time, effort, and attention to inner workings of the SCA that are required for creation of SDR waveforms. Thus some of the lab exercises can be consolidated due to the increased efficiency of the tools, and some additional steps may need to be added, e.g., browsing XML files to see how configuration information is stored and used in the SCA. New labs that introduce digital modulations and multiple-input multiple-output (MIMO) communications were introduced in the fall 2009 course. These two exercises are expected to be significantly improved in the next year due to planned use of the new Liquid Radio DSP library [Liquid, 9]. In addition to consolidating the lab exercises, software-only exercises and parts of exercises that do not require access to RF hardware will be assigned as homework. These steps will make room for expanded software and systems engineering content and coverage of additional software architectures in the course, while allowing inclusion of hardware oriented exercises.

CONCLUSION

Software Defined Radio (SDR) design is important in the field of electrical engineering in both the civilian sector and military sectors, as is evidenced by software defined cellular basestations and the multi-billion dollar Joint Tactical Radio System (JTRS) Program. There exists a largely unmet demand for communications engineers with SDR expertise. Thus, there is a role for engineering universities to enhance curricula to meet that demand. This paper describes recent enhancements to the VT and NPS SDR courses described earlier [Kragh, 7]. These enhancements include restructuring the course to enable more hands-on laboratory exercises and project work, in-depth coverage of synchronization methods and discrete-time approaches to radio design, new simulation exercises, additional laboratory exercises, substantial new features to the software design tools, and refinements to the laboratories. These courses are training our students to meet the demand for this expertise in industry and government.

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