2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #38842

Considerations for software-defined radio use within a project-based learning subject

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Considerations for Software-defined Radio Use within a Project-based Learning Subject

Abstract

In this paper we reflect on the use of software-defined radio (SDR) within a project-based learning (PBL) subject at the master's level that incorporates a semester-long wireless communication design project. PBL as a pedagogy is an important tool for addressing disparities existing between the capabilities with which engineering students graduate and those demanded by employers. Ideally, it enables 'dual impact' activities in which both technical and professional skills can be developed concurrently. For the teaching of wireless communication systems, SDR has been the key enabling technology for a wider adoption of PBL pedagogies. SDR's use of programmable software frameworks and general-purpose hardware lowers the barrier-to-entry for students to model, implement, debug, and verify real-world communication systems. As with any example of PBL, when using SDR to meet intended learning goals it is important to give due consideration to key subject design characteristics such as project complexity and open-endedness.

The subject reported in this paper exists as an opportunity for students to integrate prior knowledge from overlapping areas in communication systems, signal processing, and embedded systems. As is common in the literature, for the design project we chose a spectrum challenge in which students optimize the performance of a secondary communication link while limiting interference to a primary user with priority spectrum access. We first give an overview of the pedagogical subject design, the chosen design project, and the software and hardware platforms employed. Drawing upon instructor observations and student self-reflections, we report on the positive outcomes and limitations inherent in the subject's design, highlighting important considerations when employing PBL to develop student capabilities in wireless communications. Among such considerations are a project's suitability for addressing theoretical and conceptual topics, the time required for students to upskill on SDR software and hardware tools, and the need to ensure students apply sufficient engineering rigor in their analysis and design of project solutions.

Introduction

Project-based learning (PBL) is an active pedagogy in which student learning is achieved through the completion of hands-on project work, and it has become an integral aspect of engineering curricula worldwide. This trend is largely a response to a perception that engineering students graduate with insufficient design experience, underdeveloped professional competencies such as communication skills and teamwork, and a poor understanding of the many societal contexts in which engineers must operate [1]. PBL is viewed as a powerful tool for addressing these needs, as project work is self-directed in nature, more reflective of an engineer's professional activities, requires the application of knowledge rather than its simple acquisition, and exercises professional competencies [1]. Unsurprisingly, PBL pedagogies are present in many engineering education reform efforts, such as the Conceive, Design, Implement, Operate (CDIO) initiative [2]. As the exact definition of what constitutes PBL is imprecise, a wide range of learning activities fall under the category with scopes ranging from small, single laboratory session practical work to large, multidisciplinary projects spanning multiple semesters. The distinctive feature of a PBL pedagogy is that students learn through doing.

For subjects related to wireless communications, software-defined radio (SDR) [3] has been the primary platform used to enact PBL pedagogies for some time. SDR as a technology emerged in the defense industry motivated by a need to concurrently support the myriad of existing radio standards. To do so, SDR implements as much signal processing as possible in easily reconfigurable software running on general purpose processors (GPP) rather than fixed-function hardware. This not only has the benefit of allowing a single platform to support multiple radio formats, but also drastically reduces design, development, and verification times as software development is generally easier than hardware design. This flexible architecture was recognized early on as a powerful tool for education [4], making it feasible for students to implement and experiment with communication algorithms through the writing of software. A diverse set of SDR software frameworks and hardware platforms exists, many of which have been employed in educational pursuits to individual advantage and disadvantage [5].

The range of learning activities in which SDRs have been deployed mirrors the breadth of PBL. This has included use in guided laboratories for wireless communication subjects [6] up to large capstone or senior design projects with a significant digital communications component [7]. Also common are extra-curricular design competitions which aim to promote research or educational objectives by having teams from different institutions compete to design the best performing system for a common problem statement. Spectrum challenges [8]-[11] have been a common format for such SDR design competitions for reasons that will be highlighted later. Such extra-curricular design competitions can be excellent learning experiences for those that participate but are generally not designed to meet specific learning outcomes.

In whatever context PBL strategies are employed, they require educators to carefully align teaching and learning activities with stated learning goals. Such strategies must balance project scaffolding that makes the task realistic for students to complete against a project's open-endedness that drives professional competency development. In this paper we share some insights around these considerations based on our experience in creating and delivering *Communication Design Clinic*, or *CDC*, a master's level PBL subject in which student teams compete in a semester-long spectrum challenge. We first give a brief overview of the subject's pedagogical design and its purpose within the context of our degree program. We then describe and analyze the design project employed in the subject for its amenability to meet stated learning outcomes. Finally, we provide discussion on both the successes and limitations of the subject design drawing on instructor observations and student self-reflections.

Subject Design

CDC is part of a seven subject *Communications and Networks* specialization within our Master of Electrical Engineering degree. A partial course structure of this specialization showing interdependencies among selected core subjects is provided in Figure 1. Here the 'clinic' nomenclature invokes the notion of a medical school clinical rotation, in which future doctors practice applying concepts learned in class through hands-on interactions with patients. The inclusion of CDC within the specialization has a similar aim, with the intention of giving students the opportunity to integrate and apply prerequisite knowledge, strengthen their design skills, and develop professional competencies required for project work. In this way, the subject can be viewed as a 'mini-capstone' for the specialization, although there is a separate year-long capstone requirement all students in the degree must complete. The clinic subject is seen as a crucial opportunity to give students project experience and formative feedback prior to their capstone projects.

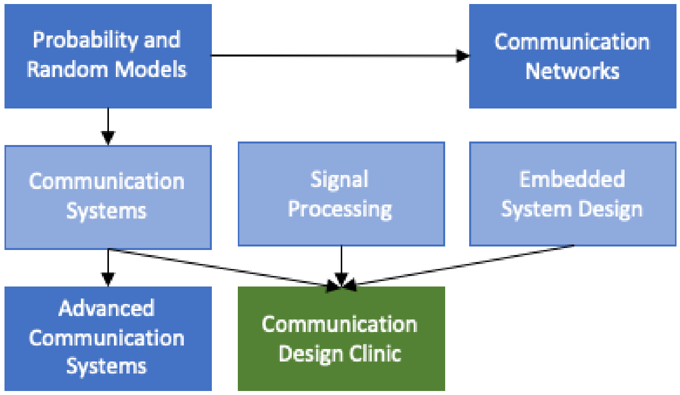

Figure 1: Core subjects of the Communications and Networks specialization within the Master of Electrical Engineering degree.

Intended learning outcomes (ILO) defined for the subject reflect a dual focus on technical and professional skills development. They state that upon completion of the subject, a student should be able to,

1. Apply established engineering design methodologies to assist in the design and implementation of communication systems and networks.
2. Analyse and devise solutions to communication systems and network design problems, drawing upon fundamental principles from areas such as embedded systems, signal processing, and communication systems.
3. Formulate appropriate models for predicting system performance and use to assess the relative merits of different communication techniques in achieving performance objectives.
4. Demonstrate competency with modern hardware and software frameworks for building communication systems and networks as well as an awareness of the broader context, implications, and applications of such technologies in society.
5. Apply systematic approaches to the conduct and management of a relatively complex electrical engineering design project in a small team.
6. Communicate effectively with professionals across different engineering disciplines, through media such as concise technical reports and informational videos.

ILOs 1-4 clearly emphasize technical knowledge and capabilities, with ILOs 2-3 placing a particular emphasis on engineering design skills. ILOs 5-6 cover the desired professional skills development we would like students to undergo in the subject. The inclusion of professional skills as explicit learning outcomes is a key distinction of the clinic subjects in our program. It implies these skills will be explicitly taught and assessed in the subject, which contrasts with other subjects in which such competencies are generic skills not formally addressed.

The focus of CDC is not on introducing new theoretical content to students but rather on giving students an opportunity to integrate and apply prior knowledge gained horizontally across different subjects and vertically over time. Most of student effort and assessment centers on completing a semester-long design project of considerable scope in self-selected teams of three or four members. Lectures and guided workshop activities are front-loaded in the first four weeks of semester to quickly upskill students on appropriate design methodologies and software and hardware platforms. The remainder of the twelve-week semester is then spent by the teams in independent project work, with regularly scheduled formative assessment to ensure teams progress their designs.

As indicated in Figure 1, there are three prerequisite subjects from which students are expected to draw prior knowledge and capabilities.

- *Communication Systems* – which covers the basics of digital modulation, optimal reception, performance analysis under AWGN conditions, and communications over bandlimited channels.
- *Signal Processing* – which introduces time- and frequency-domain representations of discrete-time signals, linear time-invariant dynamical systems, and the design of digital signal processing systems.
- *Embedded System Design* – which covers the modelling, analysis, and design of microprocessor embedded systems.

A more detailed listing of concepts covered in these subjects is provided in Table 1. To varying extent, the CDC project requires student teams apply or at a minimum comprehend all the concepts listed for the *Communication Systems* and *Signal Processing* prerequisites. Topics in *Embedded System Design* generally serve more as important contextual knowledge for the project, but a sizable design project completed in the second half of the subject serves as crucial prior experience with project work for CDC. Even though deep connections exist between these prerequisite subjects, many students fail to recognize these connections. This 'siloing' of knowledge is an artefact of the block structure in which students are exposed to the topics, i.e., in separate subjects they may assume to be unrelated.

Table 1: Concepts covered in CDC prerequisite subjects.

Communication Systems	Signal Processing	Embedded System Design
- Signal space representations - Baseband modulations - Passband modulations - PSK, QAM, and FSK - AWGN channels - Correlator and matched-filter demodulation - ML and MAP detectors - Probability of error analysis - Intersymbol interference - Pulse-shaping - Nyquist criterion - Linear equalization	- Sampling of analog signals - Frequency domain analysis using DTFT, DFT, and FFT - Design and analysis of FIR and IIR digital filters - Multirate signal processing, up- and down-sampling - Non-parametric spectral estimation	- Microprocessor architectures - Operating system concepts - Multitasking - Resource management - Real-time behaviors - Compilers and debuggers - FSM design

Notably, two specialization subjects are not prerequisites: *Communication Networks*, which covers the layered network architecture and network protocols, and *Advanced Communication Systems*, which covers channel coding, channel modelling, multicarrier modulation, and multiple antenna techniques. Both subjects are highly relevant for the CDC design project but were not made prerequisite for two reasons: to ensure students can take CDC prior to completing their degree capstones and to allow students not interested in the full *Communications and Networks* specialization to still gain design experience in the field. Interestingly, the balance of students in the first two cohorts of CDC was tilted towards students not in the specialization. It seems many students were keen for hands-on engineering design experience and often concurrently enrolled in other clinic subjects.

Assessment for the subject is in line with the PBL pedagogy employed with most major assessment closely tied to the design project. The first major project milestone is submission of a project plan that breaks down anticipated tasks, determines a provisional timeline for work completion, and outlines team protocols and procedures. A mid-project design review is conducted as an oral presentation and enables instructors to give important formative feedback on a team's technical approach and engineering analysis. The main assessment instrument for the project is a written report submitted at the end of semester, which is expected to thoroughly document the design solution in terms of analysis, implementation, verification, and performance. Students also complete a 1500-word written self-reflection at the end of the semester in which they contemplate their experiences completing the project in order to raise awareness of the underlying technical and professional skills they have developed.

A more detailed discussion of the subject and its sister clinic's pedagogical design can be found in [12].

Design Project – A Spectrum Challenge

Use of PBL requires careful project selection to ensure desired learning outcomes can be met. One important dimension for consideration is the complexity and open-endedness of the project, which directly impacts the balance of technical and professional learning outcomes for the students. A more complex and open-ended project will require students to spend more time on project management and self-directed learning, ultimately limiting their time for technical achievement. Such projects, however, are a better reflection of actual industry work and more fully develop professional skills. These latter characteristics align with ILOs 5-6, and so ideally the CDC project should be significantly open-ended and complex in nature. A large, open-ended project can also force students to employ a robust and repeatable process in their engineering design rather than fixating on getting a 'working' solution through ad hoc trial and error.

In the first two offerings of CDC the assigned project has been to design, implement, and test a communication link capable of operating in a dynamic spectrum access (DSA) scenario [13]. In DSA, a secondary communication link opportunistically utilizes the licensed frequency spectrum of a primary user so long as it sufficiently limits its interference to the primary link. In this way, the secondary link can take advantage of possible underutilization of the spectrum by the primary user in either temporal, spectral, or spatial dimensions. Although not a primary focus of CDC, the DSA scenario is also an excellent way to introduce the broader economic and regulatory contexts in which communication networks must operate. A typical setup for a spectrum challenge [8]-[11] is to have teams design and implement their own secondary communication link for a DSA setup and then compare their achieved performance in terms of a combination of performance metrics on the primary and secondary links. Spectrum challenges have been common as extracurricular design projects, but their inclusion within curriculum necessitates accounting for student prior knowledge and competencies.

The specific DSA scenario employed in CDC is illustrated in Figure 2 and is a simplified version of the IEEE DySPAN 2017 Spectrum Challenge [8]. A primary user (see Table 2 for a summary of parameters) operates in the 915 MHz ISM frequency band with a total available bandwidth of 2 MHz. The primary user divides its bandwidth into two consecutive 1 MHz channels, employing an independent OFDM waveform on each channel. On a given channel, the primary user transmits in 50 ms timeslots with the event of an active transmission in any given timeslot having probability p and being independent of transmissions in all other timeslots and channels. The primary user also periodically reports its achieved throughput to a central database that can be queried by the secondary link. The job of the secondary user at any given time is to decide, based on possible observations of the spectrum and statistics from the central database, the communication strategy it will employ. In this way, the possible design space for a secondary user is extensive. The performance of the secondary link is evaluated based on its achieved throughput and degradation caused to the primary link's throughput.

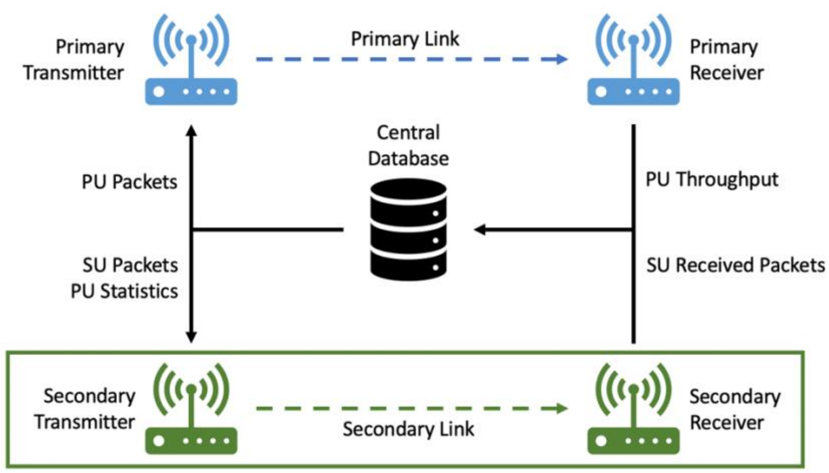

Figure 2: Dynamic spectrum access scenario that forms the basis for the CDC design project – a simplified version of [8].

Table 2: Parameters of primary link in CDC DSA scenario.

Parameter	**Value**
Center Frequency	915 – 928 MHz
System Bandwidth	2 MHz
Channelization	2x 1 MHz channels
Channel waveform	OFDM (1 MHz bandwidth)
Channel occupancy duration	50 ms

Within the DSA setup of Figure 2 there are four separate SDR nodes: a transmitter and receiver node for each of the primary and secondary links. The SDR hardware employed for all nodes in the network is the Nuand bladeRF 2.0 micro xA9 [14]. This board is built around the popular Analog Devices AD9361 RFIC found in several other SDR platforms and was chosen based on several important factors.

- At a price of USD 860 per unit, the relative affordability allows sufficient kits for all teams enrolled in the subject.
- A tunable center frequency from 47 MHz to 6 GHz covers the important 900 MHz, 2.4 GHz, and 5 GHz ISM frequency bands.
- Two transmit and two receive chains allow the possibility for multiple antenna techniques to be employed by highly motivated student teams.
- A sizeable FPGA with 301k logic elements, 13.9 Mb BRAM, and 342 DSP blocks that is programmable using freely available vendor supplied tools.

Taking the FPGA size and programmability into consideration runs somewhat counter to the SDR focus of the subject but was done in case future versions of the subject wish to include a digital hardware design component.

The software framework provided to students was GNU Radio [15], the most popular open-source tool for software radio. GNU Radio has an extensive library of existing components and applications that could be leveraged by students in their development. It also allows application and component development at different levels of difficulty depending on a user's expertise. At the most user-friendly level, the GNU Radio Companion (GRC) is a graphical tool for creating applications by configuring and connecting signal processing blocks in a block diagram. Intermediate users can quickly develop new signal processing blocks in Python or opt to spend additional time developing more computationally efficient signal processing blocks in C++.

GNU Radio was run on an Ubuntu virtual machine installed on laboratory computers accessible to students during workshop hours. The virtual machine image was also made available so that students could install the environment on their personal computers if desired. A functioning link based on the GNU Radio packet communication example was provided to students to serve as a baseline for starting their projects. Much of the time in the front-loaded lectures and guided workshops was spent familiarizing students with this baseline link from theoretical and practical perspectives.

Discussion

In this section we reflect on the positive outcomes and limitations inherent in the subject's design. We start by analyzing the design project in terms of stated learning outcomes and then reflect on important lessons learned. The first two offerings of the subject had limited enrolments so qualitative data on subject outcomes, such as end of semester student survey results, are expected to be unreliable and thus not reported here. Rather, insights are drawn from instructor observations and recurring themes in the self-reflections submitted by students. In general, students reported positive experiences with the subject, enjoying the project even if they were not able to achieve fully functional solutions. Common themes in self-reflections indicated an appreciation for the chance to interact with peers after the pandemic, learn from the different design approaches of their teammates, and increase confidence in their ability to practice as professional engineers. Some students did report frustration that they were not able achieve more functional solutions to the project.

Suitability of the Design Project for Learning Outcomes

A spectrum challenge was a well-suited project choice to meet the stated learning outcomes for several reasons. It required students to engage in self-directed learning to implement subsystems outside of their existing expertise. Traditionally, the prerequisite *Communication Systems* subject has dealt only with idealized theoretical models such as the AWGN channel. Common real-world impairments, including timing offsets, frequency offsets, and RF front-end impairments, have not generally been addressed. By requiring solutions be implemented on actual hardware, rather than simply in simulation, it was necessary for teams to design and analyze their solutions considering these practical concerns, e.g., creating or configuring subsystems for synchronization, etc. This is, of course, not just a benefit of a spectrum challenge but of any SDR project: the ability for relative newcomers in the field to quickly move beyond simulation and experience practical challenges. The spectrum challenge was also effective at forcing students to move beyond the physical layer, as dynamic spectrum access is by its nature a medium access control problem. This drove integrated learning between traditionally siloed subjects in the specialization. Self-directed learning on the topic was also necessary by many students because they had not yet completed the *Communication Networks* subject.

One reason spectrum challenges have been popular in extracurricular design competitions is the diversity of approaches afforded to develop an effective solution. This allows competing teams to produce unique and differentiated design outputs. As formulated, there are many (possibly overlapping) approaches to creating a workable solution for the CDC secondary link. A short sampling of possibilities includes:

- A simple energy detection subsystem controlling medium access of a single-carrier physical layer on one of the two OFDM channels.
- The use of OFDM on the secondary link for flexible spectrum usage based on the primary user’s current occupancy pattern.
- More advanced detection methods based on specific properties of the primary link’s signal, such as training sequences or cyclostationarity.
- Transmit beamforming to limit the spatial distribution of interference.
- Transmit power control along with rate adaptation to limit interference levels inferred from the primary user’s reported throughput.

From this short list we can see the project is very open-ended in nature. A key learning goal for CDC is that students develop a systematic approach to engineering design (ILO 5), a crucial component of which is dealing with high levels of uncertainty. This uncertainty arises when there is not one clear solution to the problem at hand. Although this situation is the norm for a professional engineer, it is quite foreign to our students at this stage in their careers. By encountering such an open-ended design problem, teams are forced to take a methodical review of possible approaches and make evaluations based on design criteria if they are to be successful.

Finally, the CDC design project is a twelve-week, semester-long endeavor and thus must be of sufficient scope to engage and challenge a team of three or four master's students for this duration. The spectrum challenge as modified was certainly of sufficient scope to do so. This was a result of multiple factors, including that students had to implement a real-world physical layer for the first time, needed to develop a baseline strategy for dynamically accessing the spectrum, and could make many possible optimizations based on the open-endedness of the approaches hinted at above. Projects of such scope can only realistically be addressed using a systems-based approach to manage complexity of the design process. Additionally, to be successful on a project of such size teams need to effectively plan, manage, and coordinated their efforts across the entire semester. Both capabilities are important components of the subject's learning outcomes, specifically ILO 5.

Limitations in Engineering Rigor

One of the main lessons learned from teaching CDC was based on an observed lack of engineering rigor in the solutions and analysis produced by the student teams. Teams often focused on 'hacking' a solution to get something working rather than following a methodical procedure, which may be attributable to outcome-focused assessment in previous subjects. Two thirds of teams (4 of 6) had workable solutions, but they generally had integration issues and limited their approach to using a simple energy detector and the baseline packet link on a single 1 MHz channel. Solutions had limited performance in terms of achieved secondary link throughput. A few teams (2 of 6) investigated more advanced approaches, such as the use of OFDM or multiple antenna techniques but did not progress beyond an initial investigation. In general, this was acceptable, as the primary focus of CDC is on the engineering design process employed and not the ultimate solution produced. This fact was reflected in the allocation of assessment points and was repeatedly emphasized to students. However, the instructors also observed, primarily through the design review and final report submissions, a lack of engineering rigor in the analysis and verification performed by the teams. This was confirmed in the self-reflections, as students commonly described their design approach as 'ad hoc' and felt that they struggled to determine a systematic approach for the project.

One major contributing factor to this lack of rigor was the scope of the assigned project. Even though they had been provided a baseline physical layer, student teams found it overwhelming to characterize and verify the link performance as well as research, implement, and verify a dynamic spectrum access strategy. As stated in the previous section, an open-ended and complex project was required for the subject, but obviously the balance between open-endedness and scaffolded student support was skewed too much in favor of the former. This issue was heightened by the project being the first substantial design experience for students in communication networks, as students had to spend considerable time mastering the basics of SDR which reduced the available time for design and analysis.

A few strategies will be employed in the next offering of the subject to better support the engineering rigor applied by students. To begin, Figure 3 shows the existing project solution path followed by students (blue) and a proposed modification (green). In the existing path, students are first heavily guided in familiarizing themselves with the SDR platform, the baseline link, and

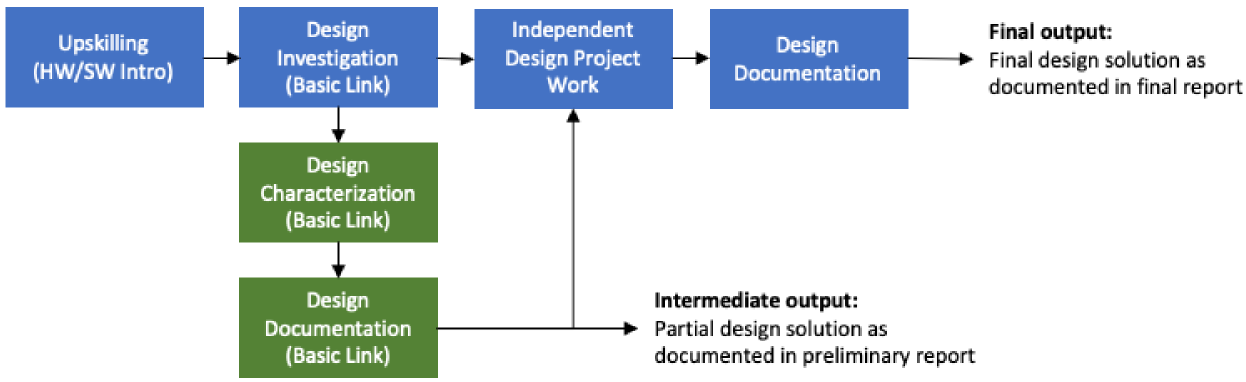

Figure 3: Existing (blue) and proposed extension (green) to CDC design cycle.

its subsystems. They then move on to independent project work where they must structure their own design cycle, culminating in documentation of their ultimate solution in a final report. In the proposed modification, the initial guided workshop sessions will be updated to place a far greater emphasis on following a design process. Teams will be guided to complete a short, initial design cycle in which they characterize and verify performance of the baseline link only, followed by documentation of the design in a preliminary report. This report will be an opportunity for instructors to provide formative feedback on expectations for the final report. It is anticipated that by leading students through a short but complete design cycle they will have a model process to follow in subsequent design iterations.

Many students enrolled in CDC also enroll in other PBL intensive subjects as they are eager for practical engineering work. PBL subjects are recognized as time consuming affairs, especially at the end of semester when assessment is due. Student reflections indicated major time conflicts with their capstone projects and other clinic subjects and that this limited what was achievable. They also reported their progress was accelerating at the end of semester. The assessment schedule in the next offering of CDC will be better coordinated with other concurrent PBL subjects to help students better manage their time. Finally, additional SDR laboratories have been independently introduced into the *Communication System* prerequisite. Future cohorts in CDC should already be familiar with the basics of SDR usage and thus will be able to allocate more time to engineering analysis and design rather than software and hardware upskilling.

Limitations of Software-related Skills

Based on our observations, another major reason for the limited achievement of teams was related to software issues. To begin, the cohorts had limited software development skills. As examples, Linux basics and object-oriented programming languages were not familiar to many students and took considerable time to learn. Software skills are not an explicit component of our degree and students enter our program from a wide range of institutions. An on-going initiative to study prior knowledge within our cohort should lend some insight into how we can better support students in developing these skills in CDC. The lack of software development capabilities in the cohorts meant that in developing their solutions many teams were limited to arranging and parameterizing existing signal processing blocks in GRC. Although it was possible to create a solution with such an approach it was limiting in what could be achieved.

The lack of software development capabilities also meant that whenever there was uncertainty about a particular block's functionality a team might not have the capacity to investigate the source code to better understand its theory of operation. This issue is compounded by the fact many GNU Radio blocks lack complete documentation and so source code inspection is particularly helpful. GRC itself was found to be an intuitive tool that could be quickly mastered by the students. However, it was observed that the convenience of a graphical development environment also limited the willingness of teams to develop their own block implementations that would be required for more complex solutions.

Finally, the primary development environment for students was an Ubuntu virtual machine running on lab-based computers. Students were able to install the same machine image on their personal computers and had access to the SDR hardware outside of scheduled workshop hours. Independent project work was a major expectation placed on students in the subject. Despite this fact, many teams viewed the weekly scheduled workshop sessions as the primary time dedicated to the project each week, but this was insufficient to develop a capable system. The next offering of the subject will hopefully drive more independent project work outside of workshop sessions by providing students with a convenient and portable development environment, such as one running on a single board computer.

Conclusion

A spectrum challenge incorporating an SDR platform proved an excellent choice for a semester-long design project around which to structure a wireless communications PBL subject. This suitability was largely due to the open-endedness and integrative nature of the project. Students participating in the subject generally reported positive experiences and learning outcomes even when they failed to achieve fully functional solutions to the project. However, instructors observed and student reflections confirmed a lack of engineering rigor in the design approaches undertaken by teams in the subject. The next subject offering will address this latter point by more heavily guiding students through a short design cycle iteration early in semester. Students will then be able to use this design cycle as a model on which to base their subsequent design iterations.

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