Instructional Strategies and Design for Immersive Wireless Communication Tutorials and Exercises

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Instructional Strategies and Design of Immersive Wireless Communication Tutorial Exercises

Abstract

This paper presents first steps towards development and assessment of a curriculum and tutorials built around hands-on exercises intended to introduce introductory and advanced concepts in wireless communications to current and future STEM professionals in a more effective way. We describe the motivation for the tutorials and our approach to designing and developing the tutorials, and provide a list of planned topics. Assessment results are provided for two tutorials, one of which included an exercise that employed CORNET, an Internet-accessible software-defined radio testbed at Virginia Tech. The tutorials were piloted with ten students in a graduate-level software-defined radio course. Based on these results we present conclusions and approaches for improving the initial tutorial exercise and tutorials and exercises to be developed.

1. Introduction

Motivation

Communications systems and techniques can appear abstract to students and STEM professionals. For example, introductory communications systems courses present a challenge to undergraduate electrical and computer engineering students who are accustomed to interacting with physical components such as power supplies, resistors, etc. These students must contend primarily with diagrams and equations, rather than hardware as they begin to study communications. Further, as ongoing changes to U.S. federal radio spectrum regulation distribute shared spectrum access to commercial and government users, operation in complex signal environments requires that both new graduates and experienced engineers who develop and implement new spectrum sharing techniques have appropriate training. Military operations outside the United States also require that radio systems operate in complex signal environments.

Low-cost software-defined radio (SDR) products such as digital video broadcast television (DVB-T) receiver USB dongles based on the Realtek RTL2832U controller and associated tuner chips (NooElec, 2017) provide potential for hands-on exercises, e.g., to demonstrate reception and demodulation of radio signals. However, because they are receive-only devices, these low-cost SDR units, if used alone, do not enable controlled experiments that include noise, interference, or signals from coexisting networks in addition to the signals to be demodulated.

Students in introductory courses should become familiar with concepts such as signal bandwidth and signal-to-noise ratio and may benefit from the ability to control as well as observe these parameters. Meanwhile, more advanced students and professionals are more likely to have adapted to the relative lack of experimental capabilities. Even so, these advanced learners would benefit from the ability to observe and create experimental scenarios as well as to develop or configure adaptive systems that can be evaluated experimentally. Remotely accessible wireless testbeds comprising multiple SDR transceivers enable such realistic experimentation.

Overview and Organization
Our objective is to teach and / or reinforce basic concepts in communications engineering as well as introduce recent research advances through asynchronous and real-time interactive experiences of otherwise-abstract phenomena and scenarios. To meet this objective, we are designing tutorials and hands-on, tesbed-enabled exercises that comprise remote laboratory, visualization, and game-like competitive or cooperative aspects.

In the remaining sections, we describe enabling technologies as well as the design, development, and initial implementation and assessment of tutorials that are intended to provide an immersive experience of otherwise-abstract concepts and phenomena for engineering students and professionals. Section 2 provides background on technologies that enable our work. Section 3 describes the approach to development of two types of tutorials, and briefly presents an example of each type in outline form. Section 4 describes implementation and assessment of one of these tutorials in a graduate SDR course, including assessment results. Section 5 is a discussion of conclusions and future steps to address issues encountered in the assessment.

2. **Background**

We describe instructional strategies and infrastructure that focus on wireless communications systems and enable development and evaluation of educational modules designed to make complex topics more accessible throughout academic and professional careers of STEM workers. These learning experiences are intended to be immersive, and include game-like, visually engaging tutorial exercises as well as asynchronous exercises in which participants program or configure autonomous radios and systems.

Gamification
One of the major hurdles to overcome in the education process is in teaching the computational processes involved in SDR technologies. A starting disparity exists between how machines are made to function and how humans reason **(**Kahneman & Tversky, 1979**)**. Studies show that humans perform terribly at a consistent rate on reasoning tasks in computational logic.

An instructional solution is necessary to resolve this disparity. One author who has studied the cognitive discrepancies concludes that biases in reasoning may be identified and mitigated through interactive decision aids (Evans, 2003; Evans, 2009). Games provide an interactive decision making environment to accomplish this. Games reinforce rational reasoning using gameplay experiences as medium for education. Serious games will also motivate and engage users (Gee, 2003), which can lead to improvements or mastery of class material, operationalized through their performance on quizzes and tests. Kimon Keramidas has suggested that what people learn in games can be used by teachers to enhance their teaching and better prepare students for technology-based society (2010).

Through the experiential process provided by these interactive experiences and subsequent augmentations to cognitive aspects such as self-efficacy, students may be guided by game-like experiences to adopt logical reasoning for the purpose of computation, better preparing them for working with SDR technologies. Hamari, Koivisto, & Sarsa suggest that gamification in education can work under the appropriate contexts, though more empirical research is necessary

(2014). It is therefore a worthy prospect to perform investigations of various game-like experiences using technologies crafted to simulate SDR operation and programming.

Self-Efficacy

Self-efficacy is a construct that functions as a component of motivational factors, defined as a subject's strength in belief of their capability of completing a task or goal (Ormrod, 2006). Self-efficacy is a well-grounded aspect of human cognition, having a demonstrated generality of operation in various fields including education (Schunk & Pajares, 2005). Within Bandura's social cognitive theory of human functioning, human motivation is more based on what an individual believes to be true rather than what is objectively true (Bandura, 1986). People will generally have less incentive to exert effort in addressing a task without the belief that they have the capacity to succeed. In this way, the failures of otherwise capable individuals may be explained. Studies suggest that self-efficacy powerfully influences academic task performances (Schunk & Pajares, 2005).

Infrastructure

The educational modules or tutorials are enabled by several technologies and will use specific instances of each as supporting infrastructure. The technologies that enable the hands-on exercises within the tutorials include software-defined radio (SDR), wireless communication testbeds, experiment management framework software for use with these testbeds, and web-based visualization and control environments. In addition, markup languages enable multimedia presentation of the tutorials to students.

Software-defined radio (SDR) is an approach to radio engineering that achieves great flexibility through rapidly programmable or configurable processing of digitized radio signals through use of analog-to-digital and digital-to-analog converters in combination with digital signal processing software or firmware running on microprocessors, field programmable gate arrays (FPGAs), or other flexible digital processing hardware. Several open-source SDR toolkits are available, including GNU Radio, REDHAWK, and IRIS (Radio, 2007; REDHAWK, 2017; Sanchez, Corley & Farrell, 2008). The exercises described here use liquid-dsp, a library of C-language functions for physical layer digital signal processing, due to its flexibility and ease of integration with C and C++ based software such as the CRTS software described below.

Wireless communication testbeds typically consist of multiple radios that are controllable via computers and that communicate over the air or through hardware and / or software-emulated channels. Examples of such testbeds include ORBIT at Rutgers University, the IRIS testbed at Trinity College, Dublin, Echo Ridge LLC's DYSE testbed (Echo Ridge, 2017; Sutton, et al., 2010; Raychaudhuri et al., 2005). The exercises presented here use CORNET (Newman, et al., 2010) an indoor testbed at Virginia Tech that allows operation over the air in several frequency bands that are licensed for experimental use.

Experiment management frameworks for wireless communications include the configurable management framework (OMF), initially developed for use with ORBIT, and others (Rakotoarivelo, Ott, Jourjon & Seskar, 2010). We use CRTS (Sollenberger, Romano & Dietrich, 2015) a framework that is able to measure throughput and other performance data for SDR-based radios that employ a highly configurable orthogonal frequency division multiplexed (OFDM) waveform. Configurable parameters include transmitting and receiving frequencies, transmitting power level, bandwidth, data rate, modulation type, error correction type, and OFDM sub-carrier allocation. This ensures relevance to operational systems while maintaining flexibility, since OFDM is used in prevalent communication systems and standards including WiFi and LTE.

Web-based visualization tools can provide a window into the radio frequency spectrum. The radio spectrum is digitized using SDRs in the testbed and displayed in a standard web browser, allowing students to observe the spectrum in real time. In addition to visualization, the web interface enables direct control of the OFDM waveform, using a standard software interface that could also connect the waveform with an autonomous controller. The visualization tool we employ, CORNET3D (Sharakhov, et al., 2014) interfaces with CRTS, which reports adaptation decisions made by radio operators or human radio operators, enabling the display to indicate frequencies used by specific radios. CORNET3D can also display performance metrics such as throughput and packet error rate (PER) as reported by CRTS.

Common markup languages such as LaTeX and HTML enable effective presentation of the tutorials that contain the hands-on exercises. The initial tutorials employ PDF documents produced using LaTeX, enabling links to multimedia content as well as a clean presentation of text and still images. However, in future editions, some of the tutorials may be HTML-based to enhance integration with the visualization tools. Students could then open the tutorial document and visualization tool in separate windows or tabs of a standard web browser application.

3. **Tutorials**

Audiences

The tutorials are intended to address the needs of two audiences: (a) Novice users (undergraduate students in introductory communication systems engineering and digital communications courses), who need to reinforce abstract concepts through demonstration and hands-on interaction; and (b) Advanced users (senior undergraduate students, graduate students, and mid-career STEM professionals) interested in learning and enhancing new technologies related to spectrum sharing and spectrum agile systems.

Tutorials developed for the first audience will also be available to advanced users to assist with review of fundamental topics as needed.

Topics

The introductory tutorials will illustrate concepts such as signal bandwidth, signal-to-noise ratio (SNR), and interference. (SNR), while the advanced tutorials will address topics that include spectrum sharing and cognitive radio, spectrum-sharing models, spectrum access systems and radio environment maps, and machine learning techniques for use in cognitive radio.

Tutorial concept, design, and development approach

Figure 1 depicts how tutorials employ the infrastructure described above. Students or STEM professionals modify radio controller code or controller configurations and / or manually operate radios using the web-based visualization tool. The radios themselves are located on an Internet-accessible SDR testbed, and operate within a signal environment generated using other radios on the testbed, controlled by CRTS. The radios report their adaptation decisions to the CRTS framework, which also measures and reports performance statistics of the radios to the student or other user via the CORNET3D web-based visualization tool.

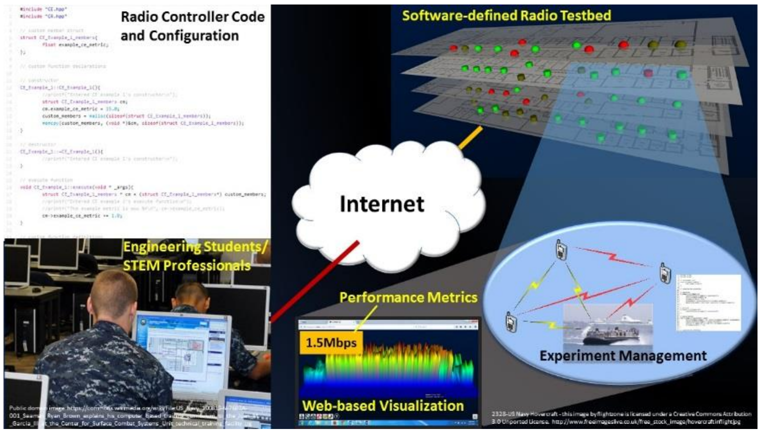


Figure 1. Tutorial concept, adapted from (Reference to be added for camera-ready paper)

Our design approach includes use of storyboards (Orr, Golas & Yao, K., 1994; Passerini & Granger, 2000) as well as spiral development (Boehm, 1988). The user interface / menu system in the web-based visualization, radio control, and performance monitoring application was developed based on storyboards, while the tutorials themselves are developed based on a spiral development / rapid prototyping approach. We have consulted briefly on a few occasions with instructional design experts, and plan to work more extensively with one of them as we develop additional tutorials and refine their format.

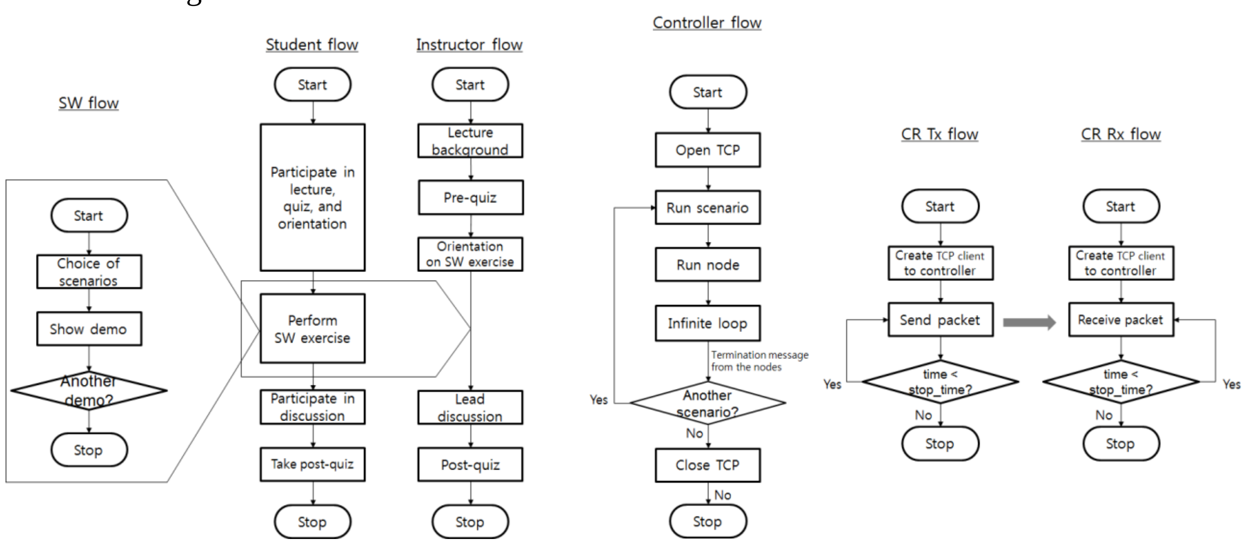
The first tutorial developed was an introductory tutorial on spectrum sharing and cognitive radio, developed for advanced users and its format was refined through repeated review, revision, expansion, and reassessment of an outline for the tutorial.

The first tutorial did not use the web-based visualization software, which was not in a suitable state at the time the tutorial was developed. While visualization is not the focus of the tutorial, it will be included when the software is available. Based on feedback from the assessment described in Section 4, addition of visualization is expected to enhance the user experience and may enhance the perception of “hands-on” interaction even when using remote resources such as the wireless testbed. A second tutorial was partially developed but the corresponding hands-on exercise was not ready for use during the assessment.

Example tutorial structure

Three documents are currently planned for each tutorial. A Developer’s Guide is a high-level document that ideally is independent of the infrastructure used in the tutorial, and provides guidance for use by future developers who may wish to re-implement the tutorial using their own software and / or hardware infrastructure. An Instructor’s Guide provides a lesson plan including a pre-quiz (for use only if assessing the tutorial), a brief slide presentation (coordinated with the quiz and suitable for stand-alone use or for use with the instructor's own slides), an orientation to the hands-on exercise, a discussion of the exercise, and a post-quiz that is identical to the pre-quiz. The tutorials are designed to fit within a 75 minute class period if using the pre- and post-quizzes in class, or within a 50 minute class period if the quizzes are administered out of class, e.g., as timed online activities. The Student's Guide contains an overview of the tutorial, and may include additional background information to supplement the slides as well as detailed instructions for the hands-on exercise, including screen shots where appropriate.

Figures 2 (a) and (b) present structure of a typical tutorial and a typical exercise. These flowcharts are included in all three of the documents described above, and serve to keep students oriented during the tutorial.



(a) (b)

Figure 2 (a) Structure of a typical tutorial, with flowcharts showing instructor, student, and software actions. (b) Structure of a hands-on exercise showing flowcharts for the experiment controller (part of CRTS) as well as two cognitive radios (CRs) that are part of the exercise.

4. Initial tutorial assessment

Self-efficacy

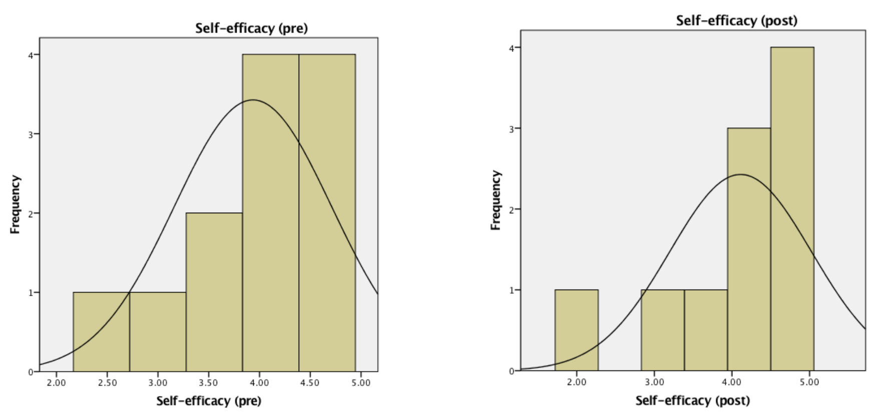
One of the goals of the tutorial suite being composed is to assess student perceptions of accessibility to the field of cognitive radio engineering. Translated into educational psychology terminology, this means assessing self-efficacy, which can be defined as "beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments" (Bandura, 1977). As part of a set of pre- and post-surveys created and conducted through Qualtrics software, a set of nine items adapted from the Motivational Strategies for Learning Questionnaire (MSLQ) (Pintrich & De Groot, 1990) were presented to students to quantitatively report their confidence regarding their future performance in and learning of cognitive and spectrum sharing radio communications. A mean score was calculated from an average of all items, which were 7-point Likert scale questions. Analyses of results from the survey were conducted in SPSS. It should be noted that the item pool for self-efficacy demonstrated a very strong level of reliability in measuring the construct. The Cronbach's alpha calculated for the measure was 0.872 in the pre-tutorial survey and 0.925 in the post-tutorial survey, which is considered good for statistical purposes.

Table 1. Descriptive statistics for self-efficacy

		Self-efficacy (pre)	Self-efficacy (post)
N	Valid	12	10
	Missing	0	2
Mean		3.9352	4.1111
Median		4.0556	4.3333
Std. Deviation		.77627	.91325
Skewness		-.741	-1.514
Std. Error of Skewness		.637	.687

Results from descriptive statistical analysis shows that, in comparison to responses to the same questions prior to participating in the tutorials, students in the trial class score higher on the self-efficacy scale after participating in the tutorials. When considering means of overall scores in self-efficacy for students that took both pre-tutorial and post-tutorial surveys, the mean of self-efficacy for the post-tutorial surveys (4.11) was higher than that of the pre-tutorial surveys (3.94).

As can be seen by the skewness statistics and the distributions in Table 1 and Figures 3 (a) and (b), the data appears to be non-normal. Additionally, the score difference distribution was similarly found to be non-normal, violating assumptions for the application of a paired samples T-test. To accommodate for this fault in using T-tests, a nonparametric Wilcoxon Signed-Ranks Test was conducted for self-efficacy, similarly yielding a report of statistical insignificance for $p < 0.05$ (Asymptotic 2-tailed significance was 0.332) with a Z value of -0.971 based on positive ranks from subtracting the post-tutorial scores from the pre-tutorial scores. This necessary deviation from paired samples T-tests largely results to the small sample available to conduct this initial analysis. Only 10 students participated in both the pre- and post-tutorial surveys such that the Wilcoxon Signed Ranks Test could compare their self-efficacy scores.



(a) (b)

Figure 3. (a) Histogram for pre-tutorial self-efficacy; (b) Histogram for post-tutorial self-efficacy

It is to be considered that the context of the delivery of these tutorials is based within a course that teaches advanced radio engineering topics, so it would be feasible to consider the potential of the intervention for less-informed participants. Near the end of a semester, students in a class will most likely feel more qualified to work on tasks based around the class curriculum than at the beginning of the semester. These tutorials being developed would ideally have been applied at an earlier point in the semester, and results may change were the tutorials to be offered then.

Tutorial and Exercise Responses

Questions in the post-tutorial survey also asked students about aspects of their impressions regarding the tutorials and exercises delivered. Items related directly to student impressions of the tutorials and exercises singularly measured distinct considerations including the clarity of tutorials, clarity of exercises, the level of usefulness of tutorials for completing exercises, the amount of learning students took away from tutorials, the likelihood that students would use the tutorials again, and whether or not the tutorials were necessary to completing exercises.

Table 2. Descriptive statistics for tutorial and exercise impressions

	N	Mean	Std. Deviation	Scale
Would you have been able to complete the exercises without the tutorials?	10	.90	.316	0 – Yes 1 – No
How much did you learn from completing the tutorials?	10	2.30	.675	0 – Nothing 4 – A lot
How useful were the tutorials in helping you to complete the exercises?	10	2.50	.972	0 – Not at all useful 4 – Extremely useful
How likely is it that you would use these tutorials in the future for a design project?	10	2.70	1.059	0 – Extremely unlikely 4 – Extremely likely
How clear were the directions for the tutorials?	10	2.80	1.033	0 – Extremely unclear 4 – Extremely clear
How clear were the directions for the exercises?	10	3.00	.816	0 – Extremely unclear 4 – Extremely clear

Descriptive statistics in Table 2 show that tutorials were widely considered necessary in order to complete the accompanying exercises. Student impressions regarding the clarity, the present and future usefulness, and the informative nature of the tutorials and exercises were moderate overall with consideration to their particular scales. These scales are also displayed in the table for transparency.

A Pearson correlation analysis showed measures of the tutorials' usefulness to performing exercises and the clarity of tutorials and exercises have a statistically significant correlation with self-efficacy as measured in the post-tutorial survey. The Pearson correlation with self-efficacy were 0.696 ($p < 0.05$) for levels of usefulness of tutorials to exercises, 0.772 ($p < 0.01$) for clarity of directions for tutorials, and 0.778 ($p < 0.01$) for clarity of directions for exercises. Also, the usefulness level between tutorials and exercises correlated strongly with clarity of directions for tutorials (0.775, $p < 0.01$), clarity of directions for exercises (0.700, $p < 0.05$), and likelihood that tutorials would be used in future projects (0.917, $p < 0.01$).

Measures of clarity for the material especially demonstrate a significant importance towards building self-efficacy. Clarity of instructions not only affects the impression of the tool for students, but also ensures appropriate application of learned principles and techniques. Through such application during exercises, students may feel more competent in the subject matter and bear greater self-efficacy as a result. The accomplishment of tasks while learning serves as a "mastery experience", which is integral to development of self-efficacy (Bandura, 1986). Effective tutorials and exercises will follow from one another in such a way that students observe how they are applying their new knowledge to solve problems. This principle shall guide further development of tutorials and exercises moving forward.

Usefulness of tutorials in completing exercises is similarly connected to self-efficacy, while also correlating with clarity of tutorials and exercises. It serves as a general indicator of a student's perceived ability to apply one segment of the intervention to the other. Clarity, as described above, plays an important role in conveying the usefulness of instruction to students, as does the amount that students perceive learning. The students' likelihood to employ the tutorials for future projects very strongly correlated to the usefulness of the tutorials for the exercises, as well. Where the tutorials apply to exercises, the students seem to believe that they would also be applicable to other practical tasks. This very strong correlation suggests that exercises may be recognized as being practical and realistic if the tutorials' applicability to them extends beyond the classroom. If this were the case, then it will be important to ensure that exercises for additional tutorials reflect real scenarios in radio engineering. One motivational aspect within Expectancy-Value Theory is the idea of utility value, which serves to motivate learners to engage in learning tasks (Eccles, 2005). Nurturing a sense of utility for the tutorials may then motivate students as they progress in a full suite of tutorials.

Table 3. Descriptive Statistics for Quizzes

		PreT1	PostT1	PreT2	PostT2
N	Valid	8	8	8	5
	Missing	0	0	0	3
Mean		70.3125	82.0313	68.4125	84.0000
Median		75.0000	84.3750	77.5000	80.0000
Std. Deviation		19.97487	6.19395	26.32399	16.73320

As shown in Table 3, mean and median scores for students participating in the tutorials increased after each tutorial was conducted. Variability in these scores also appeared to narrow as a result of the intervention. However, results from Wilcoxon Signed Ranks tests showed that no statistical significance could be reported, yielding Z values of -1.611 for PostT1-PreT1 and -0.271 for PostT2-PreT2, both based on negative ranks (PostTX < PreTX). The asymptotic 2-tailed significance factors were 0.107 and 0.786 respectively for Tutorial 1 and Tutorial 2.

The non-parametric method of statistical analysis for comparing the quiz scores was considered in place of a paired samples T-test due to the very small sample size that could not yield a normal distribution of quiz score differences to be considered valid. Due to this small sample size, these findings do not prove one way or another whether or not the tutorials were successful in improving understanding of cognitive radios. It is expected that, with larger samples of students in future iterations of this work, more definitive results will follow.

Qualitative Feedback

The survey provided students with the opportunity to provide free-form feedback for the tutorials and exercises.

When asked for suggestions to improve clarity and overall effectiveness of the tutorials and exercises, some students solicited crucial feedback. Possible ways to improve upon tutorials included presenting more visual and direct demonstrations of material, such as showing "real data and experiments" or "visualization" of controller interactions over a radio network, with TX and RX signals. According to the students, exercises could benefit from the inclusion of videos, "step-by-step instructions and explanations", and a prepared listing of files for configuration during the exercises. A common thread of technical issues students took with the exercises was the lack of factual data presented, which may have obscured the process and outcome of the activities.

The survey asked students what they liked and disliked the most about the tutorials and exercises. Perhaps as would be hoped for an interactive instructional approach, students appreciated using the radio programming system and network to learn about cognitive radios. One aspect that students suggested they did not like about the exercises was a "lack of hands-on experience" as a result of the tutorials. Considering that students interacted with a real system during the exercises, understanding what this means in context is difficult. One hypothesis is that students may prefer to have direct access to radio devices and be able to probe them while programming and operating them.

Depending on resources and time available, direct access to software-defined radios may not necessarily be a practical change for the tutorials. Nevertheless, the desire for students to have more direct access to software-defined radios for study may be something to keep in mind. A direct interaction with equipment may aid students in alleviating some ambiguities of the processes the exercises ask them to undergo. With less ambiguity, it may be possible that self-efficacy improves as a result by helping students feel they were in control of the equipment and mastering the material.

Other constructive negative feedback for the tutorials included a lack of visual information in describing content or scenarios. A lack of organization and detail in the documentation, possibly leading to wasted time during class, also appeared among students' remarks. Greater inclusion of visual information may provide additional clarity to documentation as well as the outcomes of exercises. Organization and an understanding of common details that required elaboration in class will similarly inform improvements to existing and future tutorials to improve clarity as well.

5. Conclusions and future work

We have described initial efforts to develop and assess immersive tutorials for novice and advanced wireless communication engineering students and professionals that include hands-on excercises enabled by an SDR based testbed and associated software. Initial assessment showed improvements in quiz scores after exposure to the initial tutorials; however the improvements are not significant. Self-reported student self-efficacy also improved slightly but not enough to be statistically significant with the small sample size (N=10) that was available for the initial assessment. Qualitative feedback indicated that some students did not perceive the experience as "hands-on," and would have liked more visual information in the tutorials and exercises.

The tutorial formatting and presentation will be refined as the remaining tutorials are developed and assessed. We plan to include the web-based radio spectrum visualization, radio control, and performance monitoring application in most or all of the exercises, including those for advanced users, and to increase the number of diagrams and images in the Student Guide documents or HTML pages, to address the perceived lack of visual information and hands-on experience. Additional assessment will involve larger classes at the institution where the tutorials are being developed, and is expected to involve faculty and possibly students at additional institutions.

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