Interactive Introductory Online Modules on Wireless Communications and Radio Frequency Spectrum Sharing

1. Introduction

The demand for wireless data transmission capacity is increasing rapidly and this growth is expected to continue due to ongoing prevalence of cellular phones and new and emerging bandwidth-intensive applications that encompass high-definition video, unmanned aerial systems (UAS), intelligent transportation systems (ITS) including autonomous vehicles, and others. Meanwhile, vital military and public safety applications also depend on access to the radio frequency (RF) spectrum. To meet these demands, the US federal government is beginning to move from the proven but inefficient model of exclusive frequency assignments to a more-efficient, spectrum-sharing approach in some bands of the RF spectrum. A STEM workforce that understands the RF spectrum and applications that use the spectrum is needed to further increase spectrum efficiency and cost-effectiveness of wireless systems over the next several decades to meet anticipated and unanticipated increases in wireless data capacity.

2. Background

CISCO Systems' annual survey [1] indicates continued strong growth in demand for wireless data capacity. Meanwhile, undergraduate electrical and computer engineering courses in communication systems, electromagnetics, and networks tend to emphasize mathematical and theoretical fundamentals and higher-layer protocols, with less focus on fundamental concepts that are more specific to RF wireless systems, including the physical (PHY) and media access control (MAC) layers of wireless communication systems and networks. An efficient way is needed to introduce basic RF system and spectrum concepts to undergraduate engineering students in courses such as those mentioned above who are unable to, or had not planned to take a full course in RF / microwave engineering or wireless systems and networks.

Over a decade ago Katz and Flynn developed and used tutorials [2] based on the GNU Radio open-source software-defined radio (SDR) toolkit [3] and GNU Radio Companion (GRC) [4] to teach and reinforce introductory material on communication systems including analog modulation and demodulation. More recently, many SDR-based labs have been developed and made available by the GNU Radio community [5] and by others, e.g. [6]. These include tutorials focused on use of specific software or hardware as well as some more general tutorials. Reference [7] describes a variety of approaches for use of SDR in education.

To promote interactive in-person and online learning [8], we have developed a series of learning modules that introduce concepts fundamental to wireless communications, the RF spectrum, and spectrum sharing, and that seek to present these concepts in context. The modules include interactive, JavaScript-based simulation exercises intended to reinforce the concepts that are presented in the modules through narrated slide presentations, text, demonstration videos, and external links. Additional modules in development will introduce advanced undergraduate and graduate students and STEM professionals to configuration and programming of adaptive frequency-agile radios and spectrum management systems that can operate efficiently in congested RF environments. Simulation exercises developed for the advanced modules allow both manual and automatic control of simulated radio links in timed, game-like simulations.

Some of these exercises will enable students to select from among multiple pre-coded controller strategies and optionally edit code to control transmission parameters for simulated radio links before running the timed simulation. This provides a very flexible environment for experimentation by students.

Additionally, we have developed infrastructure for running remote laboratory experiments that can also be embedded within the online modules, including a web-based user interface, an experiment management framework, and software defined radio (SDR) application software that runs in a wireless testbed initially developed for research. Although these experiments rely on limited hardware resources and introduce additional logistical considerations, they provide additional realism that may further challenge and motivate students.

The project builds on experience from a cross-institutional collaboration that resulted in proof-of-concept game-like remote laboratory exercises and initial slides. The "serious game" concept as well as some of the lecture slide material are being integrated into a series of online learning modules.

3. Online learning resources

We are working to develop robust open-source software to enable the remote laboratory exercises, and producing online learning modules and short courses that include interactive simulations and will include remote laboratory exercises or mini-projects as well as lecture and demonstration videos and pre- and post-quizzes for automatic assessment of student learning.

Initial versions of three out of five planned short courses are complete or in progress (approximately 60% of planned lecture materials). Professional software developers and subject matter experts continue to develop software to support interactive simulations and remote laboratory exercises. Courses to date comprise over 300 lecture slides for inclusion in videos as well as demonstration videos produced using a wireless testbed, experiment management system, RF spectrum visualization tool, the liquid-dsp signal processing library, and the GNU Radio open source SDR toolkit. The current courses include interactive simulation exercises. Remote experiments that use radio hardware in the testbed will be integrated into selected courses as an option once the enabling software has been made sufficiently robust and scalable.

The PIs have piloted the current version of the interactive online learning modules with approximately 100 undergraduate and graduate students. The materials were delivered using the Canvas learning management system. The interactive simulation exercises used in the modules were embedded in HTML pages within Canvas using iframes. Statistical analysis of student responses to pre- and post-surveys and scores on pre- and post-quizzes for the online modules indicated statistically significant increases in student performance and self-reported knowledge of topics addressed in the modules. Additionally, we have received positive anecdotal feedback from those who have seen and used the materials.

3.1 Course topics

Online courses developed to date include the following:

Course #1: *Fundamental Concepts for Wireless Communications (FCW)*, including

- High-level view of Physical layer communications including transmitters, receivers, and their subsystems as well as channels and signals
- Information capacity of a wireless channel and factors that limit this capacity
- Decibels and link budgets

Course #2: *Introduction to the Radio Frequency Spectrum and Spectrum Management (RFS)*, including

- Frequency-domain representation of signals
- Radio resources, transmission parameters that can be changed to adapt to varying RF environments, and measures of radio link performance
- Software-defined radio (SDR)
- Spectrum Sharing, Spectrum Access Systems, and overview of the related military concepts Electromagnetic Battlespace and Electromagnetic Maneuver Warfare

We have also developed some of the planned materials for the following courses and expect to make these available to the public as CEU courses by late 2021:

Course #3: *Methods for Smart Control of Spectrum Agile Radio Frequency Systems*, including

- Rule-based adaptation
- Machine-learning / statistical methods
- Knowledge-based artificial intelligence methods

Course #4: *Controller Implementation for Spectrum Agility*

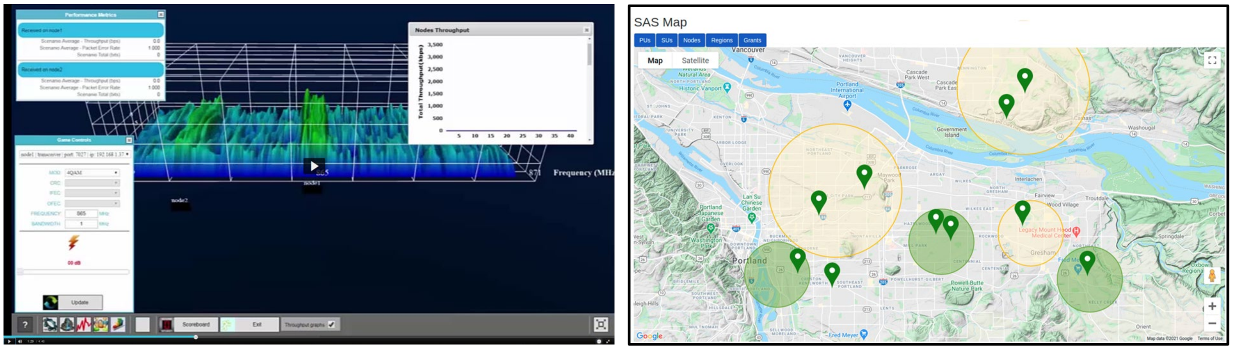
- Application of methods from Course #3 to control frequency-agile radio links in challenging and congested RF environments

Course #5: *Dynamic Radio Spectrum Management*

- Application of methods from Course #3 to dynamic frequency assignment in challenging and congested RF environments

3.2 Course content

Course content in Canvas includes a combination of narrated slide presentations, text notes that provide details or clarification of specific topics, and links to external resources as well as in-line demonstration videos and interactive simulations produced by the course development team, with interactive remote-lab exercises to be added pending software development to enable robust implementation of the exercises and scheduling of testbed resources.



(a) (b)

Figure 1. (a) The online modules include a demonstration of the effects of interference, shown using SDRs and 3-dimensional RF spectrum visualization. (b) The map view of the open-source spectrum access system (SAS) that will be used in the later modules.

3.2.1 Demonstration videos

Demonstration videos include a frequency-domain view of a signal, developed using the GNU Radio software running on a testbed server. Fig. 1a shows a demonstration of the effect of interference on a RF link and was produced using an experiment management framework, RF spectrum visualization application with updates to enable interactive control and monitoring of radio links, and computational and software defined radio (SDR) resources from the wireless testbed. Fig. 1 b shows a map view in the user interface of an open source spectrum access system (SAS) that will be used in later modules.

3.2.2 Interactive simulations

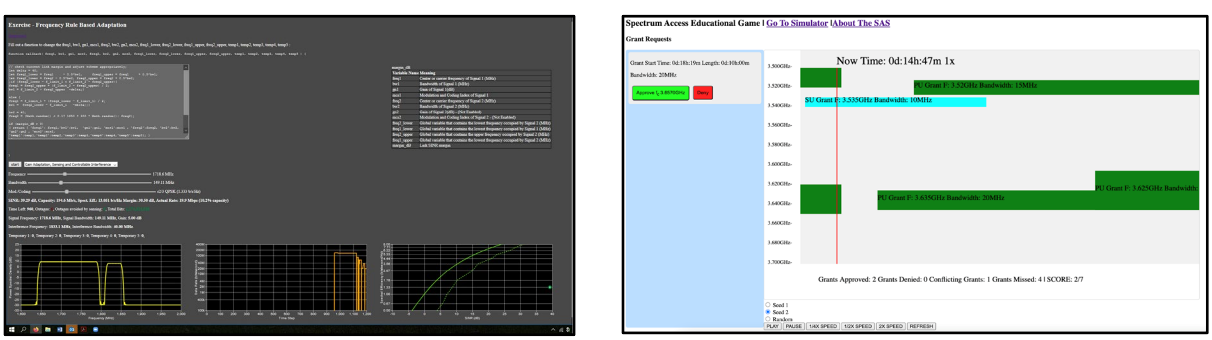
Interactive simulations can be used from within the Canvas modules or independently, and are being developed using HTML, JavaScript, SVG, and the d3 JavaScript graphical library [d321] to provide interactive control and visualization of radio signal parameters and their effects. Students interact with the simulations using sliders, draggable markers, menus to select parameter adaptation strategies, and in the more advanced exercises, code to implement the adaptation strategies that can be edited by students within a text box embedded in the simulation web page. The simulation code runs on the client device and includes all required libraries so that all simulations can be downloaded for offline use, an approach that is inherently scalable and also suitable for students who primarily work in environments that do not have Internet access.

Topics addressed in the exercises that have been developed to date include the following:

1-4. Signal parameters and effects in the time and frequency domains
- Frequency
- Gain / Amplitude
- Bandwidth
- Frequency, Gain / Amplitude, and Bandwidth

5. Logarithmic vs. linear magnitude scale in a frequency domain display

6. The effect of nonlinearity or compression, e.g., in an amplifier, on a signal in the time and frequency domain
7. Interference between two signals when the overlap in frequency, and its effect on information capacity; the effect of the interference is assumed to approximate that of additive white Gaussian noise (AWGN)
8. Free-space path loss between two radios; the student can move markers that represent the radios on a two-dimensional grid and vary the frequency, and the radios' antennas are assumed to have 0 dBi gain at all frequencies
9. Interference in a free-space path loss environment with two co-channel transmitters and one receiver; the student can move markers that represent the radios on a two-dimensional grid
10. Information capacity in an AWGN channel for a signal whose amplitude, bandwidth, and modulation and coding scheme (MCS) can be controlled by the student
11. Spectral efficiency vs. signal-to-noise ratio for a signal that has user-controllable bandwidth
12. Timed, game-like simulation in which student adjusts modulation and coding strategy (MCS) to maximize number of bits transmitted in a noise-limited environment using a signal that varies in amplitude and bandwidth*
13. Timed, game-like simulation in which student selects from among pre-configured MCS adaptation strategies and optionally edits the code or provides new code to maximize the number of bits transmitted in a noise-limited environment using a signal that varies in amplitude and bandwidth*
14. Manual adaptation of signal transmission parameters (frequency, amplitude / gain, bandwidth, and MCS) to maximize data throughput while operating in a band of frequencies that is also used by another, frequency-hopping signal
15. Rule-based adaptation using user-selectable strategies for adapting transmission parameters to maximize data throughput while operating in a band of frequencies that is also used by another, frequency-hopping signal
16. A timed, game-like simulation using user-selectable and user-editable, pre-configured, rule-based strategies for adapting transmission parameters to maximize data throughput while operating in a band of frequencies that is also used by another, frequency-hopping signal, shown in Fig. 2 (a)
17. An additional simulation in which the student plays the role of a spectrum access system (SAS) and approves or denies requests for spectrum access grants, shown in Fig. 2 (b).



(a) (b)

Figure 2. (a) Spectrum-sharing simulation with user-programmable radio link adaptation. (b) Spectrum access system (SAS) simulation.

3.2.3 Remote laboratory exercises

Remote laboratory exercises are also under development. Figure 4 shows two such exercises. In the first of these, a student controls the amplitude, bandwidth, and frequency of a signal and can observe increases in out-of-band frequency content as the amplitude is increased, causing the amplifier to saturate. In the second remote-lab exercise, a student controls transmission parameters for a radio link in the presence of one or more other signals that share the same RF band.

4. Evaluation methodology

The first two courses developed have assessment systems and surveys in place to allow measurement of student performance and confidence with the material. This gives the research team the ability to evaluate the courses' effectiveness in realizing their learning objectives.

4.1 Surveys and quizzes

Each set of modules that comprise a course is preceded and followed by a survey. Each individual module is preceded by a quiz and followed by another quiz, with pre- and post-quiz questions drawn from the same pool. Each of these quizzes is formatted with multiple choice or matched pairs questions, allowing for automatic calculation of quiz scores without manual grading. There are four sets of pre- and post-quizzes for each course making up a total of 16 quizzes across both courses. The pre-surveys allow students to opt in or out of having their survey and quiz results used anonymously in research. They also asked students to rate their knowledge of course topics before and after completing the courses. In total, there are two pairs of pre- / post-surveys, one for each course, resulting in a total of 4 surveys across the two courses.

4.2 Student samples

Release of data for analysis was optional for all sampled groups. Within distinct samples, the number of valid participants tended to decrement by some amount between the first and last section of each course. The initial modules have been used by three groups of students: (1) students in an undergraduate Introduction to Communication Systems course; (2) an interdisciplinary group of engineering students, including computer science students, who are participating in a related undergraduate research project; and (3) students in a graduate-level communications course that includes both electrical and computer engineers. These groups shall be referred to respectively as Group 1, Group 2, and Group 3 hereafter.

Group 1 participated in only the FCW course with a range of $N = 46$ to $N = 44$. Groups 2 and 3 participated in both the FCW and RFS courses. Group 2 had a range of $N = 25$ to $N = 14$ across both courses. Group 3 had a sample size of $N = 16$ for all of the FCW course and $N = 13$ for all of the RFS course.

4.3 Data analysis

Comparative analyses were performed within Group 1 as well as within and between Group 2 and Group 3 for performance improvements and comparisons for pre- and post-quizzes. Group 2 and Group 3 data from surveys were also compared similarly. Paired samples t-tests compared data collected within groups to determine statistical significance while independent samples t-tests compared data between Group 2 and Group 3 as a juxtaposition for undergraduate and graduate learning outcomes from the coursework. All data were compiled and analyzed in SPSS. Comparative analyses used $p < 0.05$ as the threshold for determining statistical significance.

5. Results

Analysis of results from Group 1 showed statistically significant performance increases from pre-quiz to post-quiz for each of four modules on fundamental wireless communication concepts. Group 2 and Group 3 similarly showed significant improvements in performance and knowledge rating for material across both courses.

5.1 Surveys

Both surveys for each course ask for knowledge ratings (from 1 to 5, with 5 being the most positive rating) on key aspects of their respective course's subject matter. In association with response codes as presented, the questions were:

- FCW_Wireless: "Rate your level of knowledge of wireless communication links on a scale of 1-5 as of right now."
- FCW_Channel: "Rate your level of knowledge regarding channel capacity on a scale of 1-5 as of right now."
- FCW_Db: "Rate your level of knowledge of decibels and how to calculate with them on a scale of 1-5 as of right now."
- FCW_Limit: "Rate your level of knowledge of factors limiting a wireless link's performance on a scale of 1-5 as of right now."
- RFS_Freq: "Rate your level of knowledge of frequency-domain representations of signals on a scale of 1-5 as of right now."
- RFS_Radio: "Rate your level of knowledge of radio resources and metrics on a scale of 1-5 as of right now."
- RFS_SDR: "Rate your level of knowledge of software-defined radio on a scale of 1-5 as of right now."
- RFS_SAS: "Rate your level of knowledge of spectrum sharing and spectrum access systems on a scale of 1-5 as of right now."
- RFS_CR: "Rate your level of knowledge of cognitive radio on a scale of 1-5 as of right now."

Data for surveys were collected from Group 2 and Group 3. Descriptive statistics and comparative statistics within and between samples from these two groups are presented below. Delta values for descriptive statistics and comparisons between the two groups are calculated based on differences found by subtracting ratings of pre-surveys from post-surveys. Sample sizes represent only the number of students that participated in both the pre- and post-survey.

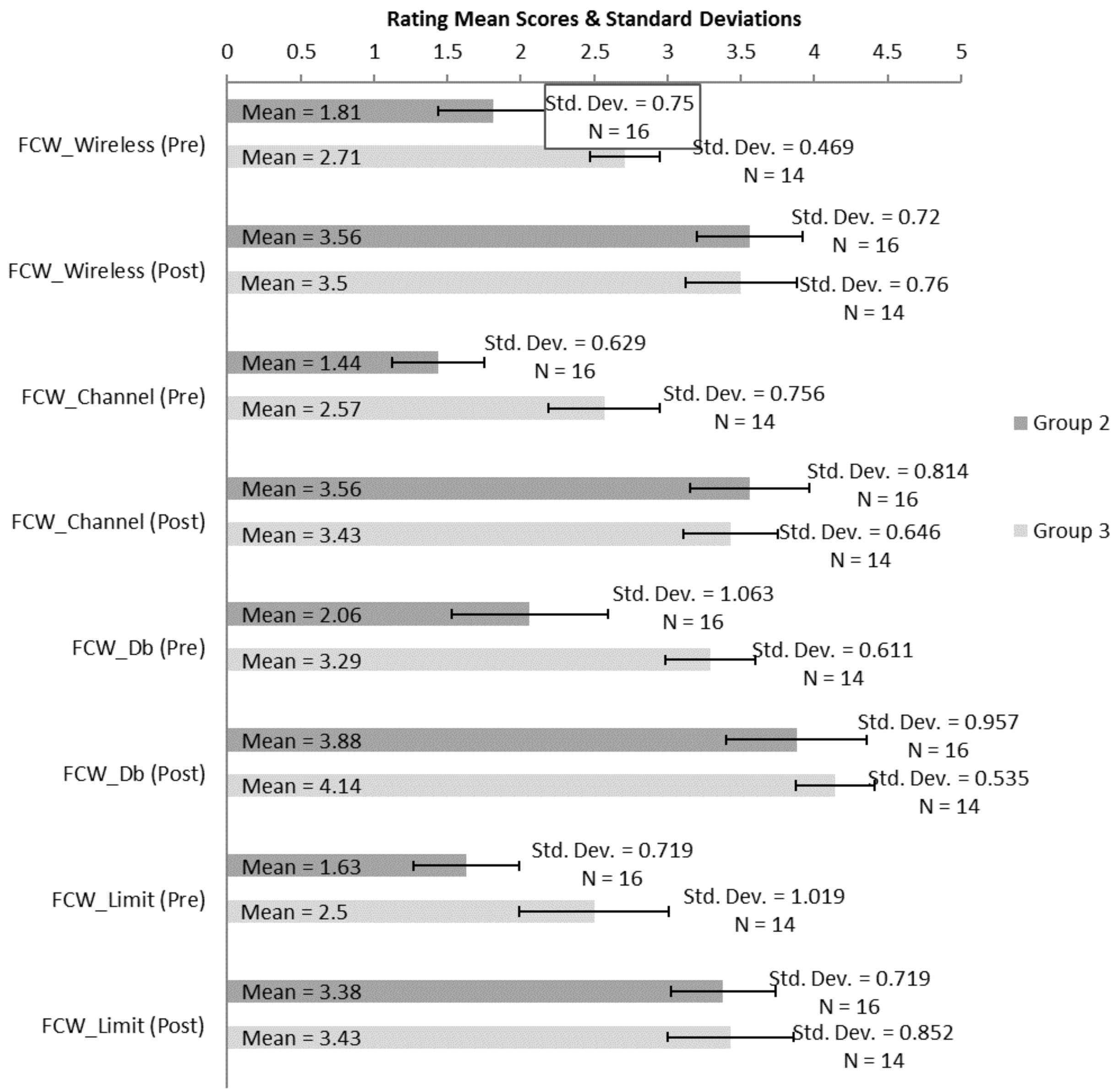


Figure 3. Descriptive statistics for FCW surveys - Groups 2 and 3

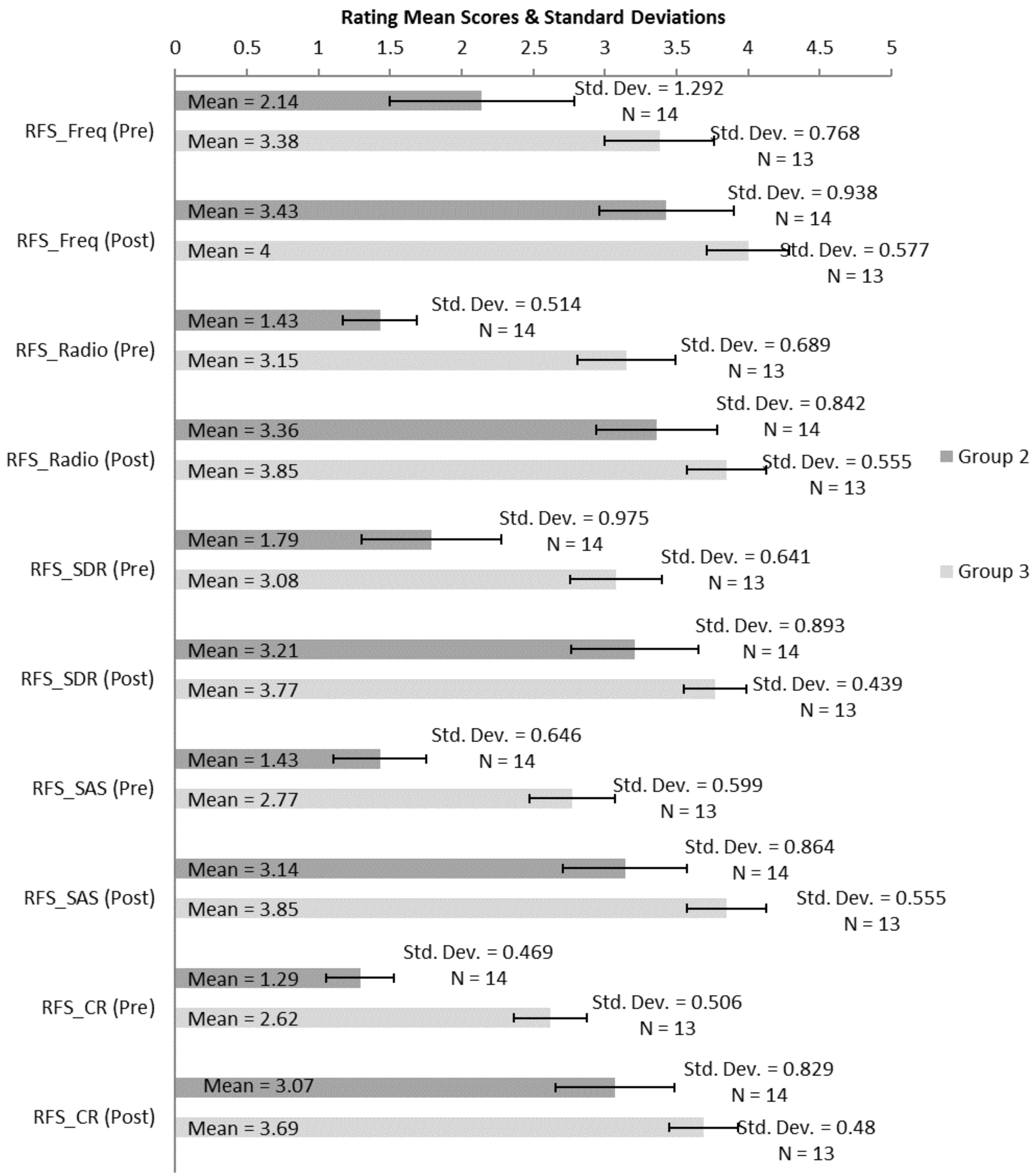


Figure 4. Descriptive statistics for RFS surveys - Groups 2 and 3

Table 1. Across-group independent samples t-tests for surveys (Group 2 - Group 3)

Rating (∆Means)	t	df	∆Mean Difference	Two-tailed significance
FCW_Wireless	3.169	28	.96429	.004
FCW_Channel	3.957	28	1.26786	.000
FCW_Db*	2.468	22.204	.95536	.022
FCW_Limit	2.536	28	.82143	.017
RFS_Freq	2.519	25	.67033	.019
RFS_Radio	4.051	25	1.23626	.000
RFS_SDR	2.537	25	.73626	.018
RFS_SAS	2.083	25	.63736	.048
RFS_CR	2.213	25	.70879	.036

*Equal variances were not assumed for this result based on Levene's Test.

For both groups and across both courses, participants felt they were more knowledgeable of the subject matter having gone through the modules. Every significance test overwhelmingly favored the hypothesis that knowledge ratings improved from the point before starting the course to the point after the course was completed ($p < 0.05$). This demonstrates a subjective improvement that could correlate positively with self-efficacy and other attitudes about the difficulty of the material.

With respect to the changes in knowledge ratings, Group 2 had greater gains than Group 3 by a significant margin for both modules ($p < 0.05$). This may be explained in part by the awareness of graduate students regarding the subject matter to come, given their higher pre-survey ratings than that of the undergraduates. Based on the means for the post-survey ratings, Group 2 participants did not appear to experience such a surge in their knowledge that they differed in an obvious way from where Group 3 was upon both groups completing the post-survey, so the low starting point is the main contribution to the observed differences in rating changes.

5.2 Pre- and post-quizzes

Descriptive statistics shall be provided for quiz scores. Quizzes are scored out of total that are presented in Table 11 below as a reference for the objective level of performance the statistics convey. These quiz score maximums apply for both pre-quizzes and post-quizzes for the units indicated, and the quiz score values reported in the following analyses are percentages of the respective total score possible instead of raw scores.

Table 2. Total score possible for each quiz set

Quiz	FCW-01	FCW-02	FCW-03	FCW-04	RFS-01	RFS-02	RFS-03	RFS-04
Total	27	16	14	15	5	11	6	12

Data for Groups 1-3 have been analyzed with percentage-normalized statistics and tests for their FCW quiz scores summarized in Fig. 5. P-values calculated from paired samples t-tests and were all less than 0.05, showing statistically-significiant pre-quiz to post-quiz improvements for all groups. Group 2 and Group 3 were scored for modules from both courses, and statistics for their RFS quiz scores are summarized in Fig. 6.

Delta values for descriptive statistics and comparisons between Groups 2 and 3 are calculated based on differences found by subtracting scores of pre-quizzes from those of the post-quizzes and, in the case of delta means, using the mean differences from paired samples only. This means that, for cases of varying sample sizes between pre-quizzes and post-quizzes, there may be discrepancies between the apparent difference of means as calculated for a particular quiz case and the delta mean calculated for the paired samples significance calculation because not all of the larger sample will compose the effective mean that determines the delta mean.

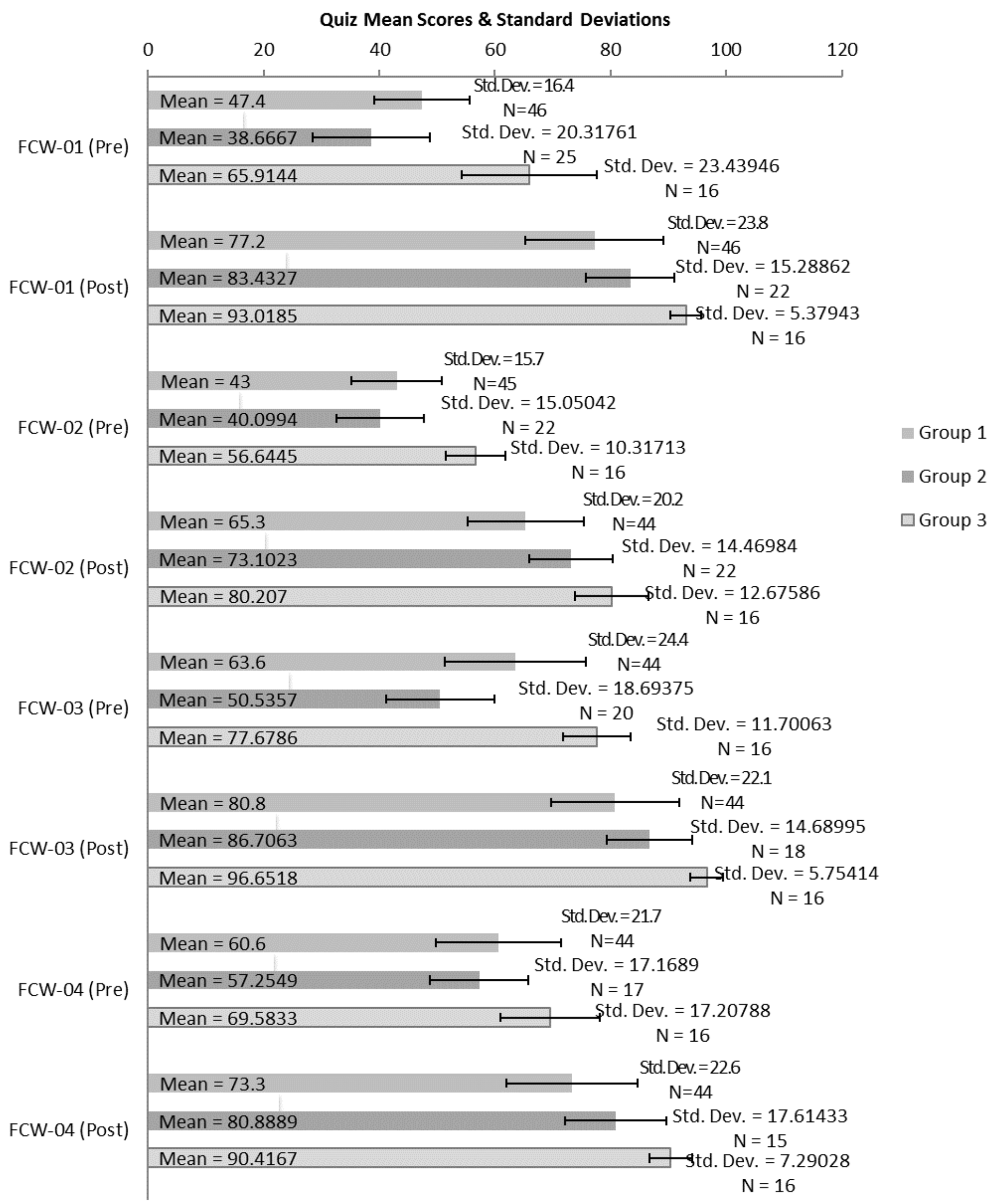


Figure 5. Descriptive statistics for FCW quizzes - Groups 1-3

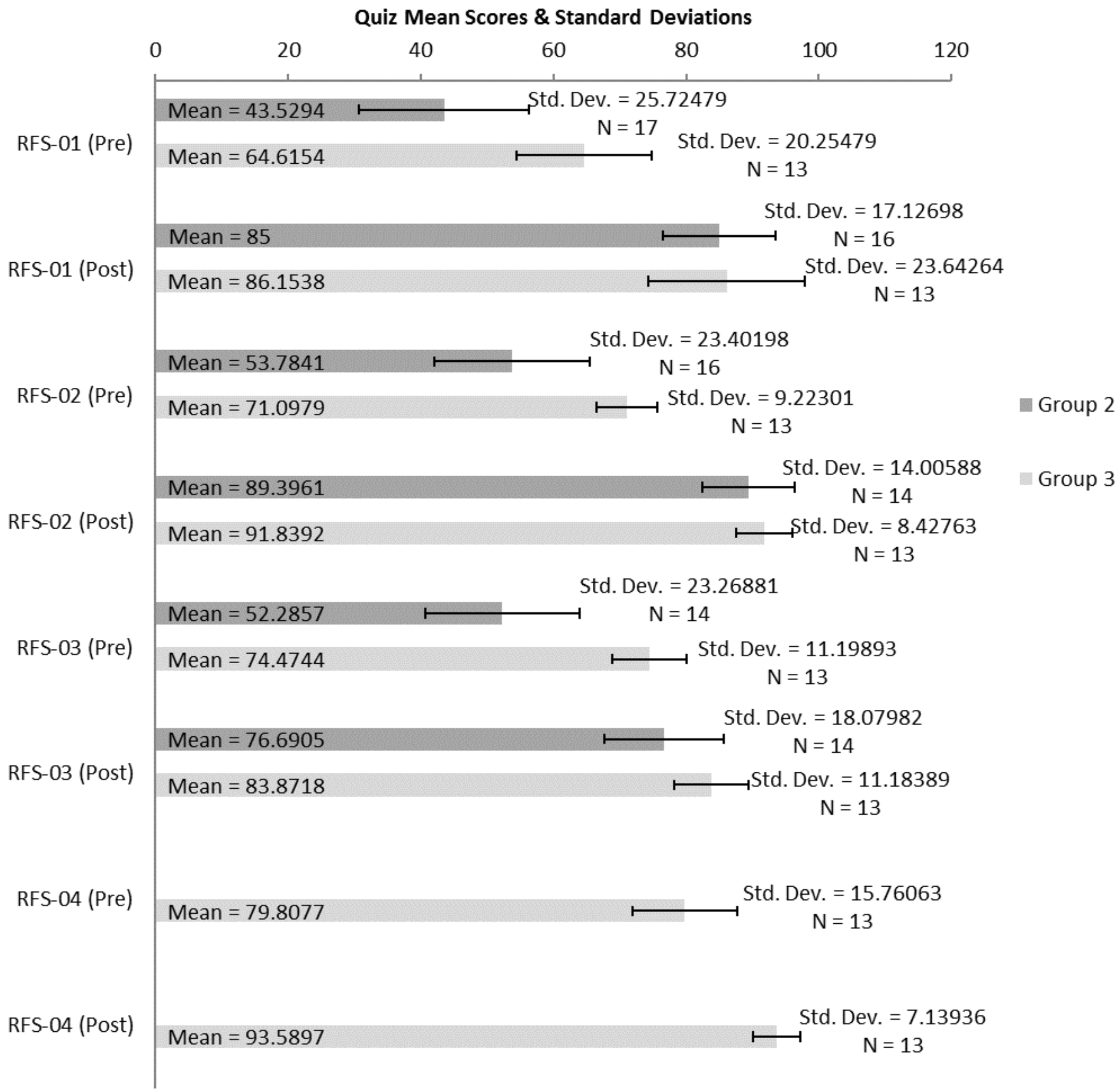


Figure 6. Descriptive statistics for RFS quizzes - Groups 2 and 3

*Note: None of the undergraduate project participants (Group 2) performed the fourth RFS unit.

Table 3. Across-group independent samples t-tests for quizzes (Group 2 - Group 3)

Quiz (∆Means)	t	df	|∆Mean Difference|	Two-tailed significance
FCW-01	2.568	36	18.44971	.015
FCW-02	1.647	36	9.44034	.108
FCW-03	3.393	32	16.34425	.002
FCW-04	.335	29	2.27778	.740
RFS-01	2.182	27	20.96154	.038
RFS-02	2.010	25	10.43407	.055
RFS-03	2.801	25	15.00733	.010
RFS-04	n/a	n/a	n/a	n/a

All modules across each course for Group 1, Group 2, and Group 3 resulted in statistically significant gains in score ($p < 0.05$), showing that the instructional efficacy of the courses applies to both undergraduate and graduate participants. Further comparison between the score improvements of undergraduate students in Group 2 and graduate students in Group 3 show that some modules had significantly greater performance gains for undergraduate students in comparison to graduate students. Arguably, the points where statistical significance disappears in the performance gains has much to do with the level of familiarity with concepts and mathematical operations that come into play within some modules that undergraduates will not have in comparison to graduate students. Even so, the post-quiz scores also show that every module had students of Group 2 and Group 3 completing the quizzes with scores that consistently averaged above 70%, which means that students were excelling more than not in the content assessed. This means that subjective improvements demonstrated in survey knowledge ratings were also accompanied by objective improvements according to the course assessment mechanisms, which presents a strong case that the modules are effective in educating participants for what is assessed and that they align with the learning goals set forth for this project.

5.3 Anecdotal feedback from students and STEM professionals

A mid-career professional who used the materials as a graduate student, commented, "*I particularly appreciated...using the teaching tools you and your students have developed*. Quite honestly, *I wish they were around when I was in undergrad - I would have understood the material so much more easily!*"

Two personnel from the Naval Information Warfare Center (NIWC) Atlantic indicated the following: "Again, *the work you have done with…interactive javascript-based tutorials appears extremely valuable and we'd look forward to having our staff be educated from* [your team's] *work.*", and, in response to an idea for a similar program on another communications-related topic, requested "*More the practical intuitive learning type stuff you were showing us earlier* [the current interactive simulation exercises]*, vs being bludgeoned by covariance matrices.*"

6. Conclusions and future work

Results for use of the initial modules by groups of students in an undergraduate course, an undergraduate team project, and a graduate course show improvements in both measured performance and self-reported knowledge within each of the groups.

Future work includes refinement of the current modules and simulation exercises, integration of remote-laboratory exercises into the modules, and completion of the remaining planned modules. Further, we plan to apply a similar approach to other related topics.

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Interactive Introductory Online Modules on Wireless Communications and Radio-frequency Spectrum Sharing

Carl B. Dietrich[1] (cdietric@vt.edu) Nicholas F. Polys[1], Kenneth Reid[2], Joshua Alexéi García Sheridan[1], Don-Roberts Emenonye[1], Xavier Gomez[1], Joseph Tolley[1], Cameron Makin[1], Joseph Gaeddert[1]

[1]Virginia Tech, [2]University of Indianapolis

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Motivation

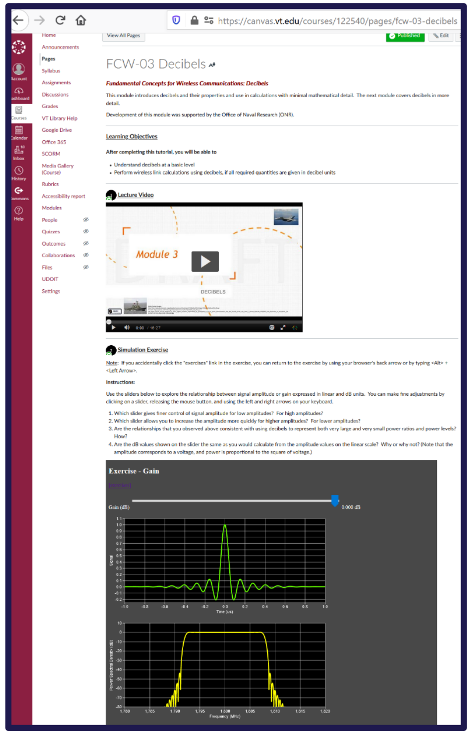
- Wireless data capacity demand continues to increase [1]
  - More devices
  - Bandwidth-intensive applications
- The U.S. military operates in an electromagnetic spectrum that is increasingly contested, congested, and constrained (complex)
- Efficient and effective spectrum use for commercial, military, and other applications requires conceptual understanding and practice
- Online modules are convenient, yet need interactivity and realism to promote engagement and problem-solving

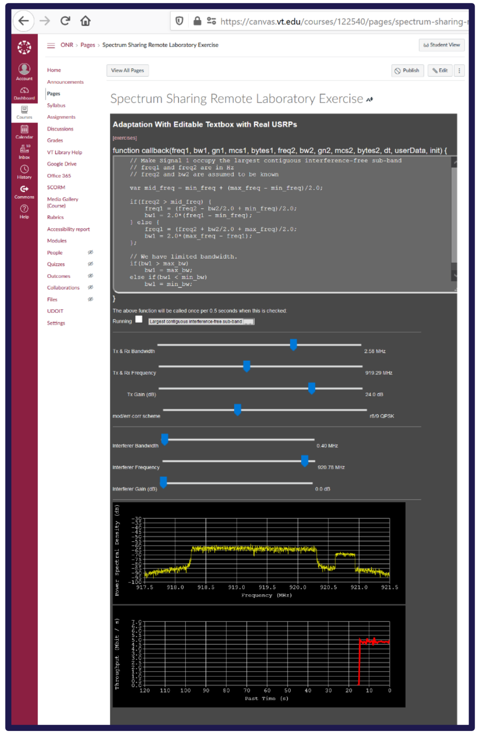
Background

- **Katz and Flynn: tutorials for communication systems course** [2] using GNU Radio [3] and GNU Radio Companion [4] software-defined radio (SDR) software
- **SDR-based labs by the GNU Radio community** [5] **and others**, e.g. [6]
- **Variety of approaches to education on SDR and using SDR**, e.g., [7]
- Pandemic-driven acceleration of work started in 2014 (SDR testbed based lab exercises) and 2018 (online RF spectrum use modules/short courses)

Project Overview

- **Learning modules** to promote in-person and online learning [8], **for use in semester and CEU courses**
- **Not intended to replace in-depth undergraduate or graduate courses**
- **Introduction/review**:
  - **Fundamental concepts for wireless** communications
  - **The radio frequency (RF) spectrum** and RF spectrum management
- Canvas learning modules integrate HTML/JavaScript-based exercises





Instructions and questions motivate exploration and problem solving using interactive exercises

Exercises supplement lectures, text, demonstration videos, and external links

Ongoing Work

- Modules in development for advanced undergraduate and graduate students and STEM professionals:
  - **Introduce configuration and programming of adaptive frequency-agile radios and spectrum management systems** for congested RF environments
  - **Exercises include simulations of radio links**
    - Some exercises enable students to **select from among multiple pre-coded controller strategies**
    - **Optionally**, students can **edit the code or supply their own code to adapt and control transmission parameters** for simulated radio links before running the simulation
    - This results in a **very flexible environment for experimentation**
- **Remote lab exercises that run on an SDR-based wireless testbed provide an additional level of realism**

Project Activities and Progress

- Producing online learning modules/short courses using interactive simulations
- Developing robust open-source software to enable exercises for the modules
- Resources include well over 300 lecture slides, demonstration videos produced using wireless testbed, experiment management system, RF spectrum visualization tool, the liquid-dsp and GNU Radio open source SDR software
- Remote labs/mini-projects planned, in addition to simulations, lecture and demo videos, and pre- and post-quizzes for automatic learning assessment
- Initial versions of three of five planned short courses are complete or in progress (approximately 75% of planned lecture materials are complete)

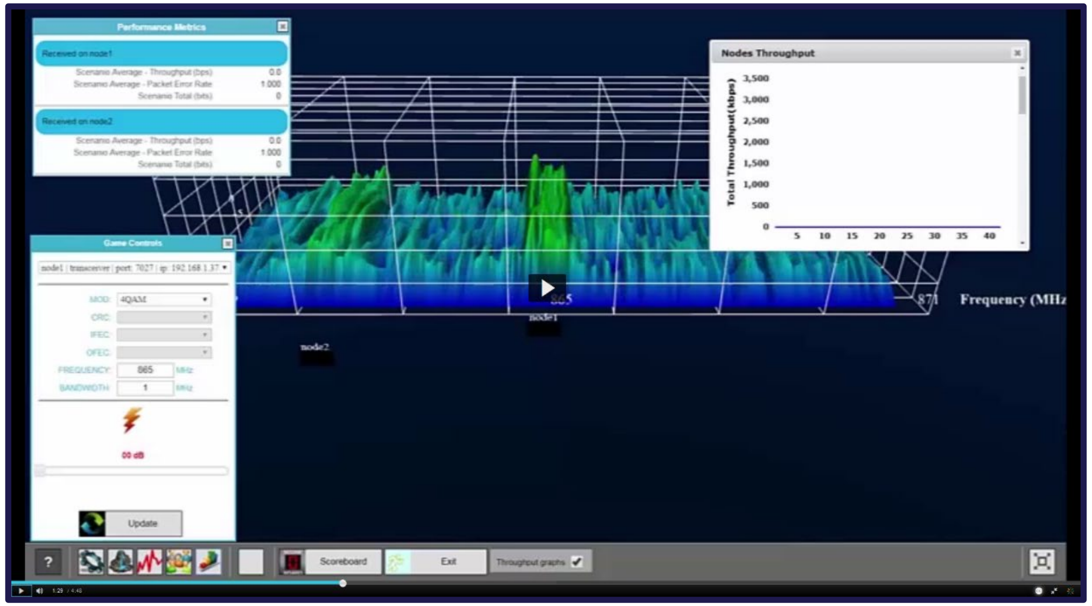
Course Topics (1 of 2)

- **Course #1: Fundamental Concepts for Wireless Communications (FCW)**
  - High-level view of Physical layer communications
  - Information capacity of a wireless channel and factors that limit this capacity
  - Decibels and link budgets
- **Course #2: Introduction to the Radio Frequency Spectrum and Spectrum Management (RFS)**
  - Frequency-domain representation of signals
  - Radio resources, parameters that can be adapted, measures of link performance
  - Software-defined radio (SDR)
  - Spectrum sharing, Spectrum Access Systems, military spectrum use

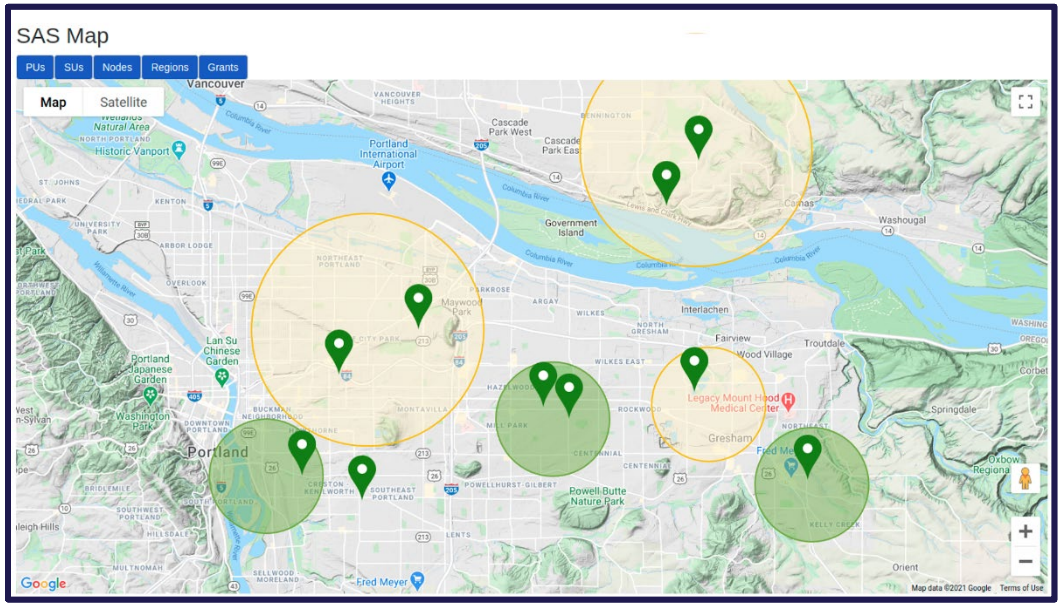
Course Topics (2 of 2)

- **Course #3: Methods for Smart Control of Spectrum Agile Radio Frequency Systems**
  - Rule-based adaptation
  - Machine-learning/statistical methods
  - Knowledge-based artificial intelligence methods
- **Course #4: Controller Implementation for Spectrum Agility**
  - Application of methods from Course #3 to control frequency-agile radio links in challenging and congested RF environments
- **Course #5: Dynamic Radio Spectrum Management**
  - Application of methods from Course #3 to dynamic frequency assignment in challenging and congested RF environments

Example Content: Demonstration Videos

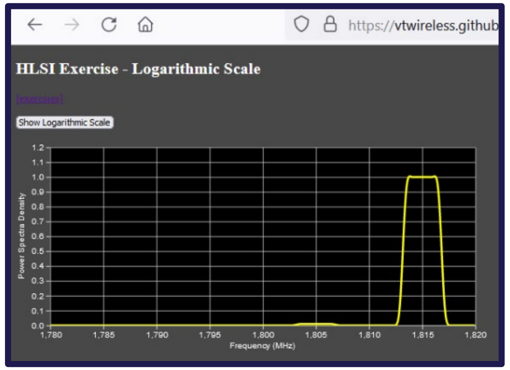


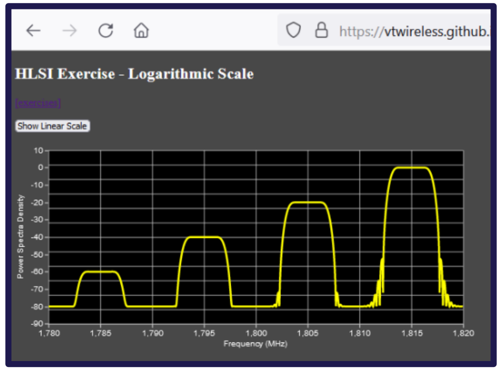
Demonstration of interference and its effect on data throughput, shown using SDRs



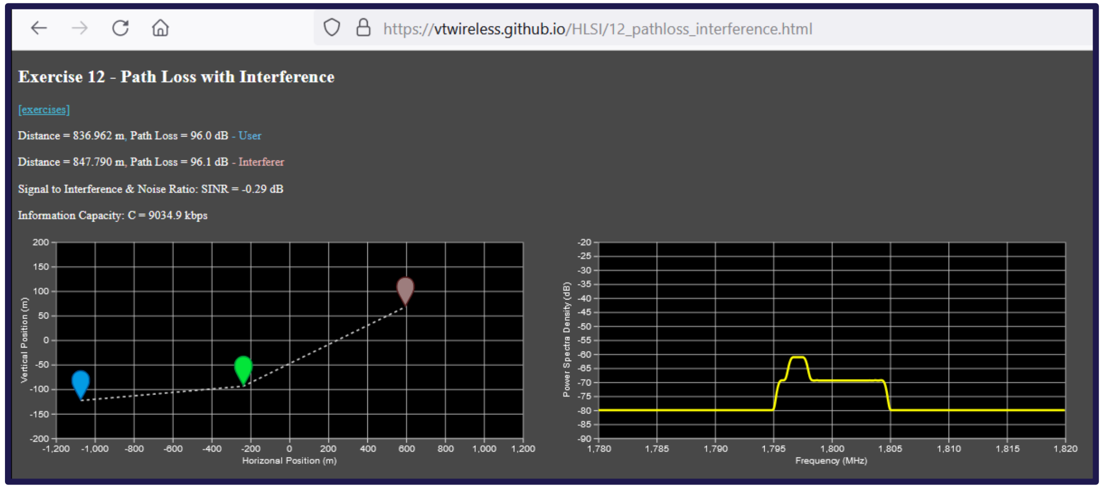
Open-source spectrum access system (SAS) that will be used in the later demonstrations

Example Content: Simulations (1 of 3)



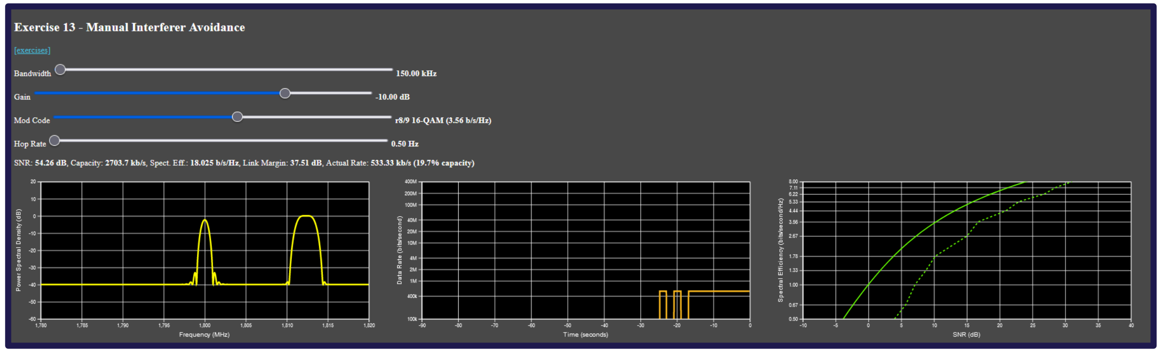


Logarithmic (decibel) scale (right) vs. linear scale (left)

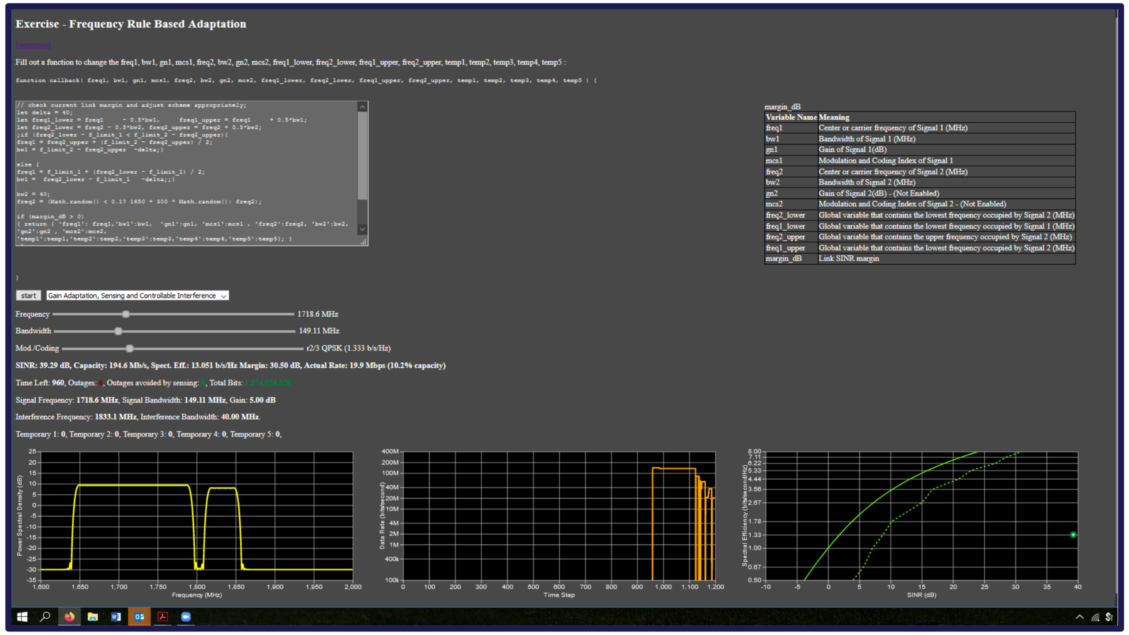


Interference in a free-space path loss environment

Example Content: Simulations (2 of 3)



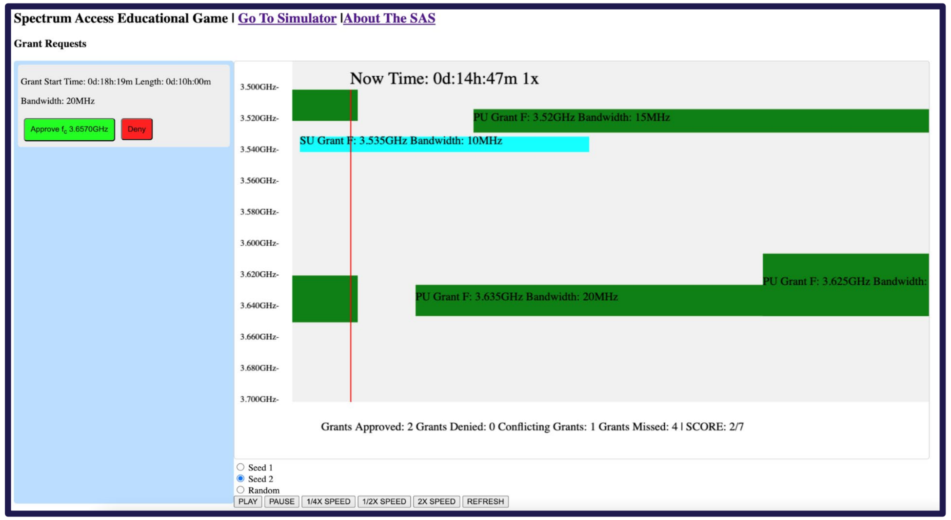
Manual control of transmission parameters to optimize data throughput



Rule-based control of transmission parameters to optimize data throughput

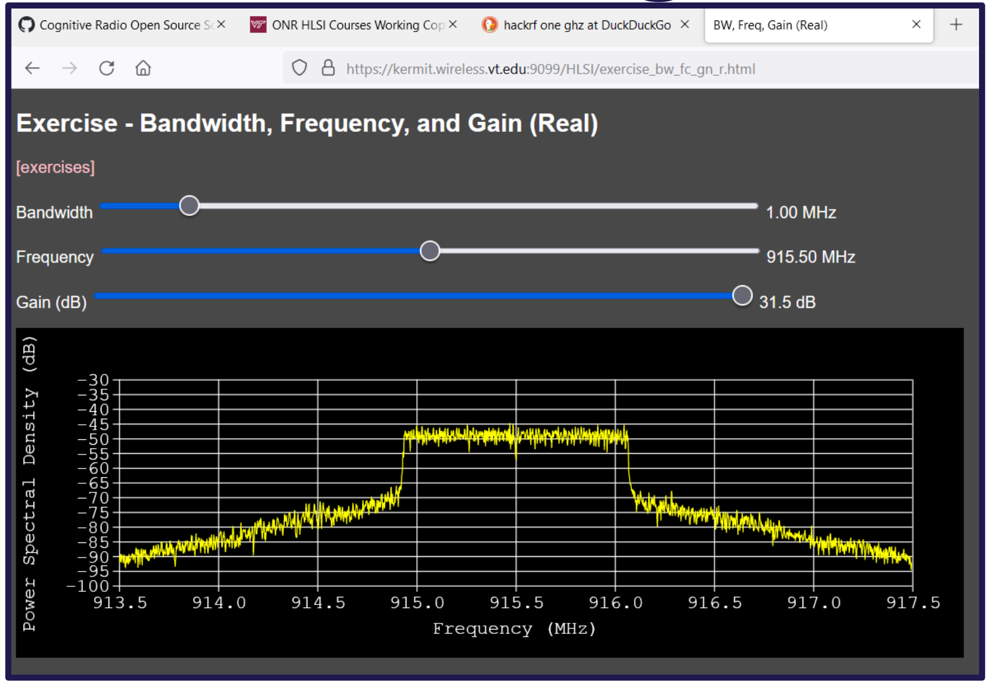
Example Content: Simulations (3 of 3)

Editable code to control coexisting transmitter behavior and optimize radio link using Q-learning

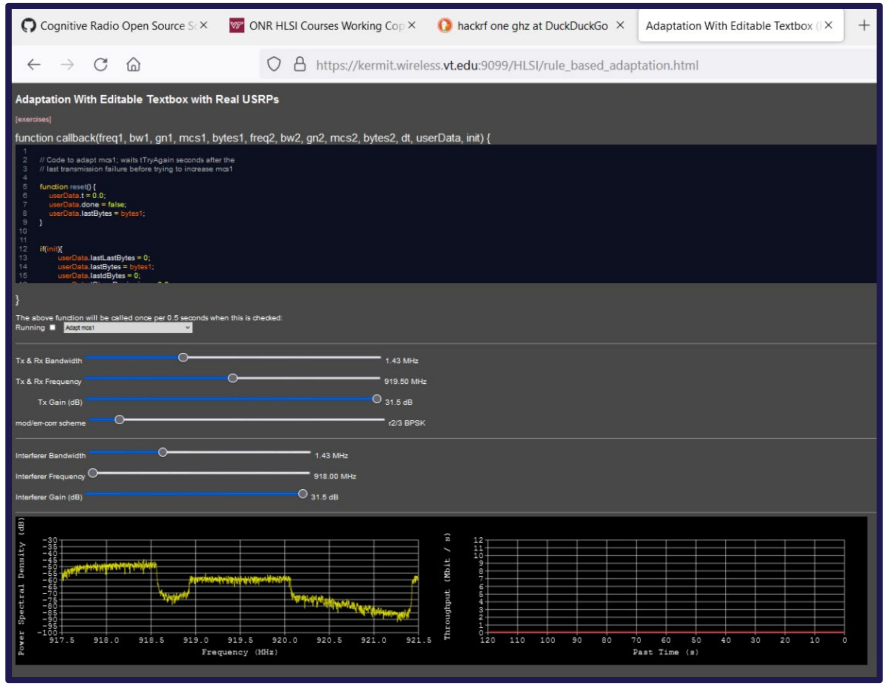


Playing the role of an automatic spectrum access system (SAS), student approves or denies requests of radio spectrum users for spectrum grants (authorizations to use a range of frequencies for a specified time)

Example Content: Remote Laboratory Exercises using SDR Testbed



Effect of transmission parameters and nonlinear amplifier response on signal spectrum



Manual and/or editable automatic adaptation of transmission parameters to maximize data rate

Evaluation Activities

- **The PIs have piloted the current version of the modules with approximately 100 undergraduate and graduate students**
  - Delivered using Canvas
  - Interactive exercises integrated using HTML iframes (also tested in Blackboard)
- Analysis indicates **statistically significant increases** in
  - **self-reported knowledge** of topics addressed in the modules
  - **student performance** from pre-quizzes to post-quizzes for the modules
- **Reviewers and users have provided valuable inputs** and positive anecdotal feedback

Anecdotal Feedback

- **Mid-career professional/graduate student**: *"I particularly appreciated...using the teaching tools you and your students have developed*. Quite honestly, ***I wish they were around when I was in undergrad - I would have understood the material so much more easily!***"
- **Two Naval R&D personnel**: *"the…****interactive javascript-based tutorials*** **[appear]** ***extremely valuable and we'd look forward to having our staff be educated from*** **[your team's]** ***work***"; Also, regarding a proposed course on antennas, "***More the practical intuitive learning type stuff you were showing us earlier*** **[the current interactive simulation exercises],** ***vs being bludgeoned by covariance matrices.***"

Conclusions

- Courses resulted in **statistically significant gains for all three groups** in self-reported measures and in understanding as measured using pre- and post-quizzes
- **Gains were greater for undergraduates than graduates**, although graduate post-quiz scores were higher
- **Greatest pre- to post-quiz improvement was by students in interdisciplinary undergraduate project**
  - This group was recruited from a wider pool that included non-ECE (CS and other engineering) students as well as ECE students who had not yet had a communications engineering course

Future Work

- Complete final three courses
- Develop/enhance simulation exercises
  - More machine learning/AI examples
- Develop/enhance remote-lab exercises and resource-sharing system
- Disseminate courses/modules, exercises, etc.
- Update courses as needed
- Develop similar courses and exercises on other topics

References

[1] CISCO Systems, “Cisco annual internet report (2018–2023) white paper,” March 2020. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[2] S. Katz, “CSUN/EAFB Software Defined Radio (SDR) Senior Project,” [Online]. Available: https://www.csun.edu/~skatz/katzpage/sdr_project/sdrproject.html

[3] “The Free & Open Source Radio Ecosystem · GNU Radio,” GNU Radio. [Online]. Available: http://www.gnuradio.org/, [Accessed: 13-May-2021].

[4] “Guided Tutorial GRC [GNU Radio Companion],” GNU Radio. [Online]. Available: https://wiki.gnuradio.org/index.php/Guided_Tutorial_GRC. [Accessed: 13-May-2021].

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[7] S. G. Bilén et al., "Software-defined radio: a new paradigm for integrated curriculum delivery," in IEEE Communications Magazine, vol. 52, no. 5, pp. 184-193, May 2014, doi: 10.1109/MCOM.2014.6815911.

[8] J. Garcia-Sheridan, S. Kim, R. Goff, V. Marojevic, N. Polys, A. Mohammed, C. Dietrich, “Instructional strategies and design for immersive wireless communication tutorials and exercises.” ASEE Annual Conference, 2017.

[9] U.S. Department of Defense, “Electromagnetic Spectrum Superiority Strategy,” October 2020.

Backup Slides

Example Content: Interactive Simulation Topics

- **Signal parameters and effects** in the time and frequency domains
- **Logarithmic vs. linear** magnitude scale
- Effects on a signal due to **nonlinearity or compression**
- **Interference** (approximated as additive white Gaussian noise) & its **effect on information capacity**
- **Free-space path loss** (FSPL); **student moves two radios on a 2-D grid** and can vary transmission frequency (0 dBi antenna gain at all frequencies)
- **Interference in FSPL** environment with two co-channel transmitters and one receiver; interface as above
- **Information capacity in an AWGN channel** for a signal with controllable parameters
- **Spectral efficiency vs. signal-to-noise ratio** for a signal that has user-controllable bandwidth
- **Timed simulation** in which **student adjusts modulation and coding strategy (MCS)** to **maximize data throughput** in a noise-limited environment
- **Timed simulation** in which student selects, edits, and/or writes MCS-control code to maximize bits transmitted in noise-limited environment
- **Manual adaptation of transmission parameters** to maximize data throughput in a band of frequencies **shared with another, frequency-hopping signal**
- **Rule-based adaptation using user-selectable strategies** to maximize data throughput while operating in a band of frequencies **shared with a frequency-hopping signal**
- **Use of selectable/editable, rule-based strategies to maximize data throughput** while operating in a band of frequencies **shared with a frequency-hopping signal**
- Simulation in which the **student acts as a spectrum access system (SAS) and approves or denies requests for spectrum grants** (authorizations to use frequencies for a limited time)
- **In development: Use of selectable/editable algorithms for spectrum grant approval/denial**

Evaluation: Methodology

- Pre- and post-surveys for each short course or collection of modules measure self-reported understanding and affective measures
- Pre- and post-quiz for each module provide an additional quantitative measure of understanding
- Three samples of students, from:
  1. Undergraduate Introduction to Communication Systems course (Modules FCW-01 through FCW-04)
  2. Interdisciplinary undergraduate project team (Modules as above plus RFS-01 through RFS-03)
  3. Graduate Software Radios course (Modules FCW-01 through FCW-04 and RFS-01 through RFS-04)

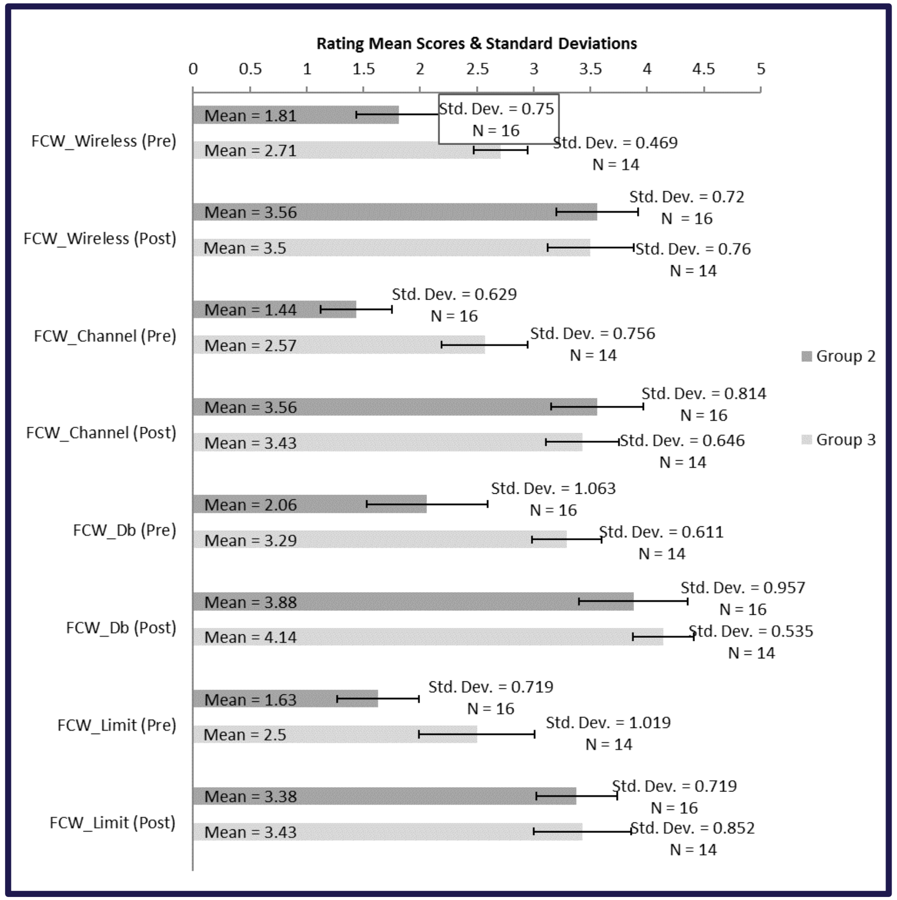
Evaluation: Analysis

- Comparative analyses within Group 1 as well as within and between Group 2 and Group 3 for performance improvements and comparisons for pre- and post-quizzes
- Similar comparison of Group 2 and Group 3 data from surveys
- Paired samples t-tests compared data collected within groups to determine statistical significance
- Independent samples t-tests compared data between Group 2 and Group 3 as a juxtaposition for undergraduate and graduate learning outcomes from the coursework
- All data were compiled and analyzed in SPSS
- Comparative analyses used $p < 0.05$ as the threshold for determining statistical significance

Evaluation: FCW* Survey Questions

*Fundamental Concepts for Wireless Communications; Pre-course surveys include opt in/out

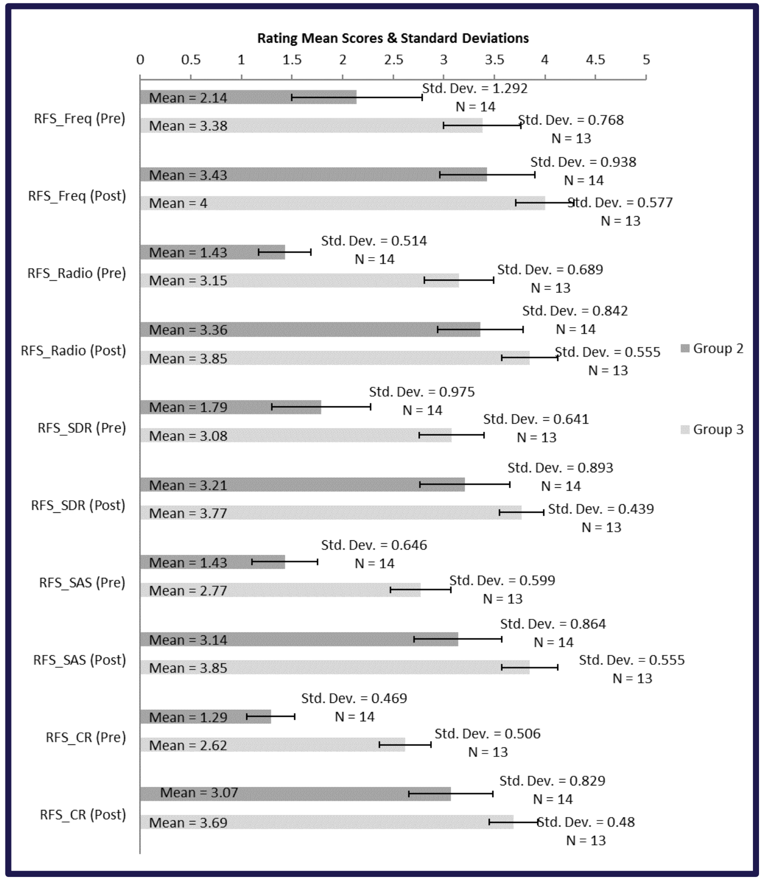
- FCW_Wireless: "Rate your level of **knowledge of wireless communication links** on a scale of 1-5 as of right now."
- FCW_Channel: "Rate your level of knowledge regarding **channel capacity** on a scale of 1-5 as of right now."
- FCW_Db: "Rate your level of knowledge of **decibels and how to calculate with them** on a scale of 1-5 as of right now."
- FCW_Limit: "Rate your level of knowledge of **factors limiting a wireless link's performance** on a scale of 1-5 as of right now."
- **Upper bars**: Undergraduate project
- **Lower bars**: Graduate course



Evaluation: RFS* Survey Questions

***Introduction to the Radio Frequency Spectrum and Spectrum Management ; Pre-course surveys include opt in/out**

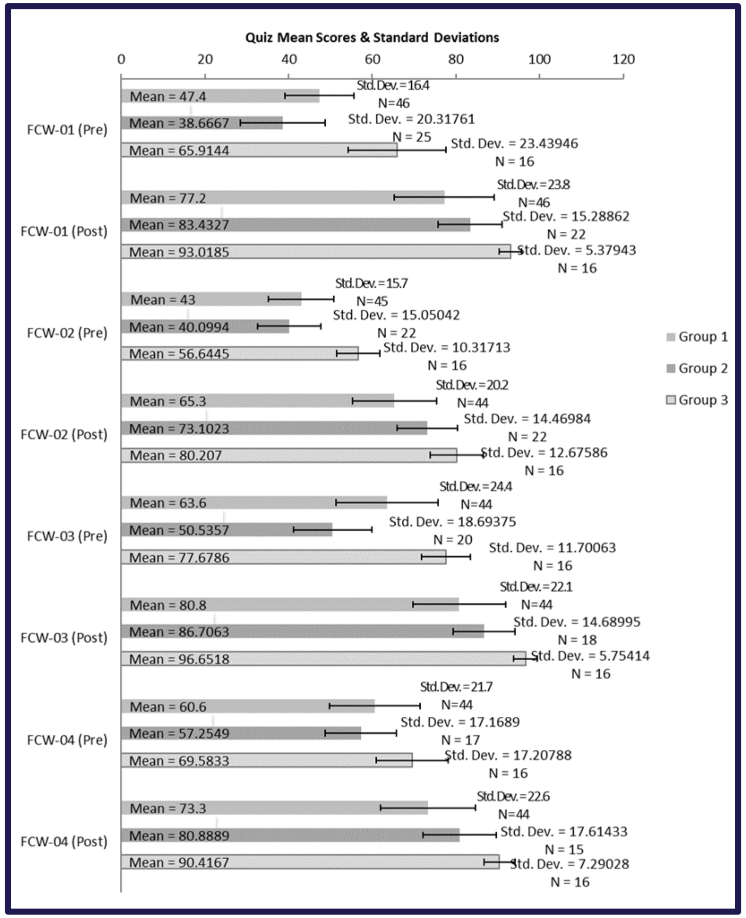
- RFS_Freq: “Rate your level of knowledge of **frequency-domain representations of signals** on a scale of 1-5 as of right now.”
- RFS_Radio: “Rate your level of knowledge of **radio resources and metrics** on a scale of 1-5 as of right now.”
- RFS_SDR: “Rate your level of knowledge of **software-defined radio** on a scale of 1-5 as of right now.”
- RFS_SAS: “Rate your level of knowledge of **spectrum sharing and spectrum access systems** on a scale of 1-5 as of right now.”
- RFS_CR: “Rate your level of knowledge of **cognitive radio** on a scale of 1-5 as of right now.”
- **Upper bars**: Undergraduate project
- **Lower bars**: Graduate course



Evaluation: FCW* Pre- and Post-Quizzes

*Fundamental Concepts for Wireless Communications

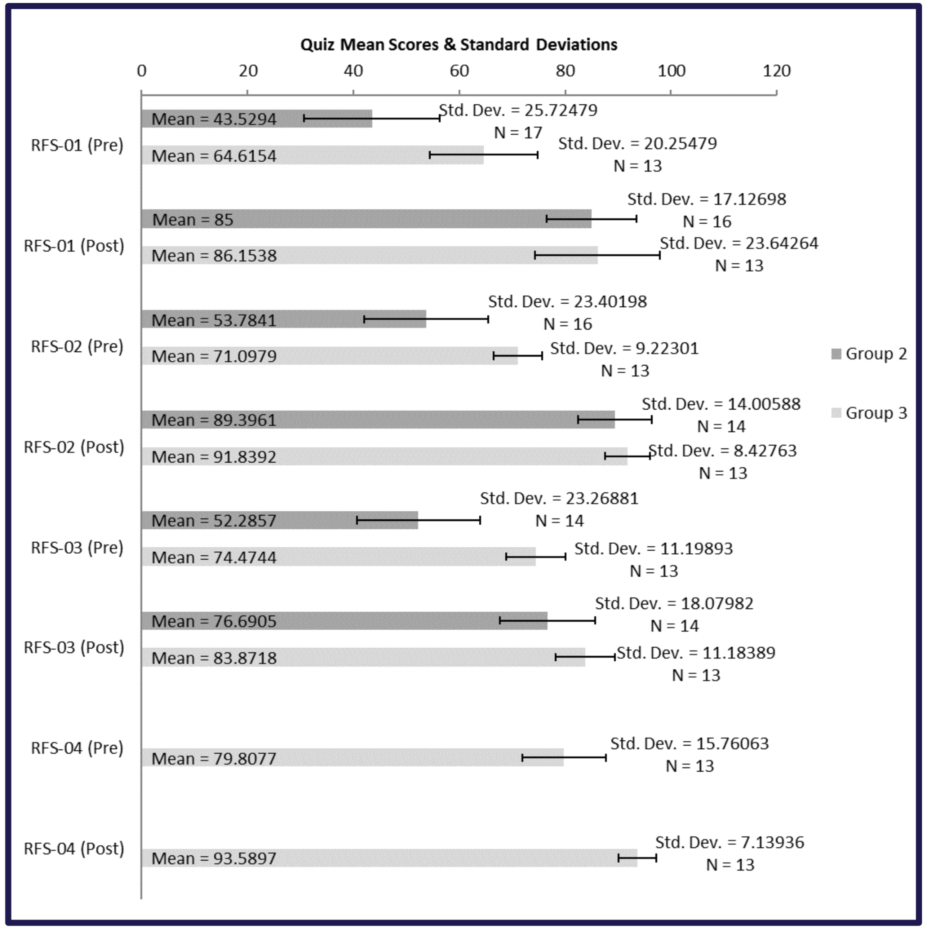
- **Upper bars:** Undergraduate course
- **Middle bars:** Undergraduate project
- **Lower bars**: Graduate course



Evaluation: RFS* Pre- and Post-Quizzes

*Introduction to the Radio Frequency Spectrum and Spectrum Management

- **Upper bars**: Undergraduate project
- **Lower bars**: Graduate course



Descriptive Statistics

Within-Group Descriptive Statistics for FCW surveys (Group 2)

Rating	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
FCW_Wireless (Pre)	16	1.81		.750	
FCW_Wireless (Post)	16	3.56	1.750	.727	**.000**
FCW_Channel (Pre)	16	1.44		.629	
FCW_Channel (Post)	16	3.56	2.125	.814	**.000**
FCW_Db (Pre)	16	2.06		1.063	
FCW_Db (Post)	16	3.88	1.812	.957	**.000**
FCW_Limit (Pre)	16	1.63		.719	
FCW_Limit (Post)	16	3.38	1.750	.719	**.000**

Within-Group Descriptive Statistics for FCW surveys (Group 3)

Rating	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
FCW_Wireless (Pre)	14	2.71		.469	
FCW_Wireless (Post)	14	3.50	.786	.760	**.001**
FCW_Channel (Pre)	14	2.57		.756	
FCW_Channel (Post)	14	3.43	.857	.646	**.000**
FCW_Db (Pre)	14	3.29		.611	
FCW_Db (Post)	14	4.14	.857	.535	**.000**
FCW_Limit (Pre)	14	2.50		1.019	
FCW_Limit (Post)	14	3.43	.929	.852	**.001**

Within-Group Descriptive Statistics for RFS surveys (Group 2)

Rating	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
RFS_Freq (Pre)	14	2.14		1.292	
RFS_Freq (Post)	14	3.43	1.286	.938	**.000**
RFS_Radio (Pre)	14	1.43		.514	
RFS_Radio (Post)	14	3.36	1.929	.842	**.000**
RFS_SDR (Pre)	14	1.79		.975	
RFS_SDR (Post)	14	3.21	1.429	.893	**.000**
RFS_SAS (Pre)	14	1.43		.646	
RFS_SAS (Post)	14	3.14	1.714	.864	**.000**
RFS_CR (Pre)	14	1.29		.469	
RFS_CR (Post)	14	3.07	1.786	.829	**.000**

Within-Group Descriptive Statistics for RFS surveys (Group 3)

Rating	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
RFS_Freq (Pre)	13	3.38		.768	
RFS_Freq (Post)	13	4.00	.615	.577	**.001**
RFS_Radio (Pre)	13	3.15		.689	
RFS_Radio (Post)	13	3.85	.692	.555	**.006 (Radio Transmission Parameters)**
RFS_SDR (Pre)	13	3.08		.641	
RFS_SDR (Post)	13	3.77	.692	.439	**.002**
RFS_SAS (Pre)	13	2.77		.599	
RFS_SAS (Post)	13	3.85	1.077	.555	**.000**
RFS_CR (Pre)	13	2.62		.506	
RFS_CR (Post)	13	3.69	1.077	.480	**.000**

Within-Group Descriptive Statistics for FCW Quizzes (Group 1)

Quiz	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
FCW-01 (Pre)	46	47.4		16.4	
FCW-01 (Post)	46	77.2	29.8	23.8	**.000**
FCW-02 (Pre)	45	43.0		15.7	
FCW-02 (Post)	44	65.3	21.9	20.2	**.000**
FCW-03 (Pre)	44	63.6		24.4	
FCW-03 (Post)	44	80.8	17.2	22.1	**.000**
FCW-04 (Pre)	44	60.6		21.7	
FCW-04 (Post)	44	73.3	12.7	22.6	**.001**

Within-Group Descriptive Statistics for FCW Quizzes (Group 2)

Quiz	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
FCW-01 (Pre)	25	38.6667		20.31761	
FCW-01 (Post)	22	83.4327	45.55387	15.28862	**.000**
FCW-02 (Pre)	22	40.0994		15.05042	
FCW-02 (Post)	22	73.1023	33.00284	14.46984	**.000**
FCW-03 (Pre)	20	50.5357		18.69375	
FCW-03 (Post)	18	86.7063	35.31746	14.68995	**.000**
FCW-04 (Pre)	17	57.2549		17.16890	
FCW-04 (Post)	15	80.8889	23.11111	17.61433	**.000**

Within-Group Descriptive Statistics for FCW Quizzes (Group 3)

Quiz	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
FCW-01 (Pre)	16	65.9144		23.43946	
FCW-01 (Post)	16	93.0185	27.10417	5.37943	**.000**
FCW-02 (Pre)	16	56.6445		10.31713	
FCW-02 (Post)	16	80.2070	23.56250	12.67586	**.000**
FCW-03 (Pre)	16	77.6786		11.70063	
FCW-03 (Post)	16	96.6518	18.97321	5.75414	**.000**
FCW-04 (Pre)	16	69.5833		17.20788	
FCW-04 (Post)	16	90.4167	20.83333	7.29028	**.001**

Within-Group Descriptive Statistics for RFS Quizzes (Group 2)

Quiz	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
RFS-01 (Pre)	17	43.5294		25.72479	
RFS-01 (Post)	16	85.0000	42.50000	17.12698	**.000**
RFS-02 (Pre)	16	53.7841		23.40198	
RFS-02 (Post)	14	89.3961	31.17532	14.00588	**.000**
RFS-03 (Pre)	14	52.2857		23.26881	
RFS-03 (Post)	14	76.6905	24.40476	18.07982	**.000**
RFS-04 (Pre)*	n/a	n/a		n/a	
RFS-04 (Post)*	n/a	n/a	n/a	n/a	**n/a**

Within-Group Descriptive Statistics for RFS Quizzes (Group 3)

Quiz	N	Mean	ΔMean	Standard Deviation	Significance (Paired Samples, POST - PRE)
RFS-01 (Pre)	13	64.6154		20.25479	
RFS-01 (Post)	13	86.1538	21.53846	23.64264	**.003**
RFS-02 (Pre)	13	71.0979		9.22301	
RFS-02 (Post)	13	91.8392	20.74126	8.42763	**.000**
RFS-03 (Pre)	13	74.4744		11.19893	
RFS-03 (Post)	13	83.8718	9.39744	11.18389	**.038 (Intro/Review of Decibels)**
RFS-04 (Pre)	13	79.8077		15.76063	
RFS-04 (Post)	13	93.5897	13.78205	7.13936	**.008**

Simulation Exercises

https://vtwireless.github.io/HLSI