A Comprehensive, Laboratory-Enhanced Communications Curriculum

Jeff Frolik

University of Vermont

Introduction

Over the past decade, the field of wireless communications has come into its own and is posed to become a ubiquitous technology with the recent arrival of 3G cellular, wireless local area networks and wireless sensor networks. As such, today's graduating electrical engineers need marketable skills which are typically not developed in undergraduate curricula. This paper presents ongoing activities at the University of Vermont (UVM) which address this need through significant enhancements in the undergraduate communications curriculum offered by the Electrical and Computer Engineering Department (ECE). The emphasis of these enhancements lies in the integration of hands-on experience in three typically, theory-based telecommunication courses and a separate laboratory course having a wireless communications focus. The enhancements, enabled by a National Science Foundation (NSF) Course, Curriculum and Laboratory Improvement (CCLI) Adaptation and Implementation (A&I) Track award and university support, features infrastructure development in terms of radio frequency (RF) and digital communications test equipment. This paper describes the new communications curriculum at UVM, resources upon which the curriculum enhancements were based, the development of two new instructional laboratory benches and the adaptation of laboratory assignments to enhance the new curriculum. UVM's ECE program is relatively small (~100 undergraduates) and thus the presented approach may serve a model for similarly sized departments.

Curriculum Development

Prior to this project's inception, UVM's offering of undergraduate telecommunication courses was limited to a junior-level *Intro to Communication Systems* course and a self-study laboratory course (*Senior Lab II*) based on Feedback Instruments Ltd.'s computer based training equipment [1]. Beginning in Fall 2002, the telecommunication curriculum was restructured due to the hiring of the author whose background is in wireless systems. To emphasize the starting point for this project, it was the author's startup resources which purchased the department's first spectrum analyzer (a hand-held Anritsu MS2711B). In short, the opportunity and challenge presented to the author was to develop a comprehensive undergraduate experience in wireless and digital communication systems from near-scratch given the limited resources of a small department. In doing so, the foremost goal was to provide students with both theoretical background and practical experience using modern test equipment.

The curriculum established is shown in Table 1. A junior-level signals course (EE 171) is prerequisite to the *Intro to Communication Systems* class. This latter course is pre-requisite to the senior level courses shown.

Table 1. UVM Undergraduate Communications Curriculum

Year	Fall	Spring
Junior	EE 171: *Signals & Systems*	EE 174: *Intro to Communication Systems*
Senior	EE 186: *Telecommunications Lab* EE 273: *Digital Communications*	EE 278: *Wireless Communication Systems*

Curriculum Adapted

To provide a unique and meaningful hands-on experience for the students, the author turned to the successful Wireless and Microwave Instruction (WAMI) program at the University of South Florida (USF) as a potential model. This program, with the support of a NSF grant (DUE-9650529), developed a state-of-the-art undergraduate laboratory and exciting course focusing on the integration of circuits and systems aspects of modern wireless applications. The funding for the project enabled the development of the WAMI laboratory, which is equipped with an array of CAD/CAE software packages and a complete set of microwave and RF instrumentation. The developed course, Wireless Circuits and Systems Design Laboratory, now has a per-semester enrollment of ~50 students [2 3 4 5 6]. The WAMI experience proved to be invaluable to the author for determining an appropriate selection of RF test equipment for instructional purposes and for understanding the scope of what could be accomplished in a single semester. Needless to say, the WAMI program with its large student enrollments with multiple faculty involvement could not be replicated at UVM in a single-semester format. As such, the approach was to adapt the USF labs to enhance multiple courses (in multiple semesters) in the UVM curriculum. Additional labs exercises were adapted from labs developed at Tennessee Technological University (TTU) where the author was a faculty member prior to joining UVM and those available from Agilent's Educators Corner[7].

Infrastructure Development

Before discussing the particulars of the course enhancements, we first present the infrastructure developed to support this project. Through a grant obtained through the NSF CCLI A&I program (DUE-0310150; Award Date: August 2003), university match and industry donations, two instructional benches were established.

RF Communications and Device Characterization Bench:

The development of this new bench (Figure 1) is the major infrastructure enhancement enabled by the NSF grant. Utilizing a portable spectrum analyzer (Rohde & Schwarz FSH3 @ 3 GHz), a combination Network/Spectrum/Impedance Analyzer (Agilent 4396B @ 1.8 GHz) and RF signal generators (Agilent E4422B @ 4 GHz and HP 8647A @ 1 GHz), this bench enables students to become proficient in performing numerous RF measurements. These measurements include modulation index, bandwidth, linearity (single and dual carrier methods), etc. With the addition of the network analyzer, students are also able to characterize existing devices or their own designs through S-parameter measurements. In addition, this unit will provide hands-on experience to complement course coverage of topics such as group delay, Smith charts, etc. The four-channel oscilloscope (Agilent 54831B @ 600 MHz) is used to complement frequency domain measurements. A PC is used to command and receive data from this instrumentation.

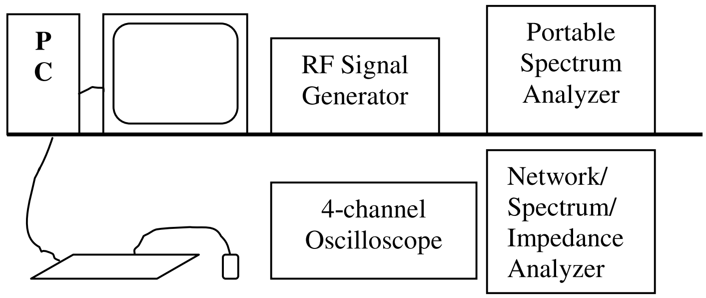

Figure 1. RF Communication and Device Characterization Bench

Digital Communications Test Bench:

This bench (Figure 2) is centered around a donated vector signal analyzer, VSA (HP 89441A @ 2.65 GHz), and a purchased arbitrary digital signal generator (Rhode & Schwarz SMIQ-03B @ 3 GHz). This bench enables complete bit-to-bit analysis of digital systems both at baseband and wireless frequencies. The four channel oscilloscope (Agilent 54831B @ 600 MHz) enables students to simultaneously characterize both the input and output signal constellations of a system. This bench is a valuable teaching tool to demonstrate, for example, the effects of running systems beyond their bandwidth specifications.

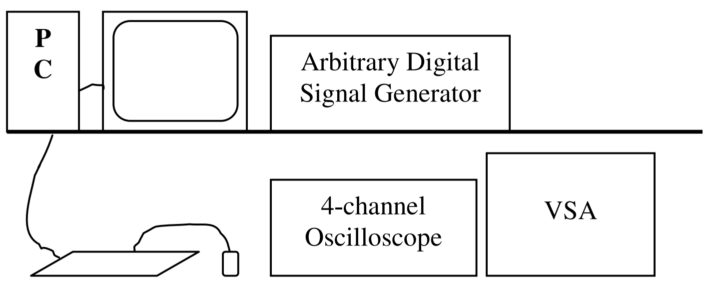

Figure 2. Digital Communication Test Bench

A key instructional enabler for this bench is the Rhode & Schwarz simulation software, WinIQSIM. While there are many powerful packages for communication system simulation and analysis (e.g., MATLAB's Simulink or Elanix's SystemView), the advantage of WinIQSIM is both its ease of use and its ability to control the R&S arbitrary digital signal generator. As shown in Figure 3, WinIQSIM provides a user with a block diagram of digital communication system along with the means to modify various parameters. For example, the figure shows a 16-QAM system that was simulated to demonstrate the effects of I-Q impairment, amplifier distortion and channel noise. The results of the simulation are shown in the constellation diagram to the right. WinIQSIM does not provide flexibility to add additional modules to the block diagram (as does Simulink and SystemView); but the real advantage to instruction is that concepts can be readily demonstrated without students having to perform any programming. As such, the author views this package as extremely powerful for undergraduate instruction. WinIQSIM is available as a free download through the Rohde & Schwarz website[8]. Students use WinIQSIM to develop and simulate signal cases prior to coming to lab (i.e., a pre-lab exercise). Lab experiments first involve loading their developed signals into the R&S SMIQ-03B. These arbitrary signals may then be use to modulate a carrier up to 3.0 GHz. The lab exercise is then to use the remaining equipment to analyze the system in the time and/or frequency domain (e.g., eye diagrams on the oscilloscope, bandwidth requirements on the spectrum analyzer, or demodulated signal on the VSA).

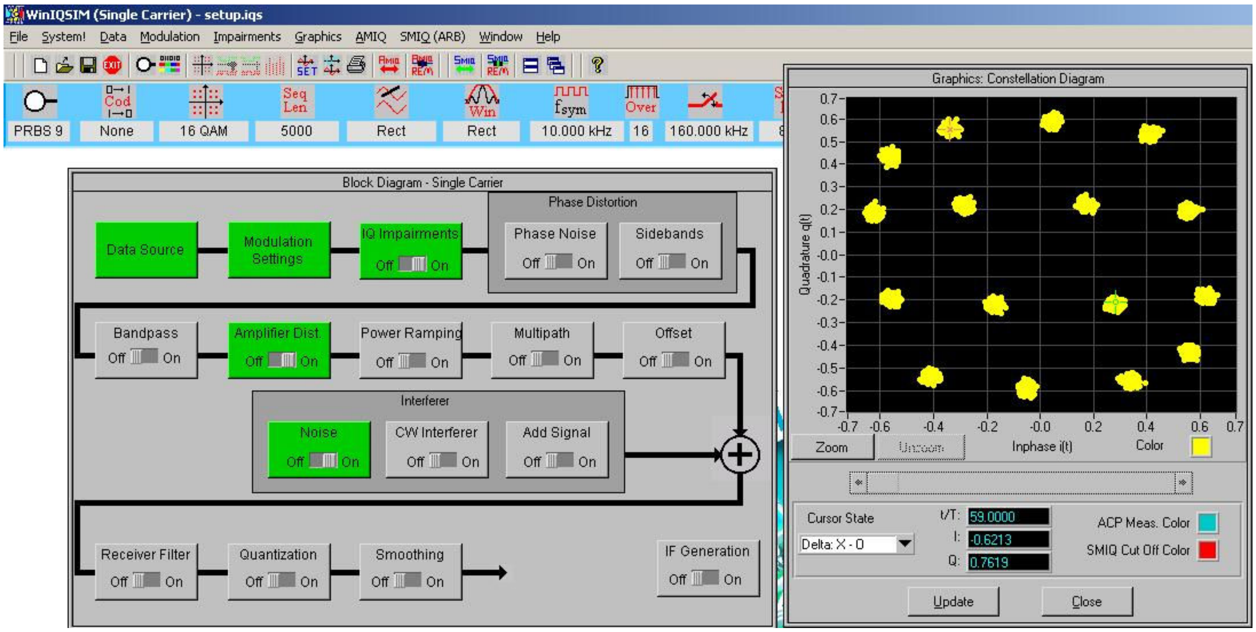

Figure 3. WinIQSIM User Interface

Curriculum Enhancement using Laboratory Experiments

As noted, the strategy employed at UVM was to (1) integrate basic laboratory experiments in each of the three communication lecture courses (EE 174, 273 and 278) and (2) developed a focus to the laboratory course (EE 186) which would enable students to pursue advanced wireless and digital communication experiments. Given that implementation of the project is ongoing, what is presented herein are the experiments as expected in final implementation (Summer 2005). Preliminary instruction for each experiment is either provide through in-class lecture or web-based video lecture[9]. The experiments themselves are performed in teams outside of class but monitored by either a TA or the instructor.

Intro to Communication Systems:

Among other concepts, this course deals with the theory behind modulation and bandwidth and the fundamentals of digital communications. These concepts are reinforced using the lab exercises described in Table 2. In addition, these labs give students a basic understanding of use of RF signal generators and spectrum analyzers. These lab assignments constitute 10% of the student's final grade. Yearly enrollment is 15-20 students.

Table 2. Lab enhancements to *Intro to Communication Systems* course

Lab No.	Subject	Lab Source	Concepts and Modifications	Equipment
1	Spectrum Analyzer Basics	TTU/USF/ Agilent	Presents students with basic concepts on operation including frequency, span and resolution bandwidth. Adapted with components from each source.	▪ Spectrum Analyzer
2	AM/FM	TTU and Agilent	Students perform bandwidth measurements for AM and FM signals and determine mod indices from spectral information. Adapted exercises extract components from both sources.	▪ RF Signal Generator ▪ Oscilloscope ▪ Spectrum Analyzer
3	WinIQSIM	UVM	Familiarizes students with various digital modulation techniques and software that will be used to control a digital signal generator in subsequent lab experiments.	▪ WinIQSIM Software
4	Eye Diagrams / Constellations	UVM	Lab introduces students to time domain measurements of digital comm signals.	▪ Digital Signal Generator ▪ Oscilloscope

Telecommunications Lab:

The *Telecommunications Lab* course was revamped for the Spring 2003 offering (prior to receiving the CCLI grant) to include many of the experiments now to be used to enhance EE 174, EE 273 and EE 278. The student response was very favorable in comparison to the self-study course offered the three previous years. Although they viewed the course as too much work for a single credit hour, they rated the revised course 4.75 on a 5.00 (Excellent) scale (as opposed to the previous three-year average of 3.65 [10]). Ten labs were performed which constituted 80% of the student's grade. The remaining 20% was based on a project chosen and completed by the student groups. Projects to date include developing experiments related to CDMA, low-frequency AM and FM modulation to illustrate both time and frequency characteristics, and small scale fading. Yearly enrollment is 10-15 students.

For Fall 2004, this course will be revised according to Table 3. In addition, the course will be expanded to include a separate lecture and increased to 2 credit-hour status. Clearly this new set of experiments is significantly influenced by USF's program. However, while many of the topics are similar, all labs will be modified to better complement the course material found in UVM's courses and to match the complement of test equipment. Specifically, USF's curriculum specializes in communication *device* design; however, UVM's curriculum emphasizes communication *systems* and thus objectives for the experiments will be focused accordingly.

Digital Communications:

This course analyzes the theoretical performance of various digital techniques in the presence of noise. This theoretical material builds upon that presented in EE 174 and thus these lab experiments do the same. These students will already be familiar with most the equipment but will gain expertise with the use of the vector spectrum analyzer (VSA). In addition, they will develop and conduct a lab project of their own design. The four lab assignments constitute 10% of the student's final grade and their projects constitute another 10%. The course is a senior-level technical elective that can also being taken by graduate students. Yearly enrollment is 10-15 students.

Table 3. Experiments planned for the *Telecommunications Lab* course

Lab No.	Subject	Lab Source	Concepts and Modifications	Equipment
1	RF Subsystems	USF	Lab introduces students to basic components and operation of the heterodyne receiver. This equipment based lab will be adapted from the USF software based exercise.	▪ RF Signal generator ▪ Oscilloscope ▪ Spectrum Analyzer
2/3	Circuit Characterization	USF	Lab introduces students to network analyzer operation and S-parameter measurements for several common RF devices. Lab will be modified content to fit into two sessions (versus the USF three) limiting the components considered.	▪ Network Analyzer
4	Frequency Conversion –Mixer Measurements	USF	Lab investigates mixer characteristics. Will be adapted to combine components of two separate USF labs.	▪ Network Analyzer
5/6	Amplifier performance	TTU	Students perform single and dual carrier amplifier distortion measurements. Will be adapted with little modification.	▪ RF Signal Generators ▪ Oscilloscopes ▪ Network Analyzer
7	VCO operation	USF	The present lab introduces the functional aspects of a VCO. Lab will be implemented with little modification.	▪ Same as above
8	Yagi/Dish Antennas	USF/TTU	Adapting the source techniques, students will investigate the return loss and gain/beamwidth performance for a variety of directional antennas.	▪ Signal Generator ▪ Spectrum Analyzer ▪ Power Meter
9/10	System Integration	USF	This lab has students building a receiver using component blocks and testing their system. Will be implemented with minimal changes.	▪ All of the above

Table 4. Lab enhancements to the *Digital Communications* course

Lab No.	Subject	Lab Source	Concepts and Modifications	Equipment
1	Digital Modulation	UVM	Builds upon Lab 4 of EE 174. Investigates higher order modulation techniques.	▪ Digital Signal Generator ▪ Oscilloscope ▪ Vector Signal Analyzer
2	Pulse shaping and ISI	UVM	Builds upon Lab 1 and introduces the benefits/costs of pulse shaping.	▪ Same as above
3	BER	UVM	Investigates the performance of various digital communication techniques in noisy channel. Students characterize BER vs. Eb/No.	▪ Same as above
4	Distortion	UVM	Students introduce various sources of distortion and determine the resiliency of modulation techniques to them.	▪ Same as above

Wireless Communication Systems:

The final course in the sequence addresses wireless communications from a systems perspective down to subsystem performance requirements. These concepts will be illustrated utilizing the complementary laboratory exercises in the area of antennas and propagation studies (Table 4). This course is also a senior-level EE engineering science elective open to graduate students.

Table 4. Lab enhancements to the *Wireless Communication Systems* course

Lab No.	Subject	Lab Source	Concepts and Modifications	Equipment
1	Dipole/Patch Antennas	USF	Characterizes antenna return loss and cross-polarization. Will adapt with antenna pattern measurement. Similar to EE 186 Lab 6 but with different antennas.	▪ RF Signal Generator ▪ Network/Spectrum Analyzer
2	Large Scale Fading Effects	UVM/Agilent	Students characterize the large scale propagation effects of a naturally occurring environment.	▪ Signal Generator ▪ Spectrum Analyzer
3	Small Scale Fading Effects	Agilent	Students characterize the small scale propagation effects of a naturally occurring environment.	▪ Same as above

It is perhaps worth noting that the topics addressed in EE 273 and EE 295 are not typically covered at the undergraduate level, yet are important fundamental concepts required of engineers working in the wireless and/or digital communications field. The innovation in this program is that UVM's undergraduate students will not only develop unique knowledge of these concepts but will in addition receive significant related instrumentation experience.

While the individual course enrollments are small (10-20), it is clear that the infrastructure enhancements comprised of the two test benches will be well utilized. In response to recent ABET recommendations, EE 174 will now be required of all students and hence every UVM ECE major will have some level of exposure to the developments of this project. To ensure sufficient availability, the following steps have been or will be taken: first, students will work in teams of no more than three; second, students will have 24-hour access to laboratory facilities through a card key system; finally, web-based access utilizing, for example, National Instrument's LabView [11] equipment drivers will be employed where appropriate.

Results to Date, Lessons Learned and Remaining Work

At present, the lab enhancements described above are still being phased in. A subset of the labs listed in Table 4 was implemented in the Fall 2003 offering of *Digital Communications*. In addition, student projects investigated the various forms of signal corruption experienced in digital communications including amplifier distortion, multipath and quadrature error. Here final student reviews are pending, but an earlier online survey indicated for the most part that the lab experiments greatly enhanced the understanding of the material covered in class. In short, although the students will note the labs do require "extra" work, they do acknowledge and seem to appreciate their benefit. As such, the author believes the approach of enhancing courses with lab experience is showing promise.

Challenges for the project in the short term are to synchronize students in their experiences. For example, some students enrolled in the Spring 2003 offering of *Telecommunications Lab* have already taken *Digital Communications* and thus have relevant lab experience, others are simultaneously taking *Intro to Communication Systems* where the lab enhancements are being phased in with similar experiments, and some fall in neither category. As such, this particular semester's offering will require an *ad hoc* approach to lab assignments based on student experience which fortunately will be feasible given the small enrollments.

Additional work to be performed is to continue the outreach efforts already started and supported through the CCLI grant. In particular the author is collaborating with UVM's Women and Minorities in Math and Engineering Programs (WAMMIE) office in outreach activities such as accompanying university recruiters to provide insight to prospective students on electrical engineering, meeting on-campus with prospective students and developing recruitment material (websites, CD-ROMs and/or brochures[12]) to promote this program and engineering in general. Finally, the set of mature experiments will be made available through the author's home page beginning in Summer 2004[13]. These experiments will also be submitted to the Agilent Educator's Corner for broader dissemination.

Acknowledgements

The work presented herein was supported in part through NSF CCLI grant DUE-0310150. Equipment matches were made available by the Electrical and Computer Engineering Department, the College of Engineering and Mathematics and the Provost's Office at the University of Vermont. Equipment donations in support of this work were provided by IBM.

.

BIBLIOGRAPHY

[1] Feedback Instruments Limited, information available online at: www.fbk.com (07-Jan-04).
[2] P. Flikkema, L. Dunleavy, H. Gordon, R. Henning and T. Weller, *Wireless circuit and system design: a new undergraduate laboratory*, Proc. 1997 Frontiers in Education Conference.
[3] L. Dunleavy, T. Weller, P. Flikkema, H. Gordon, and R. Henning, *A versatile test bench for characterization of wireless RF/microwave components*, Microwave Journal, May 1998.
[4] T. Weller, P. Flikkema, L. Dunleavy, H. Gordon and R. Henning, *Educating Tomorrow's RF/Microwave Engineer: A new undergraduate laboratory uniting circuit and system concepts*, 1998 IEEE MTT-S Digest, June 1998.
[5] T. Weller, et al, *Educating tomorrow's RF/microwave engineer: a new undergraduate laboratory uniting circuit and system concepts*, IEEE MTT-S Int. Microwave Symp. Digest, 1997.
[6] T. Weller and L. Dunleavy, *Wireless and Microwave Education: From Circuits to Systems*, Proc. 1999 European Microwave Conference, invited paper.
[7] Agilent, Educators Corner, online: www.educatorscorner.com (12-Nov-02)
[8] Rohde & Schwarz, *Simulation Software WinIQSIMTM 4.1*, download at www.rohdeschwarz.com (13-Jan-04).
[9] Sample video lectures available online: www.emba.uvm.edu/~jfrolik (26-Nov-02)
[10] Dept. of Electrical and Computer Engineering, University of Vermont, *ABET 2000 Self Study Report*, June 2003.
[11] National Instruments, *About Labview*, on-line: amp.ni.com/niwc/labview/overview.jsp (30-Oct-02).
[12] J. Frolik, *Hands-on engineering activities at UVM*, available at www.emba.uvm.edu/ece/handson.pdf (13-Jan-04).
[13] J. Frolik, CCLI enabled lab enhancements, to be found at www.emba.uvm.edu/~jfrolik/labs_nsf_03.htm (Aug-04).

BIOGRAPHIES

JEFF FROLIK received the B.S.E.E. degree from the University of South Alabama, Mobile in 1986, the M.S.E.E. degree from the University of Southern California, Los Angeles in 1988 and the Ph.D. degree in Electrical Engineering Systems from The University of Michigan, Ann Arbor in 1995. He is currently an Assistant Professor in the Electrical and Computer Engineering Department at the University of Vermont (UVM). He is the recipient of the ASEE Southeastern Section New Teacher Award in 2002 (while at Tennessee Technological University).