A SENIOR-LEVEL RF DESIGN COURSE COMBINING TRADITIONAL LECTURES WITH AN OPEN LABORATORY FORMAT

William B. Kuhn[1], Donald R. Hummels[2], and Stephen A. Dyer[3]

***Abstract** - In Kansas State University's Design of Communication Circuits course, 10 to 15 students each semester are introduced to the theory behind wireless communications hardware used in modern products such as pagers, wireless LANs, and cellular telephones. In contrast to typical senior-design courses that have separate laboratory and lecture sections, the class combines lecture and laboratory work, with the instructor managing and grading both. This allows scheduling a series of projects that can be combined at the middle and end of the semester to produce relatively sophisticated products, such as working FM broadcast transmitters and receivers. An additional feature of the course is the use of an "open-laboratory" where students can work at any time during normal business hours to build and test their circuits. This allows a class of 10 or more to share a single copy of expensive equipment such as a spectrum or network analyzer, while providing a studio-type environment in which students can share experiences more effectively with others.*

Index Terms - *RF, wireless, design, laboratory, projects*

INTRODUCTION

A laboratory experience is an essential part of any engineering student's education, and all ABET-approved programs provide some form of laboratory exposure. However, the typical situation is one in which the laboratory is a stand-alone course taken only after necessary prerequisites are met, or a companion to a lecture course, run by a separate instructor such as a graduate student. Hence, the laboratory experience is often disconnected, or only loosely connected to the background lecture material, and much of the potential for reinforcing lectures with the lab experience is lost. Too often, these courses are reduced to ones that simply expose students to hardware and measurement practices through a series of small experiments, missing the opportunity to tackle complex systems and thereby fully engage a student's enthusiasm.

Recognizing this, Kansas State University's Department of Electrical and Computer Engineering developed a new course format in the early 1980's, in which in-depth lectures and laboratory work are combined into a single three-credit course, with the same instructor handling both facets to provide tighter coordination. Based on the realization that students have an inherent motivation to build things [1,2], the course was designed to take students through the design, construction, and testing of a significant and useful system -- an FM broadcast radio receiver. Over the years, the construction of an FM transmitter has been added as well, and the course has developed into one of the most popular offerings in the department, with students regularly identifying it as one of the classes in which they have learned the most material throughout their undergraduate educational experience.

COURSE STRUCTURE

Offered as a three-credit-hour course, the class is presented as two 50-minute lectures a week, with the remaining time allocated to laboratory work. The lecture content is carefully sequenced to remain in step with the laboratory projects throughout the semester -- a requirement that can be efficiently met only when the instructor is present for both the lecture and lab segments.

The laboratory component of the course is conducted in an "open laboratory" format similar to that described by Palais and Javurek [3], but smaller in scale. There is no scheduled laboratory time. Instead, students can use the communication circuits laboratory facilities at any time during the day and can check out keys during the weekend when necessary. As pointed out by Palais and Javurek, the open-lab format has a number of advantages, including:

- Lab scheduling is flexible, making it easier for students at enrollment time, and making time management more flexible for students during the semester,
- Teaming is enhanced, since students can better schedule when to get together to work on their projects, and
- Equipment can be better shared, allowing students access to facilities that would otherwise be cost-prohibitive.

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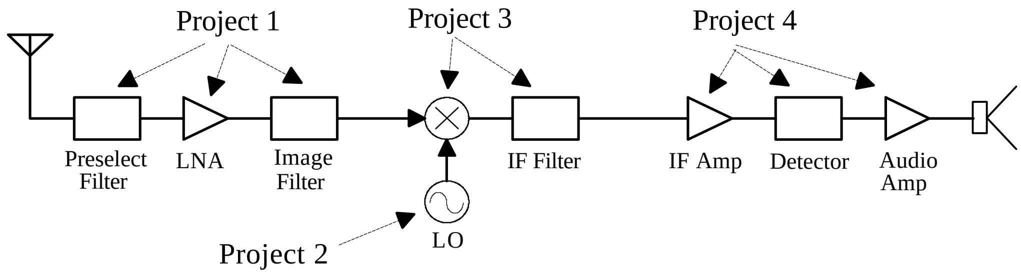

FIGURE 1.
PROJECT SEQUENCE LEADING TO FINAL RECEIVER PRODUCT.

In addition, we have found that a small-scale open laboratory promotes a "studio-like" setting in which students can share experiences in building and testing their projects that is superior to the forced two-person teams characteristic of traditional labs. For example, it is not unusual to find students working together for long hours and discussing solutions to problems though face-to-face interactions or through notices left on the chalk board -- features of the class that are strongly encouraged, since there is ample opportunity to assess individual understanding through the written lab assignments and midterm/finals described below.

To allow time to design and test relatively sophisticated circuits while keeping the workload on students and instructor reasonable, there are no traditional homework assignments during the semester, despite the fact that there are two hours of lectures each week. Instead, students are required to complete a carefully timed sequence of four to five projects over the semester, involving detailed design writeups and notebook entries. In the first several projects, they turn in a preliminary design writeup containing their proposed circuit schematic, their layout, and circuit-design calculations and discussions. This preliminary design is then graded and returned at the next class period, with suggestions for what needs to be improved (though not necessarily the details of *how* to improve it). The student then makes the required changes and proceeds to build and test the circuit, recording the final schematic, circuit explanation, and laboratory measurements in his or her laboratory notebook for a final grade on the project. These writeups, as well as all construction work and measurements, are done individually by each student, although they are allowed and encouraged to help each other in understanding core material and in working through problems encountered in the lab. This approach, combined with student interaction in the open laboratory, accommodates multiple learning styles well, while providing good individual accountability. It is generally possible to separate students performing at excellent, good, or fair levels of comprehension and effort after only a few labs have been turned in and reviewed.

Additional individual accountability and performance assessment is provided through midterm and final "exams." Around the middle of the semester, students have constructed enough circuitry to form a small working product (an FM broadcast band transmitter). For their midterm grade, they are required to demonstrate the product to the instructor and to document it in the form of a "Service Manual". The demonstration provides a good motivational milestone for the student while the Service Manual provides an excellent vehicle for the student to develop technical writing skills and the instructor to gain insight into the student's level of understanding. In the Service Manual writeup, the student is told to provide a block diagram and a schematic diagram of the full circuit, and to explain the system and circuit operation to an audience with general knowledge of electronic circuits, but with no knowledge of radio or of the specific assignments that led to the product. Thus, they must understand the material in sufficient depth that they can explain it to others -- a task that forces the student to think beyond canned equations to the engineering that underlies the product, and a feature of the course that several employers have cited as valuable training for engineers.

Generally, it is found that students' writing styles and adherence to the service manual format varies widely at the midterm, so that this "exam" is weighted relatively lightly and is used primarily as a "trial-run" to provide feedback prior to the "final exam." In the final exam, students must demonstrate and document the complete working receiver built from the full sequence of projects detailed in the following section.

PROJECT ASSIGNMENTS AND ASSOCIATED LECTURES

With two out of three credit hours devoted to in-class lectures, the class retains many features of a lecture-based course, allowing complex circuit design theory to be covered in an efficient manner. However, unlike traditional lecture-only courses where the presentation sequence is fixed by available textbooks or the instructor's personal preferences, all work in a course of this type centers around a sequence of projects leading to a final product such as that shown in Figure 1. Since the final product is relatively complex, (a complete radio receiver), projects begin immediately, rather than being pushed to the latter half or third of the semester, and lectures are carefully structured to cover the material needed for each project 'just-in-time'.

Although the exact content and sequence of projects has varied over the years, the sequence shown in Table I is representative.

TABLE 1
SEMESTER PROJECTS

Project	Description	Weight
0	SMT Soldering Exercise	5%
1a	Simple CE or CB Amplifier	15 %*
1b	Tuned, matched RF amp	15 %*
2	Voltage-controlled oscillator	15 %*
Midterm	FM transmitter (Combine projects 1 - 2)	10 %
3	Mixer and IF filter	10 %**
4	IF amp, demod, and audio	10 %**
Final	FM receiver (Combine projects 1 - 4)	20 %

* 5% for preliminary design and 10% for lab notebook writeup
** 10% total - no preliminary design writeup required

Project '0' was introduced in recent years, when surface-mount technology (SMT) was adopted into the course. It consists of a simple circuit, such as a bandpass filter and resistive attenuator network, which is predesigned and is to be constructed by the student. This project allows students to practice soldering SMT components which are now standard in industry, but are still largely unused in university labs.

To address the unique construction concerns associated with SMT devices, the course uses "Ivanboards" [4] such as that shown in Figure 2 (circuit pictured is more complex than Project 0!). The board contains a grid of square pads on 0.1" centers on the top side, and a tinned copper ground plane (essential for building high frequency circuits) on the backside.

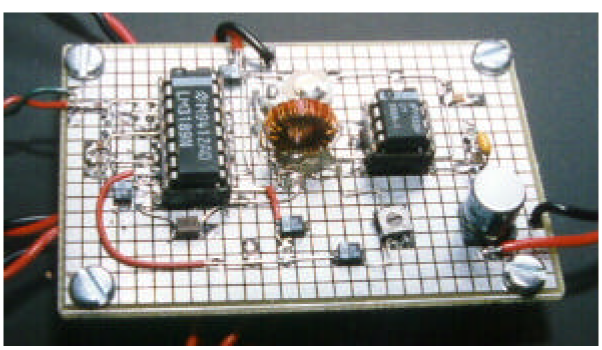

FIGURE 2.
IVANBOARD WITH SMT COMPONENTS

During construction of Project 0, lecture material required for Project 1a is presented. In Project 1a, students design a simple common-emitter or common-base amplifier to meet particular specifications (e.g., bias current, total current, gain, and lower corner frequency). This project and associated lectures helps students recall the essentials of analog circuit design (bias and small-signal AC circuits), and helps them become familiar with the signal generators and oscilloscopes in the lab. More importantly, it demonstrates the problems associated with trying to achieve high gain at high frequencies, and the loading and parasitic effects encountered when trying to use oscilloscopes for circuit measurements at radio frequencies.

During the design, construction, and testing of Project 1a, a series of lectures covers the essential radio-frequency (RF) design concepts needed to overcome these problems, including resonant circuits, stability and cascoding, matching networks, and transmission lines. This material is then employed in Project 1b where the amplifier is outfitted with a resonant circuit to provide gain within a passband centered around the frequency of interest (e.g., 100 MHz) and with matching networks to convert I/O impedance levels to 50 ohms. Testing of this project provides the student with exposure to vector network analyzers and S-parameter measurements that are now employed almost universally in the RF hardware-design and manufacturing industries.

Project 2 entails the realization of a voltage-controlled oscillator (VCO), suitable for use as a direct modulated FM signal source for the midterm transmitter and as a local oscillator in the final receiver assembly. The Colpitts oscillator topology is presented during construction of Project 1b and naturally follows the tuned RF amplifier concepts previously covered, being simply a common-base RF amplifier with feedback added. A varactor diode is used for frequency tuning, with an associated IC-based voltage regulator added for stability and potentiometer added for frequency control.

At the completion of project 2, the basic circuits needed to assemble a simple FM transmitter are available, and the addition of an electret condensor microphone and demonstration and documentation of this transmitter constitutes the midterm exam (See Figure 3 below).

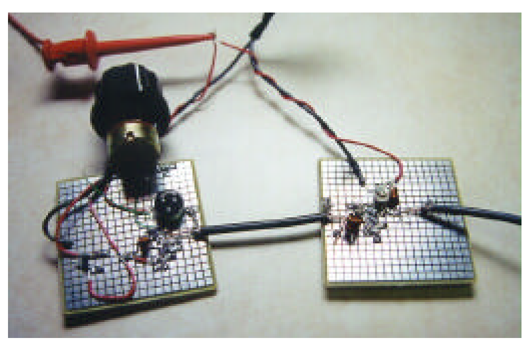

FIGURE 3.
FM TRANSMITTER BUILT FROM PROJECTS 1 AND 2.

This midterm exam is typically well-received by students since it allows them to see their efforts combine into a useful and fun circuit, and for the first time demonstrates the magic of radio -- an experience that is enriched by the knowledge they have gained of how the circuits are designed, built, and tested in practice.

Following the midterm, Projects 3 and 4 complete the semester sequence with the design, testing, and documentation of an RF mixer used to convert the received signal to a classic 10.7 MHz intermediate frequency (IF), and the design and construction of an IF subsystem and audio amplifier. Student interest level developed in the midterm is maintained in project 3 by measuring the FM broadcast-band spectrum using a spectrum analyzer connected to an antenna, and then viewing the downconverted spectrum at the output of their mixer before and after IF channel-select filtering. Project 4 then takes the student through the internal workings of an IF subsystem and audio-amplifier IC (such as the LM1868) around which they must design and add necessary external components associated with demodulation and audio signal processing. The circuits of Project 4 are tested and then combined with Project 3 and an RF signal generator to allow their favorite radio station to be heard -- a second exposure to the magic of radio which is typically as well enjoyed as the first. Subsequently, the full set of projects is assembled into a radio receiver by wiring together all projects built during the semester and mounting them on a suitable board as shown in Figure 4.

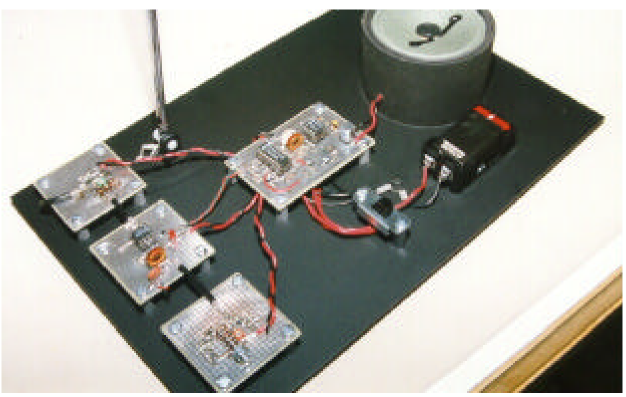

FIGURE 4.
PROJECTS 1 THROUGH 4 COMBINED INTO COMPLETE RECEIVER.

LABORATORY FACILITIES

Setting up a laboratory for radio-engineering education involves the purchase and maintenance of special equipment such as SMT soldering stations and some expensive test instruments. For a small-to-moderate size student population, purchasing multiple copies of such equipment to outfit several benches may be cost-prohibitive. Fortunately, however, the open lab concept has worked well, allowing a single state-of-the-art spectrum analyzer and vector network analyzer to be efficiently shared by 10 or more students.

In addition to a spectrum analyzer and network analyzer, and a small collection of signal generators and power supplies, etc., the lab is outfitted with two benches devoted to circuit construction. Fine-tipped (0.015” radius) soldering irons are used for SMT soldering, and special tweezer irons and hot-air irons are provided for SMT component removal when needed. Other equipment provided includes a BNC-connector crimp tool to allow students to build up their own cable assemblies, a small drill press for creating via holes to the Ivanboard’s backside ground plane, a large-tipped 90W iron for soldering to this ground plane, and various optical aids for working with the small SMT components (see Figure 5). Aids ranging from typical lab bench magnifying glasses with fluorescent lighting to a video camera and monitor have been tried, although simple $30 head-mounted 2.5X power magnifiers have been found to be the best value.

FIGURE 5.
CONSTRUCTION OF CIRCUITS.

PROJECT KITS AND SMT PARTS INVENTORY

Student projects are constructed around standard core circuits discussed in class (e.g., CE amplifier, SA602 mixer IC, LM1868 or LM3189 IF subsystem IC, etc.), with the details of the design (resistor, capacitor, inductor values and some variations in circuit topology) to be worked out by the student. Thus, the major components to be used, such as transistors, varactor diodes, ICs, and hardware (coax connectors, Ivanboards, etc.) are ordered in advance and placed into student-purchased kits. This allows the laboratory’s parts inventory to be kept to a manageable level, consisting mainly of a set of standard-value 0805 SMT resistors and capacitors, and some spare kits for breakage and loss. Total cost of the kit purchased by the students averages $50, an acceptable amount since students are not required to purchase a text for the class.

Summary and Conclusions

Combining lecture and laboratory elements in a senior design course allows sophisticated projects to be tackled, increasing enthusiasm in the classroom. The tight coordination of these elements allows project work to begin immediately and run throughout the term, as new lecture topics are presented. By carefully sequencing projects, complex systems such as a complete radio receiver can be constructed in a single semester.

By running the lab component in an open laboratory format, such courses can offer students exposure to state-of-the-art circuit construction facilities and test equipment that is too expensive to duplicate at multiple lab stations. Moreover, we have found that a small-scale open-lab format provides a studio-like setting that enhances the educational experience by allowing improved interaction between students.

For the majority, the final product and associated Service Manual are viewed with substantial pride, and many have reported significant interest in the class by employers during job interviews. Some students even report using their receiver years after they leave campus. Overall, comments from students on the course instruction have been overwhelmingly positive, supporting our conclusion that the class structure provides an effective and enjoyable learning experience, not generally matched by traditional laboratory formats.

References

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[4] Ivanboards are manufactured by Circuit Engineering and Development (CED), 1312 E. Wieding Rd., Tuscon, AZ, 85706.