Undergraduate Laboratory for Radio Frequency Systems with Design and Manufacture

William C. Barott[1] *and Sugoon Fucharoen*[2]

Abstract – The undergraduate electrical engineering curriculum at Embry-Riddle Aeronautical University includes a three-course sequence in electromagnetism, radio frequency systems, and the RF laboratory (taken concurrently with the RF class). These courses are designed to support novice students in attaining the final learning objective of the RF Lab: the design and understanding of a simple digital radio to transmit information, wirelessly, from one microcontroller to another using a RF carrier. This paper describes the format of the sequence, its evolution, lessons-learned, and future plans.

Keywords: Microwave, Radio, RF, Laboratory, Printed Circuit Board (PCB)

INTRODUCTION

The engineering curriculum at the Embry-Riddle Aeronautical University (ERAU) Daytona Beach campus reflects the school's focus and heritage in aerospace and aviation by related focus areas within the engineering disciplines. Three tracks in electrical engineering include (a) aerospace systems, which emphasizes systems engineering practices, (b) avionics, which includes elements of sensors, navigation, and communication, and (c) a non-track option that substitutes electives for avionics-specific courses in the avionics track. Both the avionics and non-track sequences require a two-semester sequence of electromagnetism (EE340) and radio frequency engineering (EE430) with an accompanying laboratory (EE430L).

Students start taking this sequence with background in basic electricity (or electronics) and non-linear circuits, but not the principles of transmission lines. Students leaving the sequence are expected to demonstrate level-appropriate competence with the computer and laboratory design, analysis, and implementation of high frequency and electrically-large systems (i.e., circuits where the structure is no longer infinitesimally small compared to a wavelength). Hands-on assignments are emphasized, and the laboratory includes an iterative design cycle with elements of manufacturing and manufacturability.

The following sections of this paper describe this sequence. First, the rationale for the structure of the E&M and RF sequence are presented. Then the computer-based experiments in EE340 are discussed in the context of how they prepare students for EE430. Next, the 430L labs are presented including detail of each experiment and module. The paper concludes with some lessons learned and future plans.

RATIONALE AND RELATED WORK

Background and Active Learning

The E&M/RF sequence helps bridge the gap between students who have finished secondary circuits and devices classes, and graduating students who are expected to demonstrate competency in electrical engineering for aerospace and related fields. Supporting sequences taken with or at about the same point in the curriculum as E&M/RF include

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analog and digital communications (presenting the mathematics and theory of information transmission), avionics 1 and 2 (presenting the architecture and theory of navigation and communications, including radio-based aids), and microprocessors & DSP (presenting the implementation of techniques in embedded systems). The E&M/RF sequence fits with these through a focus on the analysis of circuits and behavior of high frequency systems.

The E&M/RF sequence was initially developed in 2006 and early decisions included focusing on the circuits and transmission line analyses (rather than fields), and including a strong practical element throughout the experience. Support for both of these can be found throughout the literature. For example, [Pozar, 10] recently noted a pedagogical shift in the role of microwave engineering away from the foundations of Maxwell's equations to circuits-based techniques. Shifting away from fields-based analyses allows more time to pursue practical applications and analyses that are more relevant to the students and their future careers. We adopt this approach but retain [Pozar, 9] as the textbook for EE430, so that more-detailed analyses can be referred to as warranted.

The inclusion of practical elements and laboratory activities is also described as "project-based learning" and "active learning," and proper implementation of these activities can enhance the learning experience. It is noted by [Pan, 7] that the benefits of project-based learning extend beyond the technical content to topics like project management and communication. [Pejcinovic, 8] describes a tightly-coupled approach to teaching microwave systems in which the classroom and laboratory are integrated. [Pejcinovic, 8] notes that this provides students immediate feedback and allows the students to try new techniques (and possibly fail) without disproportionate penalty.

The format of ERAU's EE340 class includes (a) in-class lecture, (b) in-class demonstrations and computer tutorials, and (c) at-home computer labs. The presentation of EE430 and EE430/L is tightly-coupled between the lecture and laboratory sections. They are formatted as 75 minute lectures on Tuesday and Thursday with a 180 minute lab on Wednesday, and each of these is led by the same faculty instructor, rather than an autonomous graduate teaching assistant (GTA). The format is intended to allow pre-lab and post-lab preparation and discussion within the lecture, and to allow the exact timing of each to be tweaked as the semester progresses.

Experiments and Labs

The importance of using a well-designed sequence of experiments is described by [Braun, 3], who noted that isolated, stand-alone laboratories can often frustrate students. A single experiment cannot dive deeply into a problem, and it was found instead that laboratories developing from building-blocks to finished products are better received by the students. An effort is made in the EE430L sequence to show the ties between experiments, which culminate in a project using many of the previous building blocks.

Given the prevalence of planar microwave circuits noted by [Pozar, 10], it is important for EE430L to contain elements of manufacturing and manufacturability, so that students understand the process from design requirements (e.g., a band pass filter having certain properties) to realization (e.g., implementation on Rogers 4003 using a coupled-line architecture). Students are expected to hand-solder connectors and SMT components to bare boards, and, as with [Blackwell, 2], it is found that this process conveys important lessons about manufacturability and the assembly process. Students are allowed the opportunity to make (and correct) mistakes, such as failing to place a SMT pad on the board, or ordering parts having the wrong package size.

In the initial offerings of EE430L, outside vendors were used for PCB production. Although there are inexpensive vendors for this purpose (as also noted by [Blackwell, 2]), it was found that this created a hole in the learning experience. Counter examples such as [Braun, 3], [Coonley, 5], and [Koretsky, 6] note the benefits of retaining PCB manufacturing within the laboratory. ERAU purchased a S103 PCB mill from LPKF in 2013 to enable students to better understand the entire design process. Having the mill in-house reduces the lab's reliance on external vendors, reduces the cost and time per-iteration, and enables students to rapidly create a revision of their board if required. The mill also enables inexpensively producing designs on microwave substrates other than FR-4.

Other sequences and laboratories in microwave engineering can be found in the literature, and similarities (and differences) between these and the ERAU offerings are worth noting. The approach of including a mix of new and old equipment and techniques is described by [Shakur, 11], who notes the benefits of "pedagogically instructive" equipment in helping the students better-understand what measurements are actually being made. A three-semester undergraduate sequence described by [Caverly, 4] is longer than ERAU's; however, we have recently designed an introductory masters level course called Sensors and Datalinks to capture the implementation of RF systems and as a natural follow-on to EE430. The outline for a satellite communications lab given by [Behagi, 1] places more focus on active circuits than the ERAU labs, which place an emphasis on passive systems, structures, and the behavior of electrically-large devices. Finally, ERAU's aerospace focus is similar to that described by [Sholy, 12], and many similarities can be found in the themes of the selected experiments.

ARCHITECTURE, FACILITIES, AND SOFTWARE

Course Architecture

The E&M/RF sequence includes both computer-based elements and hardware-based elements, which are distributed throughout the courses as shown below.

- Computer-based: Sonnet for simulation and MATLAB for data analysis (EE340, EE430, EE430L)
- Mix of older and newer hardware-based test equipment (EE430L)
- PCB manufacturing (limited in EE430L)

A conceptual and topical outline is shown in Fig. 1. EE340 follows a transmission-lines-first approach using the text of [Ulaby, 13]. Five integrated computing projects are designed to reinforce the topics from the class and also prepare students for the experience in EE430. The EE430 curriculum follows a circuits-based approach of selected topics from [Pozar, 9], emphasizing the themes of S-parameters and frequency-domain analysis, while illustrating the purpose of each module in the context of an RF system or aerospace application. The EE430L laboratory has fifteen weeks emphasizing observation, interpretation, design, and implementation of various systems, and culminating in a three-week design topic.

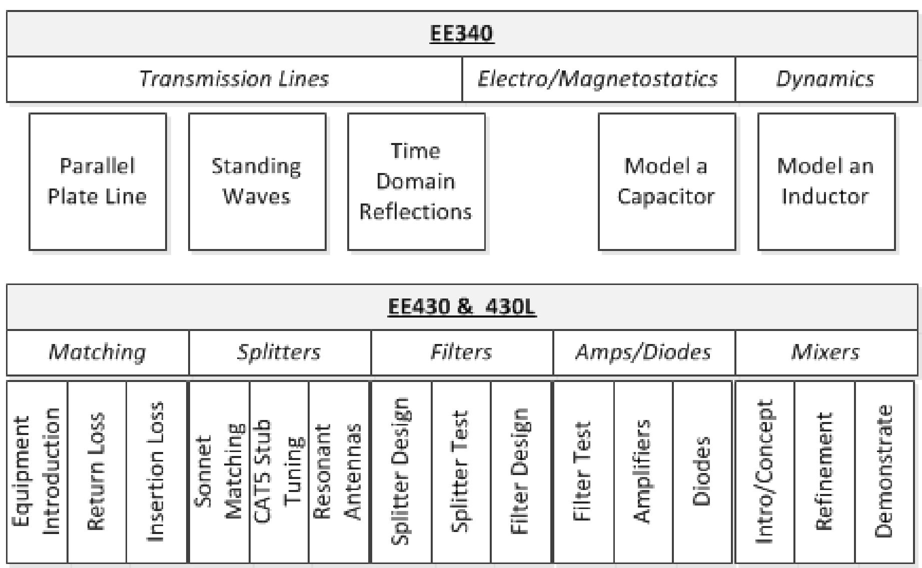


Figure 1. Topic outlines. EE340 includes both in-class (italic) and simulation (below) topics. EE430 includes in-class modules (italic) and coordinated experiments for EE430L (below).

Laboratory Stations

The labs in EE430L use laboratory stations that have been configured specifically for this course. Each station is identically-configured and most experiments are designed to be performed by two or three students on a team. A lab station is pictured in Fig. 2, and the particular hardware is itemized as follows.

- Tektronix 2712 Spectrum Analyzer with Tektronix 2707 Tracking Generator (to 1.8 GHz)
- Two Hewlett-Packard 8656B Signal Sources (to 990 MHz)
- Tektronix PS2510G Programmable DC Power Supply
- Tektronix TDS 320 Two-Channel Oscilloscope (to 100 MHz)
- Tektronix CFG280 Low Frequency Generator
- Desktop computer, Sonnet, and MATLAB

The laboratory maintains supplies of cables, connectors, couplers, splitters, and parts required for each experiment. In addition, the laboratory has one each of the following equipment.

Figure 2. Image of the Lab Stations

- Agilent ENA series 4-port network analyzer
- LPKF S103 Circuit Mill

INTRODUCTORY EXPERIMENTS: EE340

In the initial offering of EE430, it was discovered that it was disadvantageous for students to be learning a new software tool (Sonnet) at the same time as they were expected to use that tool for significant design. Students reported frustration with integrating new techniques (for which they were unsure if they would achieve the desired result) with new tools (in which they were unsure if they were viewing the results correctly). In response to feedback, a sequence of introductory experiments was introduced to EE340. These labs are significantly scripted and designed to work as step by step tutorials with up to 40 individual steps (such as opening a window or pressing a button) per assignment. These ensure that the student achieves the correct results from the simulation tool, and then the interpretation of those results in the context of the class is a required task for the individual student report. Individual topics are listed as follows.

- Lab 1: Create a parallel plate transmission line and observe calculated vs. simulated impedance.
- Lab 2: Create lines terminated in open, short, load, and mismatch and observe the response on a Smith Chart.
- Lab 3: Simulate the open, short, load, and mismatch across many frequencies, and apply an inverse Fourier transform to obtain the impulse response (Fig. 3).
- Lab 4: Simulate a parallel plate capacitor of varying geometries and identify regimes where fringing fields become important.
- Lab 5: Model a transformer (Fig. 3) and observe transformer behavior as well as the effect of parasitic capacitance, and identify the self-resonant frequency of the inductor.

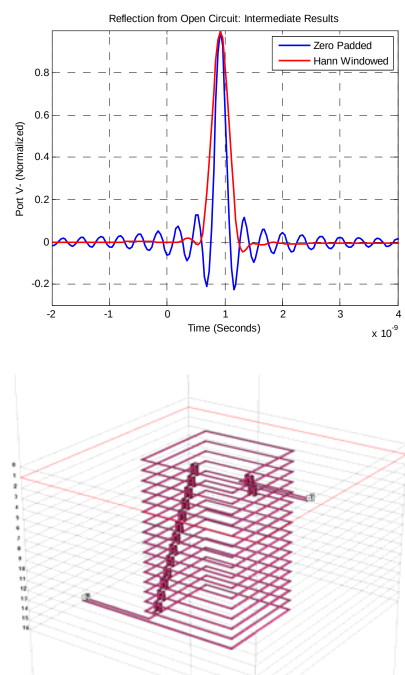


Figure 3. Two examples of EE340 Sonnet tasks. (Top) Interpretation of multi-frequency refelction data to produce a time-domain reflectometry plot. (Bottom) A multi-layer inductor used to teach about transformers and parasitic self resonance.

LABORATORY EXPERIMENTS: EE430L

The EE430L laboratory progresses through a sequence of experiments designed to build on each other and to support the topics taught in the lecture section. The topics are roughly grouped by weeks as follows, and are explained in more detail on the following pages.

- (1) Students are introduced to the equipment and perform basic measurements identifying radio stations.
- (2-3) Students measure the return loss and insertion loss of simple devices, and to show that the measurements match predicted results.
- (4-5) Students first simulate then build resonant impedance matching devices.
- (6) Students observe resonant behavior inherent to monopole antennas.
- (7-10) Students design, manufacture, test, and evaluate microwave splitters and filters.
- (11-12) Students observe non-linear behavior of amplifiers and diodes.
- (13-15) Students use their assembled knowledge to wirelessly transmit simple data between microcontrollers.

Introductory Experiment (Week 1)

The first lab is designed to orient students with the tools of the laboratory and to become familiar with decibel-scale measurements. They are tasked with making simple measurements of attenuation and frequency using a spectrum analyzer and a RF signal generator. They are asked to use the spectrum analyzer, connected to an antenna, to identify VHF and UHF radio, television, and aviation-related signals.

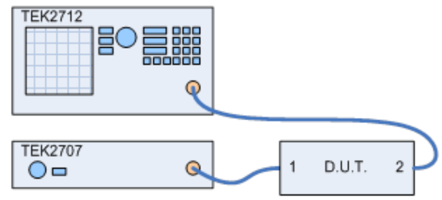
Return Loss and Insertion Loss (Weeks 2 and 3)

The second module introduces students to the directional coupler and the concept of return loss, insertion loss, and calibration. In the second lab, they first measure the characteristics of a directional coupler, and construct a scalar s-parameter matrix for the device. Next, the students measure the return loss of several unknown resistive devices and must use the underlying theory (from the class) to determine possible values for the loads.

The third lab changes to insertion loss measurements, and adds reactive components. Students must determine the component values by analyzing the insertion loss versus frequency. The inductor is selected to have a self-resonant frequency within the measurement band so that the students readily observe the effects of the parasitic capacitance, as shown in Fig. 4. This is meant to reinforce the inductor simulation from EE340.

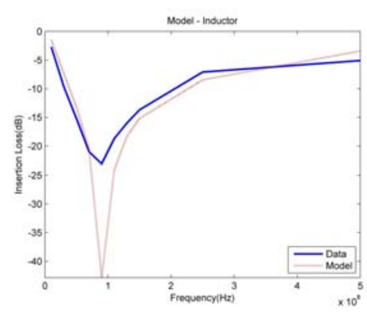
Analysis and modeling for this module is presently limited to MATLAB. Based on student feedback, Sonnet modeling requirements are being developed to improve proficiency with including lumped-element components in Sonnet models.

(a) A series SMT device



(b) Configuration using a tracking generator and spectrum analyzer

(c) Analyzer display showing both inductive and capacitive behavior



(d) Analysis comparing measured data to a best-fit parasitic model

Figure 4. Experiment and analysis for self-resonance in an inductor.

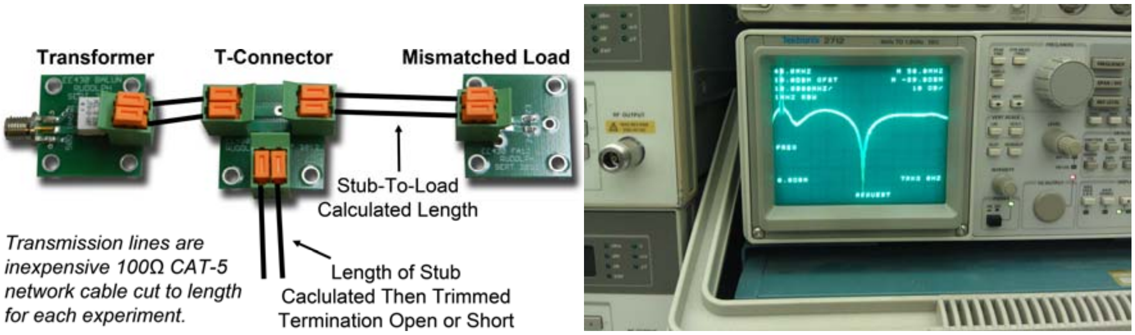


Figure 5. Custom CAT-5 adapter boards (left) and image of the spectrum analyzer illustrating the resonant match at the intended frequency (right, courtesy of students ME and JS).

Impedance Matching (Weeks 4 and 5)

After demonstrating proficiency with measuring impedance mismatches through insertion loss and return loss, students are introduced to impedance matching through design and simulation. Lab four is entirely computer-based using Sonnet, and implements single stub, quarter wave, and L-section designs. This lab is typically accompanied by tutorial help during the lab session, as it is the first major Sonnet assignment since EE340. Students put impedance matching into practice in a single stub tuner in lab five, which uses Cat-5 twisted pair cable as the transmission line. Cat-5 was selected both because it is inexpensive and also because it is familiar to the students. This experiment is illustrated in Fig. 5. Custom PCBs are used to interface the Cat-5 with coax, provide a T-connector, and provide a termination to a known, mismatched load. The students must design and implement a single stub tuner for 50 MHz using both open-circuited and short-circuited stub ends. A directional coupler and tracking generator are used to measure the return loss, and students often react positively to observations of their first good match, shown as the resonance illustrated in Fig. 5.

Resonant Antenna (Week 6)

Lab six continues with the theme of resonant matching by exploring naturally-resonant monopole antennas. This lab allows students to identify that monopoles are resonant when operated at a quarter wave, and to observe how the resonance shifts as they change the length of the antenna. Through their interactions with the antenna and with neighboring groups, they can also observe the phenomena of radiation and parasitic effects. A pre-lab component to this lab is based in Sonnet and introduces the concept of modeling the antenna's resonance and radiation pattern.

Design and Manufacturing of Splitters and Filters (Weeks 7 to 10)

Weeks seven through ten include the two manufacturing modules, each of which is designed to take students through processes beginning with requirements, including design and manufacturing, and ending with measurement and verification. The process is outlined as follows.

- Identify the requirements and type of structure
- Complete a paper design
- Implement in Sonnet subject to specified constraints
- Export the design to Gerber format
- Mill the design using the mill in the circuit prototyping lab (pictured in Fig. 6)
- Assemble components, connectors and plate vias
- Measure the S-parameters on a vector network analyzer
- Compare the measured, simulated, and intended results

Figure 6. LPKF S103 circuit mill in the circuit prototyping lab at ERAU.

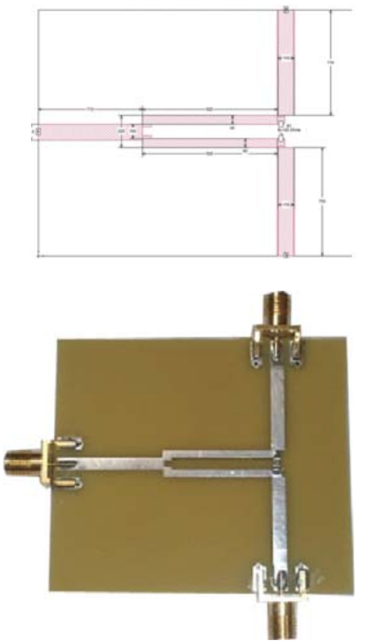


Figure 7. Sonnet layout (top) and resulting structure (bottom) of a Wilkinson power splitter fabricated on FR-4. Images courtesy of student JS.

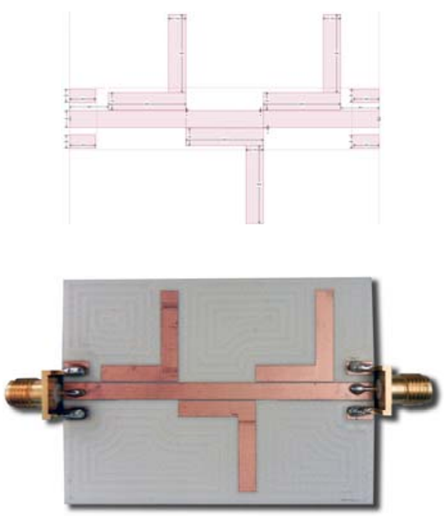


Figure 8. Sonnet layout (top) and resulting structure (bottom) of a band stop filter. Images courtesy of student MA.

Subject to the constraints of the modules (splitters and filters), students may utilize an arbitrary set of requirements provided by the instructor or are free to propose their own (for example, a band pass filter for GPS).

The design process is intended to reinforce the techniques instructed in the lecture section. These include Wilkinson, branch line, and ring hybrids in the splitter section, and discrete-element, resonant stub, and coupled line architectures in the filter section. However, students are encouraged and incentivized to research design alternatives available in the literature. This external research is aligned with ABET Student Outcome “i" (life-long learning) and also ERAU’s *Ignite* initiative for undergraduate research.

Transferring the paper designs to Sonnet requires correctly assessing the materials and manufacturing constraints, such as board size, permissible via sizes, and component footprints. Students are expected to have begun the process of the Sonnet layout before the first lab session of each manufacturing module. This session is used as a help session to assist students in finishing these designs, which are then exported for manufacturing. The boards are panelized and assembled using the in-house mill. Students are invited to observe the mill operation, and may participate with the oversight of the mill operator.

The boards resulting from these modules are tested using an Agilent 4-port vector network analyzer. Students are taught the process of calibrating the instrument and exporting measurement data. Reports from these modules are expected to integrate data from the VNA, Sonnet, and the original requirements into a single plot to allow for critical comparison of the performance of the finished product.

Students learn important lessons about manufacturability in these labs. Examples of devices that have good simulated characteristics, but cannot be manufactured, include those in which the transmission lines are too close together for the connectors to fit, component pads have been omitted, or vias are not properly sized for the tooling.

Nonlinear Devices (Weeks 11 and 12)

The final structured laboratory module consists of two weeks exploring the behavior of nonlinear devices (amplifiers and diodes). Each of the labs uses bare PCBs with simple designs so that students can observe the supporting circuitry, such as bias resistors, decoupling capacitors, and RF chokes. This also allows components to be replaced if they are accidentally destroyed during testing.

First, lab eleven explores the properties of RF amplifiers, using inexpensive chips from Minicircuits. Students are first tasked to measure gain and isolation, and this represents the first non-reciprocal device measured in the class. They next explore linearity by measuring gain versus input RF power, and finding the 1 dB compression point. Next, they configure their system for a two-tone intermodulation measurement, and observe the strength of the intermodulation products as a function of input power. A photograph of the two-tone measurement is shown in Fig. 9. Finally, the students interpret their data to find the third order intercept point, and compare their measured data for gain, compression, and IP3 to that provided by the manufacturer.

Lab twelve examines the properties of RF diodes using boards designed for PIN and Schottky diodes. The Schottky diode is used as a rectifier, and students use a modulated RF carrier and oscilloscope to determine the conversion efficiency of the diode as a function of the bias current. They record and save the optimal value. Next, the RF properties of a PIN diode are examined as a function of bias current, and the component is evaluated as a switch and variable attenuator.

The final task of lab twelve requires the students to use the PIN diode as an on/off modulator for an RF carrier. The bias current is modulated using a low-frequency generator, and the resulting RF is passed to the Schottky rectifier, which is biased with its optimal value. The students must demonstrate that the rectified waveform is a suitable representation of the original modulation signal.

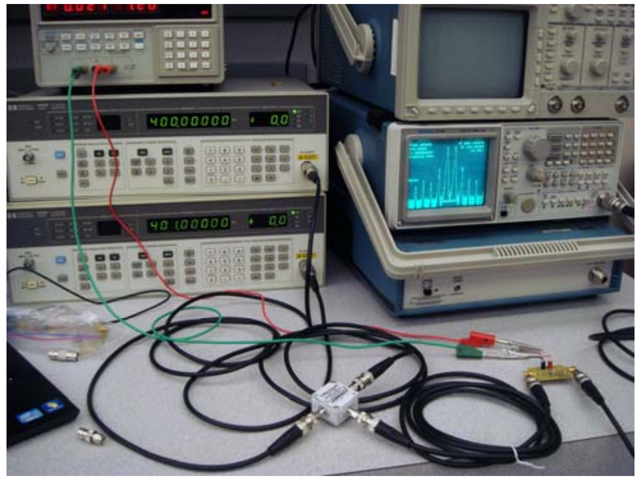


Figure 9. Configuration for an experiment measuring intermodulation distortion, showing the two-tone setup, amplifier, and harmonics.

Freeform Experiment (Weeks 13 through 15)

The final three weeks of the lab are a free-form experiment meant as a culminating experience for the course. Students are tasked to create a system meeting the following general requirements, which are meant to illustrate the transmission of one bit of digital information from a transmitter to the receiver:

- The system must have a transmitter and a receiver, which communicate only through a RF wireless channel
- The system must have three states, called "red," "green," and "off"
- The transmitter should include supporting hardware of two switches, two LEDs, and a microcontroller
- The receiver should include supporting hardware of two LEDs and a microcontroller
- Depressing the red or green switch on the transmitter must cause the corresponding color LED on the transmitter and receiver to illuminate; otherwise the LEDs must remain off.

Students are encouraged to select unique design approaches within the spirit of the assignment, and groups are incentivized to compete through measurements of the successful transmission distance. Completion of this project is anticipated to include most of the material from the preceding labs, as well as to use knowledge from other courses. Possible aspects that may be included are itemized below. The lab may be successful using some or all of these, allowing students to achieve the required outcome at a level appropriate to their skills.

- (Labs 1-5) Performing RF Measurements
- (Lab 6) Implementing a resonant antenna at the transmitter and receiver
- (Labs 7-8) Splitting the signals to implement multi-antenna gain or diversity
- (Labs 9-10) Designing a RF filter for the receiver
- (Lab 11) Implement a RF amplifier for the receiver or transmitter
- (Lab 12) Use a PIN diode for amplitude keying and a Schottky diode for envelope detection
- (External) Integrating the PIN and Schottky diodes with microcontroller boards
- (External) Designing a baseband op-amp circuit to amplify the rectified envelope

Conclusions, Lessons Learned, and Future Plans

Student feedback and instructor evaluations have guided the evolution of this sequence since its first offering. The introduction of Sonnet to EE340 was a direct response to student performance so that they would be more familiar with the tool in EE430. In addition, the EE430L laboratories continue to evolve. Four key areas for future improvement have been identified, and are detailed as follows. It is anticipated that these changes will continue to improve the student experience and attainment of the learning objectives of this sequence.

Hands-On Design

Many authors report the benefits of hands-on activities and design labs, and it has been observed in EE430L that students respond best to assignments with these aspects.

- **Current Lab:** Manufacturing labs, recently-added SST lab and final project.
- **Future Opportunities:** Incorporate design elements in labs currently limited to measurement and phenomenology. For example, modify the amplifiers lab (11) to include a section on designing a link for the best symbol error rate (maximum power with minimum distortion), based on the measurements. Include tutorials on how to effectively read datasheets for component selection.

Laboratories as Building Blocks

[Braun, 3] notes that students prefer labs in which the individual experiments are building blocks of a final experiment.

- **Current Lab:** The themes of individual labs are incorporated into the final project and some components (e.g., diode boards) are used directly.
- **Future Opportunities:** Modify each lab so that the resulting product (e.g., filter, splitter, or antenna) is directly useful for a later laboratory or the final project, without restricting the freedom of design in the final laboratory.

Pedagogically-Instructive Techniques

The pedagogical effectiveness of older equipment and techniques is noted by [Shakur, 11], and the assertions of that work have been generally observed at ERAU.

- **Current Lab:** Initial experiments use manual insertion-loss and return-loss measurements. The vector network analyzer and automated measurements are taught, but restricted to the manufacturing labs.
- **Future Opportunities:** Introduce in-class labs to EE340 using less-modern (but more-transparent) techniques like slotted line measurements and transmission lines made of copper foil tape (after [Caverly, 4].

Expanded Sequence and Course Coupling

The two-semester sequence provides foundational material, but additional coursework would improve the mastery of the material (for example, [Caverly, 4] describes a 3-course sequence).

- **Current Lab:** Two-semester sequence that feeds naturally to a first-semester graduate course, EE528 *Sensors and Datalinks*. Ties to communications and low-frequency circuits in the final laboratory. Ties to computer programming in some data analysis assignments.
- **Future Opportunities:** Improve coupling with EE417, *Digital Communications*, which is taken the semester immediately following EE430, since the final lab is an introductory communications task.

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Sugoon Fucharoen

Mr. Sugoon Fucharoen holds a BS in Electrical Engineering from Stanford University and is now pursuing his graduate studies for the Master of Science in Electrical and Computer Engineering at ERAU. His areas of interest include avionics, air navigation aids and phased arrays, and his current graduate research work focuses on implementing novel beamforming techniques in a software-defined beamformer for Allen Telescope Array. Upon graduation, Sugoon will serve as a system engineer for Aeronautical Radio of Thailand, an air navigation service provider for Thailand’s airspace, where his work will likely focus on performance-based navigations and international cooperation toward seamless Asia-Pacific sky.