

# Low-Frequency Wireless Communications System— Infrared Laboratory Experiments

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**Abstract**—A communications systems course laboratory component using an infrared (IR) communication system has been developed as part of the wireless education initiative at the Rose–Hulman Institute of Technology (RHIT), Terre Haute, IN. Students build the system up over several laboratory periods from distinct subsystems, each of which illustrates specific communications concepts. The multiweek laboratory project has the features of being easy to implement on breadboards owing to the low modulation frequency and of being highly motivational to students because of their interest in building a “working system” with a familiar application. The course, the curricular context, and the laboratory experiments are described, along with student survey data on the perceived effectiveness of the laboratories. The students and instructors have found this laboratory project to be very effective in reinforcing classroom concepts, motivating students, and enhancing debugging skills.

**Index Terms**—Amplitude shift keying, bandpass filters, communication systems, electrical engineering education, infrared (IR) communication systems, light-emitting diodes, optical communication, wireless communication.

## I. INTRODUCTION

HOW can a communications system laboratory experience simulate the design of a real-world system so that the experience is exciting and motivating to the students? How can the details of the subsystems be made understandable? How can the subsystems be integrated to produce an operational system that demonstrates important concepts of communications systems? How can these goals be accomplished by relatively inexperienced students with common laboratory equipment in a reasonable amount of time? These are the questions that have driven the development of a communications systems laboratory project at the Rose–Hulman Institute of Technology (RHIT), Terre Haute, IN. This work is detailed in this paper.

Ideally, laboratory work in communications should be a time for students to experience the complexities of a real communication system and integrate many of the topics they have learned in courses leading up to and including their communication systems course. The motivational value of experimenting with a wireless communication system is particularly high, because of the familiarity most students have with cell phones, broadcast media, and wireless networking. Unfortunately, working with the high frequencies required for most radio-frequency (RF) communication is difficult in a breadboard-based undergraduate

laboratory, where the “wiring” impedance is high, and there are no shielded enclosures.

The purposes of the RHIT communication systems course laboratory component are as follows:

- to reinforce concepts taught in the classroom;
- to motivate and excite students about the course material;
- to teach about the use of common instruments and develop circuit building and debugging skills;
- to demonstrate how the various parts of a communication system work together.

The use of an interesting application as a motivator for laboratory work appears often in the literature [1]–[3]. For example, the idea of using optoelectronics laboratories in electrical engineering is discussed in [2]. Although [2] is not for a communication systems course, the Optical Voice Link module was ranked the students’ favorite in every offering. The idea of building up a communication system over several laboratory sessions using the 2.4-GHz band has also been discussed [1].

One very motivational approach to teaching communication systems with a real application is the design of a telephone modem system on a digital signal processing (DSP) board. Tretter’s approach [4] is one example that goes deeply into the details of digital communication systems. Although this approach has the advantage of working at a low-frequency range, it does not emphasize the instrumentation and circuit debugging skills mentioned in the goals above because the implementation work is done in software.

Because of the limited length of laboratory sessions and the difficulty of working with RF systems, many communications laboratories concentrate on simple stages of a communication system without ever building up a working system. The result is that students do not feel they have ever seen a communication system “work” at a level that they understand. Typically, laboratories that do build up an RF system do so with very specialized equipment [1] or resort to connecting “boxes” without encouraging students to understand how the low-level functions are achieved [5].

The current solution to this challenge in the RHIT Department of Electrical and Computer Engineering (ECE) is a series of laboratory projects in which students build up a complete wireless communication system using modulated infrared (IR) as a medium. The resulting system is functionally similar to most IR remote controls. This approach makes it quite practical to build up a complete working system at a low frequency (40 kHz), with inexpensive parts assembled on breadboards. The few digital system elements that are relatively complex can be implemented in programmable logic devices (PLDs), drawing on student experience from other courses. This communications

Manuscript received October 15, 2004; revised June 9, 2005. This material is based on work supported by the National Science Foundation under Grant no. EEC 9221460.

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Digital Object Identifier 10.1109/TE.2005.856150

TABLE I  
A LIST OF RHIT COMMUNICATIONS SEQUENCE COURSES

Communications Sequence Course	Required for Major	Prerequisite
ECE300 Signals & Systems (with lab)	EE, CpE	ECE200
ECE380 Discrete-Time & Continuous Systems	EE, CpE	ECE300
ECE310 Communication Systems (with lab)	EE, (CpE elective)	ECE300

laboratory experience has been quite successful, both in reinforcing classroom material on the processes needed to modulate and demodulate a signal and in motivating the students with an interesting and “working” system with which they are already familiar from their living room. The challenge and sense of accomplishment students gain from building up an IR system from very low-level components gives them confidence in their troubleshooting skills and their understanding of material from previous courses.

## II. COURSE AND CURRICULAR CONTEXT

At RHIT, the communications sequence for electrical engineering majors consists of three required courses and several electives. The required courses are shown in Table I. Two circuits courses are prerequisite to ECE300, covering basic circuit analysis, ideal op-amp circuits, and ac power. Both circuits courses have integral laboratories. Most students in ECE310 will have also had courses in digital logic design, digital systems, and electronic device modeling.

ECE300 is an introductory course covering Fourier analysis, convolution, filtering, and sampling. The ECE300 laboratory is designed to include an introduction to MATLAB as a simulation tool. ECE300 laboratory sessions follow a theme of teaching students to predict harmonic behavior of various periodic and filtered signals and compare predictions with measurements made on a spectrum analyzer.

ECE380 is designed to link the continuous-time material of ECE300 to the world of digital signal processing. It covers sampling and reconstruction, system properties, frequency-domain system analysis, finite-impulse response (FIR) and infinite-impulse response (IIR) filter design techniques, and the discrete Fourier transform. ECE380 has no laboratory but includes several MATLAB projects, which are completed outside of class.

ECE310 covers basic communication systems with an emphasis on communication of digital data, and its laboratory is the topic of this paper. ECE310 lecture topics include line codes, probability of error, intersymbol interference, various modulation techniques, and frequency translation. Synchronization is covered when time allows. The IR transmitter and receiver project has been used as the basis for the first six laboratory sessions for about six years, since one of the authors (Black) reduced a “hallway discussion” to a set of laboratory instructions. His work was assisted by a summer grant from the National Science Foundation (NSF)-sponsored Foundation Coalition. Prior to the development of the IR system laboratories, all the communication systems laboratories were of the “stand-alone” variety, which treat a single topic in one laboratory session and have little interconnection between the laboratory sessions. Stand-

TABLE II  
LIST OF RHIT WIRELESS- AND COMMUNICATION-RELATED SENIOR/GRADUATE ELECTIVE COURSES

ECE 410 Communication Networks
ECE 414 Wireless Systems
ECE 415 Wireless Electronics
ECE 510 Error Correcting Codes
ECE 511 Data Communications
ECE 540 Antenna Engineering
ECE 541 Microwave/Millimeter-Wave Engineering
ECE 580 Digital Signal Processing
ECE 581 Digital Signal Processing Projects

alone laboratories are normally used in ECE300 and the last few laboratories of ECE310. One ECE310 laboratory session is used to conduct a discussion of professional ethics.

RF design issues, such as impedance matching, parasitic elements, and transmission line effects, are not dealt with in ECE310 but are reserved for another course, ECE415 Wireless Electronics. ECE415 is a course with a very similar project strategy, based on *The Electronics of Radio* [6], which uses a simple amateur radio transceiver as the project. Both courses tie in to RHIT’s wireless curriculum in affiliation with the Global Wireless Education Consortium (GWEC).<sup>1</sup>

Various other senior-year and first-year graduate-level electives in communications and wireless systems are available, many of which require ECE310 as a prerequisite. A list of these courses is given in Table II.

Courses with an integral laboratory at RHIT typically have three 50-min lectures and one 160-min laboratory period each week for the ten weeks of the quarter. Students normally work in groups of two per laboratory bench with a suite of equipment that includes two signal generators, an oscilloscope, a power supply (+5 V,  $\pm 12$  V), a multimeter, and a spectrum analyzer. RHIT students purchase a required laptop, and computer control of instruments and automated data capture are available.

## III. IR SYSTEM DESCRIPTION

The IR communication system project has several purposes. The primary purpose is to familiarize the students with the parts of a communication system in a way that forces them to consider the purpose of each functional unit, and the effect of each part on the total system’s performance. An important feature of the IR project is the low level at which the system is implemented. Students are not merely assembling a kit according to instructions but must choose component values and make design tradeoffs in the process, working with op-amps and transistors with which they are familiar from other courses. In the RHIT ECE curriculum, especially in early courses, many of the laboratory projects concentrate on a single functional block so

<sup>1</sup>The home page of the Global Wireless Education Consortium can be found at <http://www.gwec.org>

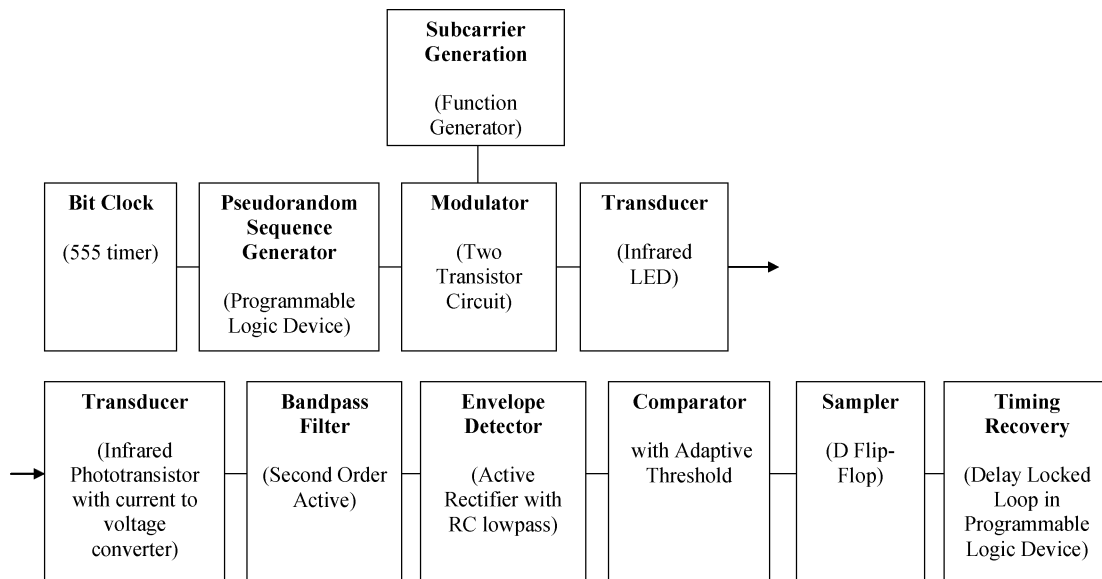


Fig. 1. Block diagram of the communication system.

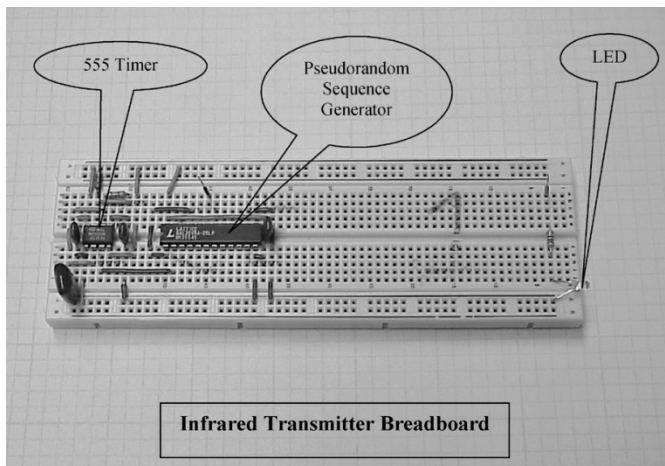


Fig. 2. IR transmitter breadboard.

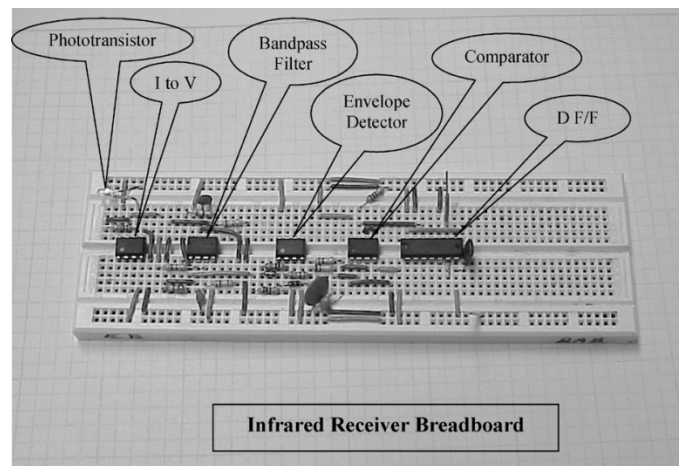


Fig. 3. IR receiver breadboard.

that most students have not had an opportunity to build up an analog system with an obvious application such as an IR remote control. Bringing in a commercial IR remote when the projects are complete helps the students see that the signals are comparable because the IR remote output is detectable by the laboratory receiver.

The system as implemented in the ECE310 laboratory performs a minimal set of functions required to transmit clocked digital data in a modulated system. A block diagram is shown in Fig. 1. Fig. 2 shows the transmitter breadboard, assuming a signal generator is used to generate the 40-kHz subcarrier and modulate it with the data signal. Fig. 3 shows the receiver breadboard, up to the D flip-flop, with room left for the timing recovery PLD (not shown).

The bit clock is usually set to about 100 Hz. Students have an opportunity to read and interpret the LM555 data sheet to produce the appropriate 50% duty-cycle bit-clock circuit. The pseudorandom sequence generator consists of a 4-bit shift register and two exclusive OR gates. It also includes circuitry for detecting the state “1111” to help with oscilloscope triggering and a few

extra gates to implement zero-state reset to prevent “mysterious” lock-ups. An early version of this project implemented all the functions in discrete logic, requiring many wires and hours of debugging. A more recent implementation uses a PLD to incorporate all these features in a single chip, usually a GAL22V10. In keeping with the theme of working at a low level, students create their sequence generator using a hardware description language (HDL), which most have learned in a previous course.

Although the carrier is actually IR light, the emphasis in the course is on the subcarrier frequency: the 40 kHz at which the light is modulated. The simple modulator circuit mixes the digital data signal with the 40-kHz subcarrier and consists of two switching transistors in series as an AND gate, so that the transmitter light-emitting diode (LED) is turned on only when both the subcarrier square wave and the data signal are high. The square-wave subcarrier signal is provided by the bench-signal generator or another LM555. The subcarrier harmonics are not an issue in this design because the IR spectrum is not regulated; therefore, no transmitter bandpass filter is required. However, the receiver includes a bandpass filter that will reject transmitted harmonics.

TABLE III  
SUMMARY OF THE FIRST SIX LABORATORY EXPERIMENTS CENTERED AROUND BUILDING AN IR COMMUNICATION SYSTEM

	Topic	Objectives
Lab 1	An Infrared Communication Channel	<ul style="list-style-type: none"> <li>• Understand the behavior of the LED and phototransistor as circuit elements</li> <li>• Model the phototransistor as a non-ideal current source</li> <li>• Use and understand V-I curves</li> <li>• Design a current to voltage converter circuit</li> <li>• Study ambient light effects</li> </ul>
Lab 2	Digital In, Digital Out	<ul style="list-style-type: none"> <li>• Use a 555 timer to produce the bit clock</li> <li>• Use programmable logic to produce a pseudorandom sequence generator, with sync output and zero-state reset</li> <li>• Learn about bypass capacitors for high speed switching circuits</li> <li>• Build a comparator and flip-flop to recover digital data, and test without demodulator</li> </ul>
Lab 3	Modulation and Receiver Front End	<ul style="list-style-type: none"> <li>• Design and build, and test an active band-pass filter</li> <li>• Build a simple switching modulator from two BJTs</li> <li>• Review AM modulation in frequency domain</li> </ul>
Lab 4	Envelope Detector & System Integration	<ul style="list-style-type: none"> <li>• Build an active circuit rectifier</li> <li>• Add a low-pass filter for envelope detection</li> <li>• Add a low-pass filter for adaptive thresholding</li> <li>• Test the demodulator with the data recovery flip-flop of Lab 2</li> </ul>
Lab 5	Timing Recovery	<ul style="list-style-type: none"> <li>• Use programmable logic to produce a delay-locked-loop timing recovery circuit</li> <li>• Test timing recovery</li> <li>• Measure maximum distance</li> <li>• Identify failure mode</li> </ul>
Lab 6	Documentation and Final Report	<ul style="list-style-type: none"> <li>• Write a formal technical report</li> <li>• Produce presentation quality schematics, block diagrams, timing diagrams, and oscilloscope images for report</li> </ul>

The IR LED is the transducer. The students are required to design their output drive so that the LED is operated near its specified limits of output power. When the system is well aimed at a range of about 3 m, the signal is strong enough to provide a sufficiently high signal-to-noise ratio (SNR) so that bit errors are negligible. Of course, the system can be operated in a room with many other systems because the LED output is very directional, and the range is quite limited. Reflections from walls, students, equipment, etc., are weak enough that few interference problems arise, a distinct advantage over an RF system in a laboratory environment where interference between systems could be a major issue.

The receiver is more complicated than the transmitter. The receiver's IR phototransistor must be used as a variable current source (light level controls the current), and measuring this current without loading the sensor requires students to implement a current to voltage converter. The students must choose a gain for the current-voltage converter so that the voltage output has an appropriate level for input to the active bandpass filter. To implement the bandpass filter, the students are presented with the transfer function and a general implementation but must choose component values to meet quality factor and center frequency specifications. The envelope detector contains an active rectifier stage that helps compensate for the forward voltage of the diodes, and a simple resistor-capacitor ( $RC$ ) low-pass filter that produces a demodulated signal for the comparator. A second  $RC$  low-pass filter with a long time constant can be used to generate an adaptive

threshold because the duty cycle of the transmitted data signal is roughly 50%. The long-time-constant average of the envelope detector output makes an excellent threshold level. An LM311 comparator restores the signal to standard logic levels, and a D flip-flop samples the signal at the middle of each bit. In early laboratories, the inverted bit clock is "stolen" from the transmitter, but by the end of the project, a  $16 \times$  bit clock is divided down and adjusted with each bit transition to recover the transmitter bit clock from the received signal. The timing recovery circuit is essentially a 4-bit counter and, as with the pseudorandom sequence generator, is implemented in a PLD.

Students make numerous measurements of the system performance, usually in terms of range and waveform quality, and observe and adjust the various receiver stages to maximize performance. Because they see direct relationships between the parameters they are adjusting and the performance of the system, they gain considerable intuition about the system's operation that they could not get from a stand-alone experiment with only one element of the system.

#### IV. ECE310 LABORATORIES, WEEK BY WEEK

Table III shows a summary of the content of the IR communication system project laboratories, weeks 1 through 6. The project is built up on both ends of the link so that a very primitive communication system exists in the very first week, and at the end of each laboratory the system remains usable and usually

improved. This approach gives the students the sense of constant improvement. They can always test the system, where they would have a much less rewarding experience if the system were built from “left to right” so that it never really worked until the last laboratory. Because each laboratory session adds a new subsystem or two and ends with an incomplete but working communication system, the students can recognize failures and accurately debug much more easily.

The ability to debug a circuit is a skill that gets substantial exercise in this project. The system has to be built on a breadboard, tested, disconnected, reconnected, and retested several times over several weeks, practically guaranteeing that every team will see multiple intermittent failures from bad connections, forgotten assumptions, etc. Students get much more than a lecture on the importance of using neat wiring and good laboratory book notes. They get an object lesson: Everyone can see which groups spend too much time debugging and wondering what they did to set up their circuit last week; this reinforcement is excellent for the many lectures they have already heard on neatness and completeness. Students see clearly that those who understand their system design can troubleshoot it much more efficiently than those who relied on too much “help.”

#### A. Lab 1: An Infrared Communication Channel

Lab 1 is designed to emphasize the channel so that the students determine the current in the IR LED and characterize the behavior of the IR phototransistor. The transmitting IR LED is a commonly available device, but it does present a few problems for the student: First, because the radiation is invisible, students have no visible cue whether the transmitter is actually working (correctly oriented in the circuit), and second, discerning the LED package from the phototransistor package is difficult since they are often very similar. The invisible light plays into the wireless motivation, since RF is also invisible and must be detected with instruments.

Once the bias point for the phototransistor is established, the current output is converted to a voltage, and students study the effects of the ambient light in the laboratory. At this stage, or sometimes much later, students discover that the sun from the laboratory windows will affect their results. Those at particularly sunny benches may have to turn their system with the receiver away from the windows (directionality helps) or use a small tube to shade the phototransistor. Students also struggle with photocurrent produced by room lights, which creates a difficult-to-remove 120-Hz component in their signal.

#### B. Lab 2: Digital In, Digital Out

Lab 2 is focused on the digital data in the transmitter and receiver. The students build a 100-Hz bit clock and a 4-bit pseudorandom sequence generator in the transmitter and a comparator and flip-flop circuit to reconstruct the data at the receiver. This laboratory gives valuable experience with applying a PLD, which reinforces the PLD material from a previous course. Students who have not completed a course involving PLD programming require special assistance. Because the PLDs can produce large switching transients, teams that neglect to install bypass capacitors for the PLD usually find that they have very unreliable systems. This problem persists

until they decide to read their instructions carefully, another valuable “real life” experience.

#### C. Lab 3: Modulation and Receiver Front End

Lab 3 develops the most important part of the project: modulation and demodulation. The design, construction, and debugging of the second-order bandpass filter is always a challenge because of its sensitivity to wiring errors and component values. A small error in resistor values can give an unstable filter, and a wiring error often gives a saturated output that can be hard to correct. A dc analysis of the active filter can be very helpful in identifying bad connections and wiring errors. The dramatic increase in performance (range) obtained with modulation is an important part of the motivational element of the entire project, which becomes apparent in this laboratory. The bandpass filter makes the receiver nearly immune to the effects of the room lighting and the afternoon sunlight from the windows, but the sun can still saturate the phototransistor and reduce its sensitivity. A common insight gained in this stage is that better performance is obtained by matching the transmitter frequency to the receiver input filter’s measured peak frequency than by matching it to the 40-kHz design specification, which helps reinforce the whole system view of the project. The approach taken in this system design is to optimize the performance between the transmitter and receiver as constructed. In a commercial design, both the transmitter and receiver would be designed and tested to specifications that would assure interoperability between similarly specified subsystems. The approach taken here is an introduction to system-level design and test. A discussion of design to specification is conducted both in the laboratory and in the class, thus preparing the student for more appropriate design methodologies in the future.

Modulation of the transmitted signal can be accomplished either in the subcarrier signal generator or by using a two transistor AND gate implementation. The transistor implementation allows subcarrier generation from a second LM555 clock. The simple modulator circuit was added to the laboratory when a pair of ambitious students suggested it as an alternative to the rather complicated signal generator modulation setup procedure.

#### D. Lab 4: Envelope Detector and System Integration

Lab 4 adds the envelope detection to the receiver with an active rectifier circuit and two low-pass filters. One low-pass filter smooths the rectified output, while the other averages the ON and OFF pulses to produce an adaptive threshold for the comparator. Although simple, the adjustment of the envelope detector time constants is very important, and students who do not understand what they are adjusting are often forced to review the theory before succeeding at this stage. This laboratory also includes a “system test” to ensure that all the system elements are working correctly. Because the timing recovery is not yet built, the bit clock is delivered to the receiver with a wire from the transmitter until Lab 5.

#### E. Lab 5: Timing Recovery

Lab 5 did not exist in the original laboratory sequence, but PLDs were found to be accessible for these laboratories; timing

recovery was clearly within reach. The system used is a 4-bit counter that adjusts the cycle length according to when data edges are detected. The adjustable counter forms a simple “delay-locked loop” (DLL) with a nominal frequency of 16 times the bit clock, provided by a signal generator. When this system works correctly, students see the inherent jitter of the timing and that the  $16 \times$  clock frequency can be varied slightly without losing lock. Once the entire system works, it must be tested, with the tests and results documented for the final report, which is not due until week 7.

#### F. Lab 6: Documentation and Formal Report

Lab 6 is the final system integration and checkout session. There are four goals for this session: the completion of all work leading to a fully functional system, the system checkout by the instructor, the collection of data verifying system operation, and the submission of the final report. During week 6, the students have an open laboratory time to fix any final problems or optimize their system. The checkout consists of a performance check for error-free operation at a minimum board separation of 18 in, including verification of the clock-recovery system from session 5. The checkout must be signed off before the final report may be submitted. The vast majority of student teams succeed in meeting the checkout conditions.

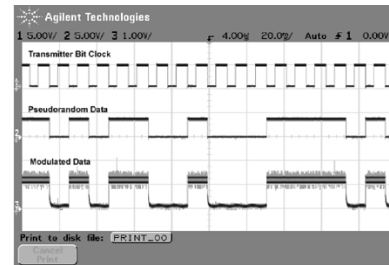
The final report is formal, with any critical laboratory notes attached as appendices. Design methodology and details are described, and measured results are used to convince the reader that the design is operating correctly. The grade for the formal report, which is a major part of the laboratory grade, is based in large part upon the proof that the system works correctly. An excellent approach to this verification is to include a set of screen captures of signals between each functional “block” and explain the system’s behavior in terms of these signal plots. An example set of plots is shown in Fig. 4. This material is then collected into a full report, which the student is encouraged to preserve for future reference and use. To quote from the laboratory instructions, “The report, not the circuit, is the ‘permanent’ part of the work!”

The final four laboratories of the term are run as “stand-alone” projects to cover several rather distinct topics that would be difficult to absorb into another multiweek project. The project of the first six weeks could easily expand to take all ten weeks, and many of the students would be appreciative; likewise, five or six more laboratory topics could be added to complement the course material; therefore, the constraints make the current arrangement reasonable. Table IV summarizes laboratories seven through ten.

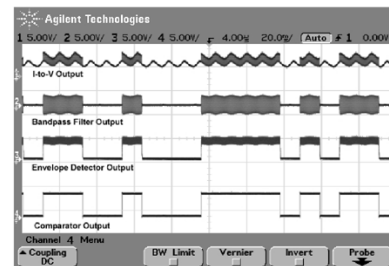
## V. ASSESSMENT

### A. Student Numerical Responses

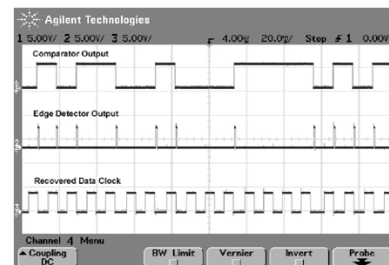
In an effort to assess the student perception of the six-week IR system project, a 15-question survey was administered to 44 students in two sections of ECE310. The survey was given as an optional opportunity for feedback at the beginning of the final exam period, after all laboratories were completed. The first 13 questions are all phrased as positive statements about the effectiveness of the laboratories [with the exception of the workload



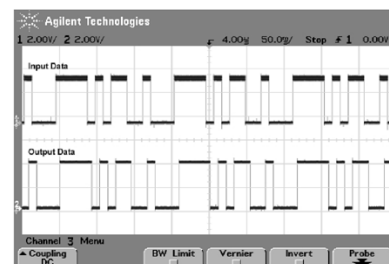
(a) Transmitter Board Waveforms.



(b) Receiver Board Waveforms.



(c) Timing Recovery System Waveforms.



(d) Input And Output Signal Comparison At A Range Of Several Feet.

Fig. 4. Images of waveforms (from report submitted by E. Tollefson and J. Morahn, April 2004).

questions (3–6)]. Although the list of positive statements might seem to bias the results, they were used because mixing positive and negative statements does not appear to avoid bias [7] and because mixing the statements might be confusing. Numerical answers were provided in the range 5—Strongly Agree, 4—Agree, 3—Not Sure/Don’t Know, 2—Disagree, 1—Strongly Disagree. The last two questions were open ended, with space allowed to comment. The questions with numerical responses are shown in Table V.

Question 11 was posed mainly because of anecdotal evidence that students sometimes extend these experiments outside the classroom. Apparently, one fourth of the students are inclined to do so. With regard to the workload questions, 3 and 6, while students indicate that they do find the ECE310 laboratories slightly more difficult than their other ECE laboratories, they are somewhat divided over whether the difference in difficulty can be at-

TABLE IV  
SUMMARY OF THE LAST FOUR LABORATORY EXPERIMENTS WHICH ARE SET UP AS  
STAND-ALONE EXPERIMENTS IN THE TRADITIONAL FORM

	Topic	Objectives
Lab 7	Intersymbol Interference and the Eye Diagram	<ul style="list-style-type: none"> <li>• Use pseudorandom sequence generator and a low-pass filter to generate eye diagrams</li> <li>• Build a driver circuit for the 50 ohm filter load</li> <li>• Analyze the eye diagram for probability of error and compare to simulated behavior</li> </ul>
Lab 8	Modulation	<ul style="list-style-type: none"> <li>• Generate amplitude modulated (AM) signals with varying percentages of modulation</li> <li>• Examine double sideband suppressed carrier (DSB-SC), square-wave carrier, and phase-shift-keying signals</li> <li>• Observe modulated signals in frequency domain, predicting and measuring spectral components</li> <li>• Use a Mini-Circuits™ ring modulator</li> </ul>
Lab 9	A Case Study in Engineering Ethics	<ul style="list-style-type: none"> <li>• Explore ethical issues arising out of engineering professional practice</li> <li>• Become familiar with National Society of Professional Engineers (NSPE) and Institute of Electrical and Electronics Engineers (IEEE) codes of ethics</li> <li>• Discuss issues and alternative responses to a “case study” scenario</li> </ul>
Lab 10	Frequency Shift Keying (FSK) and the Phase-Locked Loop (PLL)	<ul style="list-style-type: none"> <li>• Design, build, and use a PLL circuit based on the LM565C chip</li> <li>• Use a signal generator to produce an FSK signal</li> <li>• Measure the hold-in and capture ranges of the PLL circuit</li> <li>• Measure the spectral bandwidth of the FSK signal</li> <li>• Demodulate the FSK signal using the PLL circuit</li> </ul>

tributed to the six-week project arrangement. The average classroom evaluation answer for ECE courses would predict that the average for question 3 should be 3.37; therefore, 3.68 does seem to indicate a higher level of difficulty than other ECE courses. Intuitively, making the entire set of five laboratories work together seems more difficult for the students than five isolated laboratories, so this result is not surprising.

### B. Student Comments

Question 14 was intended to elicit positive comments and was stated, “14. My favorite aspect of ECE310 Communications laboratory was ...” The responses can be summarized as “getting it to work!” The students felt gratification in building something “real world” with an obvious application and seeing it work correctly. Almost all of the comments included some element of this idea.

Question 15 was intended to elicit critical comments and was stated, “15. The aspect of ECE310 laboratory which most needs improvement is ...” The responses were much less concentrated, with comments mainly on workload, PLD programming, and equipment issues. As noted previously, the workload for the laboratories is somewhat high, but this fact is also a tradeoff. The workload could easily be lowered if fewer topics were covered in the laboratory. One significant problem is that although the course covering PLD programming is normally taken before ECE310, it is not a prerequisite; thus, a few students have not had previous exposure and have legitimate difficulty. Some optional tutorials are available, but everyone having the same back-

ground would be better. Efforts to pair students without PLD programming experience in a team with a student with PLD experience sometimes fail because some students who have had previous exposure to PLDs did not become competent. While the difficulties of the lackluster student are not considered to be a bug but a feature, the impact on the unfortunate partner cannot be ignored, so that teams lacking prerequisite experience are sometimes provided with an explanation and a programmed PLD.

A few complaints mention the ambiguity of the laboratory instructions on specifications or types of voltage measurement (peak-to-peak, root mean square, etc.). This ambiguity is intentional, forcing the students to rely on context and intuition to interpret instructions correctly. This case of “real world” experience that they do not perceive as positive is beneficial nonetheless.

## VI. VARIATIONS

A number of variations of these experiments have been tried, with varying success. The current final laboratory project of implementing timing recovery is only the latest “finale.” Others have included a competition between teams to maximize their range or the bit rate of their system; another was to maximize the number of different values or symbols displayable at the receiver. Many solutions were based on pulsewidth modulation and an analog–digital (A/D) chip as suggested by the instructor, but one team used a full digital serial data arrangement to send 13 bits in a “word” and pioneered the use of PLDs in the ECE310 laboratory.

TABLE V  
ASSESSMENT SURVEY NUMERICAL RESPONSES

Question Number	Question	SA (5)	A (4)	NS / DK (3)	D (2)	SD (1)	avg
1	The ECE310 lab helped me understand the lecture portion of the course.	13	28	1	2	0	4.18
2	The ECE310 lab improved my circuit debugging skills.	17	23	2	2	0	4.25
3	The workload for ECE310 lab was higher than the average ECE lab experience.	9	19	9	7	0	3.68
4	The assignments in ECE310 lab motivated me to learn more than the average ECE lab experience.	9	24	10	1	0	3.93
5	The assignments in ECE310 lab were more fun than the average ECE lab experience.	12	25	5	2	0	4.07
6	Building up a system over several weeks increased the workload compared to doing weekly "stand-alone" lab assignments.	7	13	4	20	0	3.16
7	Building up a system over several weeks was more interesting than doing weekly "stand-alone" lab assignments.	22	20	0	1	0	4.47
8	ECE310 lab helped me learn to use the lab instruments with confidence.	2	32	8	2	0	3.77
9	I used skills in ECE310 lab that I learned in other courses.	17	25	2	0	0	4.34
10	I learned more about measuring the performance of a "system" (of several elements working together) in ECE310 lab than I have in previous courses.	12	27	4	1	0	4.14
11	I intend to experiment with infrared data communication systems outside of class.	3	8	19	11	3	2.93
12	I feel that ECE310 lab helped me understand how communication systems work, as opposed to just being able to solve textbook problems.	16	23	5	0	0	4.25
13	I believe that ECE310 lab helped me understand how real infrared communication devices like infrared remote controls and infrared network connections work.	14	27	3	0	0	4.25

In the authors' experience, almost any performance-related goal can be turned into a competition with excellent results from at least a few of the teams and good results from most.

#### VII. ANECDOTAL DATA

These projects have a history of inspiring students to extend and experiment with IR technology. Two examples occurring in class have been mentioned already: the students who designed their own data transmitter and receiver that led to the addition of timing recovery and PLD use in the laboratories, and the students who found that building a two-transistor switching modulator was simpler and easier than correctly setting up the signal generator's modulation function. Enthusiastic students have extended the project in other ways. One team experimented with substituting a laser diode for the LED, causing some safety concerns. A PLD-challenged team implemented all the digital functions using discrete 74XX logic. Their result was large and unwieldy but worked extremely well. Other students have used their laboratory experience outside of class to build an IR remote control for an older television set or have applied their experience directly at technical internship jobs. To hear a student return from an internship to say, "I used exactly what we learned in ECE310 laboratory at my job!" is quite gratifying.

#### VIII. CONCLUSION

This laboratory experience is accomplishing many of the goals of this course. A communication system is successfully completed; students learn how to construct, troubleshoot, and integrate functional subsystems to integrate into a communication system; and the experience is accomplished with challenging, but not unreasonable, requirements on students' time.

Students believe that the ECE310 laboratories are successful at helping them with the lecture material—41 out of 44 agreed or strongly agreed that the laboratory "helped me understand," as indicated in question 1 of the survey.

The IR communication system project has been very successful at motivating students. The benefits of using a familiar technology with a familiar application seem apparent and possibly apply to other laboratories and courses, as well. Students really seem to enjoy the experience of "getting it to work." The benefits of using a wireless technology with a low modulation frequency that is easy to implement on breadboards also seem to be quite attractive, since most of the disadvantages of RF are avoided without losing the motivational element. Most students agreed that the laboratories helped their debugging skills (question 2) and improved their confidence with the laboratory instruments (question 8) as well. These results are intuitive since the



requirements of getting several weeks worth of circuit working each week forces these results if the team is to succeed.

The laboratories help students see the interaction of individual elements in the entire system (question 10) in a way that is difficult to achieve in stand-alone laboratories and at a low level that is difficult to achieve with prebuilt elements. These laboratories have been a positive experience for the students and so successful in engaging them in learning that the instructors have been enthusiastic, as well. One has said the laboratories result in “better depth of understanding by the class as a whole than any other teaching experience I have ever had!” This paper is intended to help disseminate an effective and practical approach to teaching communication systems principles in the context of a working system.

#### ACKNOWLEDGMENT

The authors would like to thank the many students who contributed to the current form of the laboratory projects, especially R. Kingsbury and C. Geiger in fall 2003 for their suggestion of a discrete component modulator circuit, as well as P. Mauer and D. Young in spring 2000 for their suggestion of the use of programmable devices in the receiver.

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