AN INQUIRY-BASED ACOUSTIC SIGNAL PROCESSING LAB MODULE FOR INTRODUCING DIGITAL COMMUNICATIONS

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ABSTRACT

We study the use of an inquiry-based lab to introduce communication systems to undergraduate electrical engineering students with prior knowledge in signals and systems. The students are not provided with an explicit list of procedures to follow, but are prompted to design and build a complete end-to-end wireless acoustic digital transceiver on their own, using inexpensive off-the-shelf components, before they have had any exposure to analog or digital radio concepts. Qualitative evaluation suggests this process of discovery, problem solving, and experimentation provides context to students when theoretical and abstract communication systems concepts are subsequently introduced in lecture. Survey results are provided which suggest this open-ended, hands-on approach is an effective teaching and learning technique for introducing communication systems, and several possible extensions of this approach are discussed.

***Index Terms*—** Electrical engineering education, student experiments, inquiry-based learning, active learning, audio signal processing

1. INTRODUCTION

At least one course in analog and/or digital communication systems is offered – or required – in most every undergraduate electrical engineering program. Since communication theory relies heavily on random processes and mathematical representations of signals, it is no surprise that the most popular textbooks in the field (e.g. [1, 2]) present the material with a strong emphasis on mathematical principles of communication systems. With a few exceptions, the majority of textbooks do not include associated laboratory exercises, and indeed most undergraduate electrical engineering programs offer the introductory communication systems course in a lecture-only format. As such, the conventional approach to introducing students to communication systems generally begins with lectures on signal theory, and lacks a hands-on, laboratory-based learning component.

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Recently, the advent of low-cost software-defined radios (e.g. RTL-SDR [3–5]) has made it much easier to conduct laboratory experiments that do provide students with real-world, hands-on exposure to digital communication systems. Because these radios are controlled by software and permit rapid prototyping of transmitters and receivers, the majority of the laboratory time can be spent exploring the operation of communication systems *concepts* rather than wiring and debugging a circuit. Electrical engineering programs have begun to offer follow-on courses in software-defined radios (SDRs), thereby adding an important practical component to the fairly theoretical and often abstract presentation of communication systems. While such courses fill an important gap, they frequently are offered as graduate or advanced senior-level undergraduate courses, and generally list a theoretical, introductory communication systems course as a prerequisite [6]. As such, students are typically not exposed to hands-on experiments in digital communications – if at all – until a possible second elective course involving a communications lab.

Since engineering is an inquiry-driven, open-ended process, the use of open-ended inquiry-based labs has been recognized as an important learning tool [7]. As opposed to conventional labs where students are provided with an explicit list of procedures to follow, inquiry-based labs pose questions to students and prompt them to develop their own procedure to discover one of many possible “answers”. In this paper, we describe an inquiry-based lab to *introduce* communication systems to students in the first week of a communications course. The students design and build a complete end-to-end wireless digital transceiver on their own, using inexpensive off-the-shelf components, before they have had any exposure to analog or digital radio concepts. Since their initial exposure to digital communications is through hands-on discovery, the hope is that the experience provides a concrete reference point. Indeed, qualitative evaluation suggests this process provides context to students that is helpful when theoretical and abstract communication systems concepts are subsequently introduced in lecture. In the sequel, we present survey results suggesting this open-ended hands-on lab is an effective teaching approach for introducing communication systems.

2. MATERIALS

A wireless *acoustic* transceiver design was selected since it can be implemented very economically with two computers, a speaker, and a microphone. Fortunately, while the acoustic transmission medium and hardware have little similarity with RF transmission, the mathematical descriptions of signals and concepts such as modulation in acoustic communication are identical to those in conventional electromagnetic RF wireless communication. Thus, by conducting experiments using acoustic hardware in the lab, the students are able to hear the signals they create, which provides a less abstract observation of the operation of wireless communication systems. In addition, since acoustic frequencies are much lower, the labs can be completed with much slower sampling rates, and with readily available hardware without sacrificing learning.

The materials used for this lab consisted of very inexpensive, off-the-shelf components including: (i) two PCs with standard on-board soundcards, (ii) two installations of MATLAB, (iii) a 28mm 0.25W 8 ohm speaker intended for use as an internal PC speaker ($1.85 ea), and (iv) a General Electric 98950 detachable desktop microphone ($11.00 ea). We note that Octave would work just as well in place of MATLAB. Our choice of speaker was driven purely by cost, and virtually any speaker or microphone would suffice.

The speaker was plugged into one PC (acting as a transmitter), and the microphone was plugged into the other PC (acting as the receiver). The setup of the speaker and microphone is shown in Fig. 1, where they are separated by a distance of 1-2 inches from each other. Due to the impedance of the speaker, and the lack of any significant amplification in the output of most soundcards, the speaker output was very soft, so transmission was only possible over short distances. However, very low volumes are beneficial in a lab full of students trying to transmit and receive simultaneously. By purposefully choosing a speaker with a low maximum volume, interference from one student acoustic radio to another was not a problem. While the low volume limited transmission distance to several inches, amplified speakers could be substituted later during experimentation and demonstration of the final design.

Fig. 1. Acoustic Transmitter and Receiver

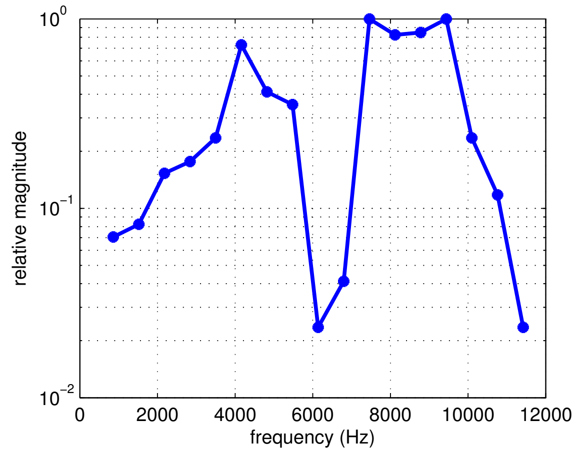

Fig. 2. Measured Frequency Response of Speaker

Since the chosen speaker was intended for use as a "PC speaker" that conveys BIOS error codes by beeping, its frequency response was highly frequency selective, as shown in Fig. 2. The added complication of a frequency selective transmitter made for a useful learning opportunity, as discussed below in Section 4.1.

3. IMPLEMENTATION

Western Washington University (WWU) has recently started a degree program in electrical engineering (EE), and in the conception of this new program, hands-on and project-based learning were identified as key components of the curriculum. As such, the introductory communications course (EE 360) has a weekly lab, as do all but 2 of the 30 courses in the program. The course begins immediately with a focus on *digital* communications [8], though analog communication techniques are used at times to motivate digital techniques. Developing a meaningful first lab assignment in an introductory communications course is a challenge because the students have not been exposed to even basic communication systems principles by the first week. However, students entering the introductory communications course at WWU have all taken at least one quarter of signals and systems, and have had exposure to MATLAB, time and frequency domain representations of signals, linear time-invariant systems, and Fourier theory.

By drawing upon their prior knowledge of signals and systems, this lab prompted them to discover a way to use signals to wirelessly transmit and decode digital information. The students were told that there was no one right answer to the lab, that they should not hesitate to ask questions of the instructor, and that moments of frustration are natural in open-ended discovery. To guide them to an answer, the lab description (available online [9]) consisted of four tasks: (i) a set of prelab exercises, (ii) a task to characterize the combined frequency response of the speaker, acoustic wireless channel, and microphone, (iii) a task to design a digital communication system capable of transmitting 1 bit per second, and (iv) a demonstration and presentation to the whole class of their transceiver design approach. The students were asked to work in pairs, and to complete task (i) before the the start of the first lab period. The students had two 110-minute lab periods to complete tasks (ii) and (iii), though 24-hour lab access was provided so that students could work outside of the scheduled lab period if desired.

3.1. Prelab

The prelab consisted of several exercises designed to review basic signals concepts, and to prompt the students to begin thinking about how binary information might be conveyed using signals. After some basic exercises requiring review of sampling, MATLAB syntax, and signals concepts, the students were asked to sketch their best guess of the combined response of a "good" speaker and microphone. This was useful for prompting them to think about the range of usable frequencies in the audio spectrum. Next, the students were asked to describe in words what types of signals they might send to convey a single bit of information. They were provided with an example of a recording of a human saying "one" or "zero", as appropriate, and were asked to list as many other pairs of signals that could be used. Finally, they were then asked which, of all the signal pairs they had listed, might be easiest to differentiate (or decode) at the receiver.

As the start of the lab period, the instructor walked around the lab to talk with each student group for approximately 5 minutes, reviewing their answers to the prelab, verbally encouraging promising responses, while encouraging rethinking of other responses. Occasionally, if students were struggling, the instructor would ask more questions to steer the students toward a more appropriate answer.

3.2. Frequency Response Characterization

As a warm-up exercise, this in-lab task asked the students to characterize the combined (magnitude) frequency response of the speaker, acoustic wireless channel, and microphone. The goal of this exercise was to introduce the students to the wireless testbed and to reacquaint them with MATLAB and basic signals concepts like frequency responses. The student pairs were provided with one PC connected to a speaker, and another PC connected to a microphone. The lab description listed the MATLAB commands to play and record signals through the speaker and microphone, but was purposefully lacking procedural details, leaving the procedural details and experimental design to the students. They were asked to write MATLAB code at both the transmitter and receiver to characterize the frequency response of the system, including at least 30 evenly-spaced points between 200 to 11,000 Hz. After completion of this task, they were instructed to show their results to the instructor, which provided the students an opportunity for feedback, and provided the instructor formative assessment of students' understanding of frequency response characterization.

3.3. End-to-end Transceiver Design

The description of the primary lab task was also purposefully lacking procedural details, and instead succinctly gave the students a design goal of building a MATLAB transmitter and a corresponding receiver to send and reliably decode at least 10 bits of binary information in 10 seconds or less. The students were told that they would need to demonstrate their transmitter/receiver pair on arbitrary bit sequences provided by the instructor. Again, after completion of this task, they were instructed to show their results to the instructor, which provided another opportunity for feedback and re-directing the students if necessary.

3.4. Final presentation and demonstration

The students were given 10 minutes to present and describe their transceiver design, and demonstrate its operation to the rest of the class. To motivate students to think more deeply about communication system design decisions and to push them to design the best transceiver they were capable of, a competition was held that awarded extra credit to the pair of students who could transmit and receive the largest number of error-free bits in 10 seconds. As such, the demonstration and final presentations also included determination of the winning project team. During the demonstrations, each team was asked to show a plot of the frequency content of their transmitted signal, and to interpret it. A chart was written on the chalkboard summarizing all teams' bandwidth usage, data rate, and modulation format.

Following the student presentations, the instructor gave a lecture which related concepts that the students "discovered" on their own to actual communication system principles. For example, many of the students unknowingly designed frequency-shift keying (FSK) transceivers, and a brief discussion of FSK was provided. In addition, the students' transceivers all employed some form of rudimentary synchronization to detect the start of transmission, so a brief discussion of detection strategies was included. This lecture was simultaneously a retrospective summary of the project, while also a preview of topics to come in lecture.

4. EVALUATION

4.1. Qualitative Evaluation

The qualitative evaluation was based on verbal interactions with students, comments on anonymous end-of-course surveys, and contents of student lab reports.

4.1.1. Prelab

The prelab prompted students to think about transmission of digital information on their own, and largely determined the trajectory of each teams' transceiver design approach. Student comments indicated that the instructor feedback received after the prelab was particularly useful in this open-ended lab since it provided validation that their proposed signaling approaches were reasonable. Many students identified variation in frequency, phase, and amplitude as possible means of conveying digital information. Some students researched by reading ahead in the textbook or consulting other sources, and other students came up with signaling strategies by using their own prior knowledge of signals.

4.1.2. Characterization of Frequency Response

To characterize the frequency response, most students chose to transmit a stimulus consisting of a stepped sinusoidal sweep to observe how the magnitude of the sinusoid at each discrete frequency was scaled at the receiver. One common misconception among students was a belief that the received time-domain signal was itself the frequency response. Furthermore, a large number of students mistakenly thought they could compute the Fourier Transform of the entire received stepped sinusoidal sweep, and that the result provided the frequency response of the system. After instructor questions directed them to realize the flaw in such an approach, the majority of students segmented the received signal into sections consisting of a sinusoid of a single frequency, and then they either computed the amplitude of each local time-domain segment, or the Fourier Transform of each local segment to determine the magnitude at each discrete frequency. Effectively, through their own reasoning, the students "discovered" and employed a Short-Time Fourier Transform (STFT), which was not a concept that they had covered in any previous course.

Multiple students conveyed that this seemingly simple exercise enabled them to "finally grasp the meaning of a frequency response". Furthermore, several students conveyed that designing their own frequency response characterization experiment, as well as the direct physical measurement of the frequency response transformed a previously abstract concept into a concrete tool.

4.1.3. End-to-end Transceiver Design

In evaluating the student lab reports, it was clear that this introductory lab module led students to immediately be confronted with – and invent their own solutions to – a wide range of digital communication system tasks, such as filtering, detecting the start of transmission, symbol synchronization, and making bit decisions. Because of the inquiry-based nature of the lab, these were not tasks or issues that they necessarily had any awareness of before starting the lab, and they were certainly not issues that had yet been covered in lecture.

Every student team had a different transceiver design, though there were similarities. The most popular modulation format was binary FSK, where a sinusoid of some frequency f_0 was transmitted to convey a 0, and a sinusoid of frequency f_1 was transmitted to convey a 1. Students generally made use of the frequency response characterization results from the previous task, and chose transmission frequencies with the least attenuation. A number of students, particularly those motivated by the competitive portion of the lab and the prospect of extra credit, realized that they could make use of more than 2 frequencies, and effectively employed a form of M-ary FSK. The concept of modulation had not yet been covered in lecture, however, so the students largely discovered these modulation formats through application of their own prior knowledge of signals.

In the receiver design, student teams mostly determined the start of transmission by measuring when the received signal power exceeded a specified threshold, though one team used a pilot tone to indicate transmission start. As a detector for making bit decisions, most students made use of the STFT for identifying the largest frequency bin of the transmitted sinusoid in a given time-slot. One project team creatively made use of the frequency selective nature of the speaker, and used received amplitude to make bit decisions on their binary FSK signals.

While many of the approaches employed were certainly not "optimal" from a communication systems perspective, they provided the students with a reference point once these concepts were introduced formally later in the course. Student feedback consistently emphasized the usefulness in having a point of reference, and in being prompted to think about communication systems principles issues on their own.

4.1.4. Final presentation and demonstration

Student feedback indicated appreciation for the chance to learn about one another's transceiver designs during the presentations. High levels of active student engagement were observed during the question-and-answer session. A large number of students also indicated that the competitive nature and chance for extra credit provided a lot of motivation, resulting in significant extra time being spent outside the designated lab period. Most student groups far exceeded the required design challenge of transmitting 10 bits in 10 seconds, with the winning team successfully transmitting 3490 bits in 10 seconds. One student indicated that the timing of the lab – right at the beginning of the quarter – permitted them to devote more effort since the competing workload in other courses is often fairly light in the first few weeks. Numerous students expressed appreciation for the lecture following the presentations that validated some of their chosen design decisions, and they were pleased with the realization that some

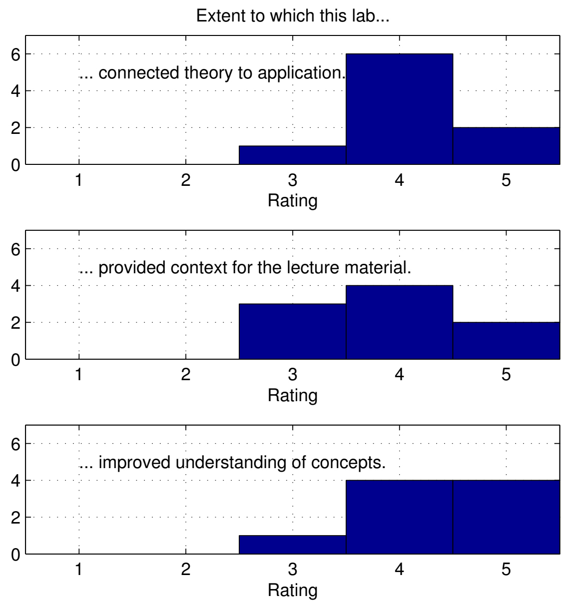

Fig. 3. Survey results from Winter 2015 offering of EE 360. Responses range from "1: Not at all" to "5: A lot".

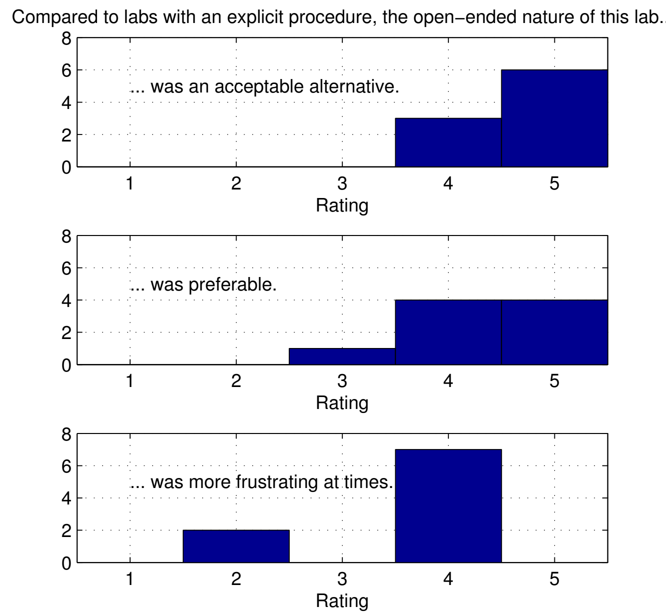

Fig. 4. Survey results from Winter 2015 offering of EE 360. Responses range from "1: Strongly disagree" to "5: Strongly agree".

of the approaches they "discovered" were actually employed in modern digital communication systems (e.g. M-FSK). One student remarked, "I felt like I was learning in a deep way with the discussion at the end", suggesting that the follow-up lecture provided an important summary.

4.2. Quantitative Survey Results

At the end of the quarter, anonymous student surveys were administered to collect student perceptions of the inquiry-based lab. As shown in Fig. 3, an overwhelming majority of students felt that the lab connected theory to application and improved understanding of course concepts. Two thirds of the class felt that the lab provided context for the lecture material, with one third expressing a neutral opinion on that question.

As shown in Fig. 4, all students in the course felt that the open-ended, inquiry-based lab was an acceptable alternative to traditional labs with an explicit procedure, with two thirds feeling strongly so. Furthermore, 89% of the class thought that it was preferable to traditional labs, with 44% feeling strongly so. Because the lab was so open-ended, there was concern that the students might find the lab more frustrating than a procedural lab [10]. Though the majority of students did find it more frustrating at times, 22% did not. In spite of the additional frustration at times, overall the students appeared to be very engaged and self-motivated, and valued this alternative lab format.

5. CONCLUSIONS AND FUTURE DIRECTIONS

We studied the use of an open-ended, hands-on lab module which appears to be effective at *introducing* communication systems to students with prior knowledge of signals and systems. By prompting students to design and build a complete end-to-end wireless acoustic digital transceiver on their own, the experience showed high student engagement and provided context to students that was very useful when theoretical and abstract communication systems concepts were subsequently introduced in lecture.

As the number of students in the class was relatively small, further studies are needed to provide more convincing quantitative data. In addition, baseline studies would enable comparison to evaluate the degree to which this lab affects understanding of communication systems concepts. The lab module requires significant student-instructor interaction, but appears to be scalable to larger class sizes with the addition of a teaching assistant familiar with inquiry-based learning approaches. Many extensions of this lab could be used to introduce other communication systems concepts, such as multiuser (i.e. downlink) transmission. For example, the students could be asked to collaboratively share a single transmitter to send N different team messages to each of their individual receivers. Or, students could be asked to competitively use a single transmitter with the goal of maximizing the number of bits they can successfully decode while trying to jam their fellow classmates.

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