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Interactive Simulations to Support Student Intuition in Radio Frequency and Wireless Communications Concepts

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Introduction

Despite growing workforce demand for electrical and computer engineers in wireless communications and related fields [1], [2], Virginia Tech has experienced a notable decline in student enrollment in communication-related courses and degree programs. This trend stands in contrast to overall growth in the Electrical and Computer Engineering (ECE) department over the past decade [3], during which student interest in communication systems and closely related areas has continued to decrease. Enrollment declines have been sufficiently pronounced that several majors adjacent to communications systems, such as Radio Frequency and Microwave, Photonics, and Space Systems, were consolidated into a single Applied Electromagnetics major [4]. These trends highlight a need for instructional approaches that lower conceptual barriers and make communication systems more accessible to undergraduate students. Inspired by this urgent need, this work explores carefully designed interactive simulations as one such approach.

Engineering students often gravitate toward courses that offer tangible concepts and clearly observable outcomes, as these experiences help reinforce intuition and demonstrate the real-world relevance of theory. In the communications domain, however, opportunities for experiential learning are limited, as the RF laboratory equipment required to create flexible, end-to-end communication systems with observable and adjustable parameters is expensive and not widely accessible. As a result, students often struggle to develop intuition about the relationships and trade-offs that govern real-world communication system performance.

Signal space, often visualized through signal constellation diagrams, provides insight into communication system performance and offers a powerful visual method for representing time-based digital communication signals. At the same time, these representations can pose a learning barrier, as students must shift from thinking about signals in the time domain to reasoning about them as points in constellation space. Students are first introduced to the concept of signal space in the baseband digital communications portion of the course, where digital information is encoded using voltage pulses for transmission over bounded, primarily wired, media.

The simulation tool presented in this work targets these challenges by enabling students to visualize the transmitted electrical signal while observing immediate updates to theoretical error rate as signal and noise parameters are adjusted. This combination of real-time visualization and quantitative feedback helps students develop intuition about how signal power and noise power jointly determine communication system performance.

Course Context

Introduction to Communication Systems at Virginia Tech is a junior-level undergraduate course designed to provide students with a foundational understanding of electrical communication systems. The course begins with analog communication topics such as amplitude and frequency modulation, followed by an extended focus on digital communication systems. Throughout the course, students analyze signals in both the time and frequency domains and are introduced to core concepts including signal-to-noise ratio (SNR), energy per bit, noise power spectral density, bit error rate, and basic transmitter and receiver design. Students also complete multiple projects that involve modeling communication systems using MATLAB.

The course is taught by faculty members involved in this NSF-funded project, including Dr. Dietrich, Dr. Dhillon and Dr. Talty who is currently teaching the course, and has been offered regularly during the project period. It is required for students pursuing the communications systems concentration within the electrical engineering program, while also enrolling students from other ECE majors who take the course as a secondary focus. The course serves as a prerequisite for the senior-level Digital Communications course, which develops the underlying mathematics in greater depth. The course is offered every semester, with typical enrollments of approximately 60 students in the Spring and 50 students in the Fall. The simulations described in this paper were introduced in beta form during the two most recent offerings of the course and the current offering of the course in Version 1.0.

Instructionally, the course is organized into three major segments: analog communications, baseband digital communications, and passband digital communications. Each segment includes regular lectures and weekly problem sets, many of which incorporate MATLAB-based analysis. Historically, students have completed project-based assignments requiring the development of static communication system simulations using MATLAB. The interactive simulations described in this paper represent an evolution of these activities, providing students with real-time visualizations and opportunities for exploration earlier in the course. Within this course structure, the simulations are used both during class and as resources students can revisit independently when working on assignments or preparing for exams. Some lectures used the simulations as a visual aid. Future offerings of the course will further extend this progression by incorporating hands-on experimentation with software-defined radio platforms, such as the Pluto SDR.

Approach and Methods

Interactive Exercises and Project-Based Learning

The simulations are introduced at the beginning of the baseband digital communications portion of the course so that students can see how the system behaves before being introduced to the associated mathematical expressions. This provides students with a visual reference that can be used as new concepts are developed throughout the lectures. The simulations are hosted on a live server and are accessible through the course webpage or a direct link, allowing students to use them both during and outside of class. Since exams in the course are open note and open Internet, students are permitted to reference the simulations while working on assessments.

Making the simulations readily available allows students to return to them when working on homework problems. For example, some problems ask students to determine the expected bit error rate at a given signal-to-noise ratio, which can be explored directly using the simulation. Students can observe how changes in noise affect the received signal and compare measured error rates to theoretical values shown in the simulation. While the simulations do not, of course, provide complete solutions to multi-part problems, they often help students get started by clarifying the system behavior being analyzed. Later parts of the same problem typically require students to modify system parameters, such as adjusting noise levels to account for changes in channel loss, and to complete the required calculations independently.

This use of simulations helps students engage with foundational communication system concepts that are often challenging when first encountered. Consistent with prior work on threshold concepts in engineering education, the simulations are intended to support students as they work through these difficult ideas rather than replace the underlying analytical reasoning [5], [6], [7].

Learning Elements

Baseband Simulation Creation

The baseband simulation is designed to help students build intuition about how changes in noise power spectral density and signal voltage affect bit error rate statistics. In the associated course, this simulation serves as students' first exposure to state space diagrams and waterfall plots. The simulation is introduced as part of the initial discussion of baseband digital communication systems.

The simulation operates by accepting user-defined values for signal voltage and noise power spectral density through sliders located in the upper-left portion of Figure 1. The state space diagram displays a set of sample messages on the upper plot, with new samples plotted every second from top to bottom. After five seconds, the plot clears and the process repeats. As messages are generated and processed internally, the simulation records error statistics and displays them in the table shown to the right of the state space diagram. These error statistics are also accumulated and displayed in the waterfall plot below the state space diagram.

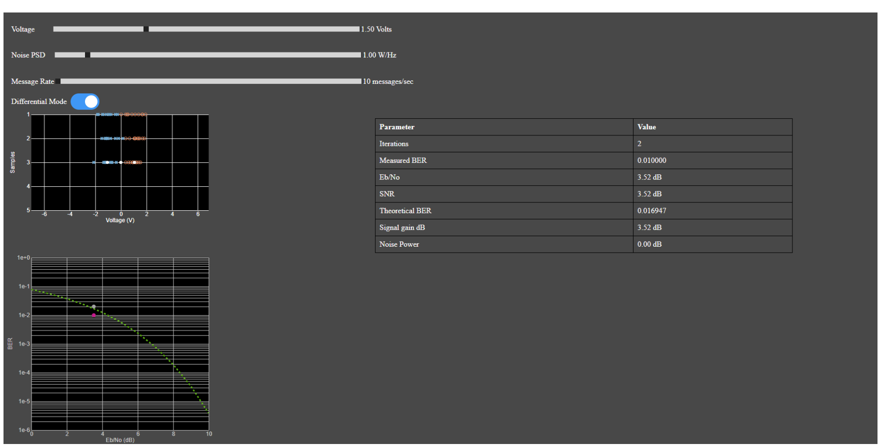

Figure 1: Baseband Simulation Opening Page

Several internal elements of the simulation are not directly visible to students but support how the simulation operates. As shown in Figure 2, the signal object and noise object receive input from the voltage and noise power spectral density sliders, respectively. The signal space diagram uses the signal gain to define the target symbol locations, shown as white reference points. At each update, a set of received messages is generated by offsetting these target locations according to the noise object gain. Every five seconds, the simulation computes the corresponding energy per bit, $\frac{E_b}{N_0}$, based on the current signal and noise parameters, and plots this value along the horizontal axis of the waterfall plot.

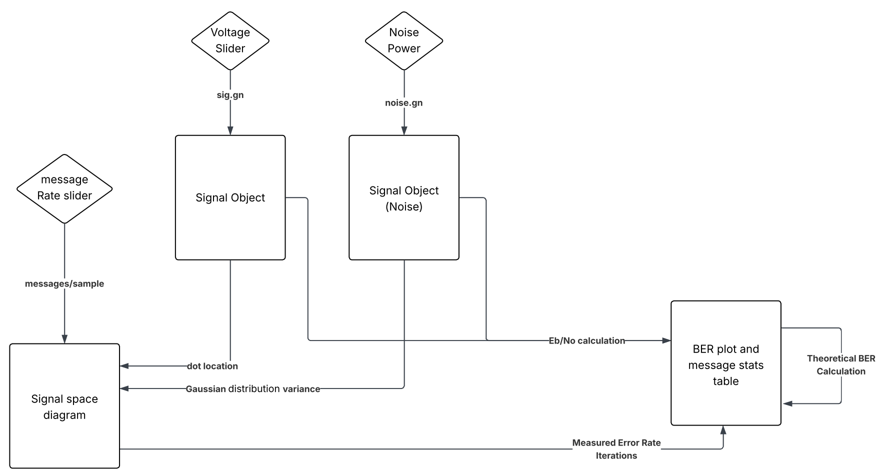

Figure 2: Baseband Simulation Block Diagram

Student Feedback

The interactive simulations were deployed during two offerings of the course described above. In the first offering, students were introduced to the simulations after completing the baseband communications material, while in the second offering the simulations were incorporated at the beginning of the baseband communications unit. In both cases, the simulations were in a beta state and were iteratively refined based on student input.

Student feedback was collected using a combination of short surveys, informal observation during class, and small-group or individual follow-up discussions. During the first course offering, students were invited to complete a brief qualitative feedback survey and to participate in a focus group. In the second offering, students completed an expanded survey following their initial exposure to the simulations, and a member of the project team observed classroom use and conducted brief interviews with several students.

Across both offerings, student feedback was generally positive. Students consistently reported that the simulations were helpful for visualizing communication system behavior, particularly the effects of noise on received signals and bit error rates. Interactive elements such as sliders were frequently cited as engaging and useful, as they allowed students to directly observe the impact of changing system parameters. Several students noted that the simulations helped them connect analytical expressions introduced in lecture with observable system behavior.

Feedback from the first offering also identified areas for improvement, particularly related to user interface clarity and interpretation of displayed results. In response, the simulation interface was revised, additional explanatory elements were added, and a waterfall plot was incorporated to better illustrate the relationship between $\frac{E_b}{N_0}$ and error performance. These changes were reflected in the version of the simulation used during the second course offering.

Survey responses from the second offering further suggested that the simulations supported students in understanding the connection between baseband communication theory and its mathematical representation. A majority of respondents indicated that they found the simulation helpful for interpreting course material, as shown in Figure 3, and many reported feeling comfortable using the simulation to explain baseband communication concepts to a peer.

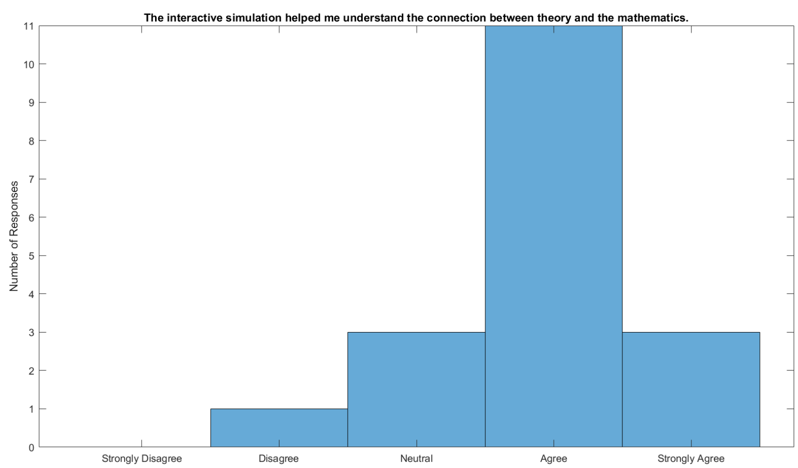

Figure 3: Self-rated impact on understanding

Outlook and Future Work

The simulation used in this work is one of many with even more simulations in development. Where this simulation only considers line codes other simulations allow students to visualize more complicated communication systems in a similar way. Students would be able to compare differential and non-differential symbols, there are simulations in development which allow students to compare different orders of QAM and QPSK modulation. Figure 4 shows a screenshot from the system with higher order modulations. This simulation is expected to be ready for the passband section of the current semester running of intro to comms.

There are also a few smaller simulations for which the underlying code is developed but the front

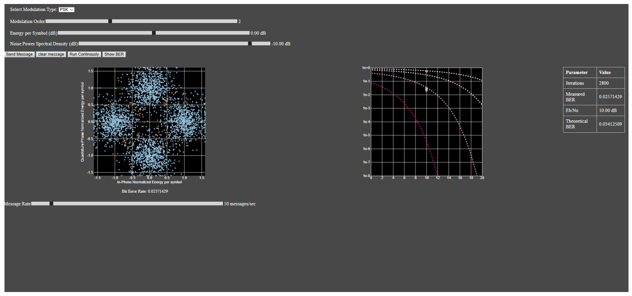

Figure 4: Higher Order Modulation Constellation Diagram

end visual has not been completed to standards. Link budgets are an important aspect of the course and there is currently a link budget related program which is similar to the simulation seen here but also includes a map such that students can drag the transmitter and receiver to be farther or closer together. The current simulation is also being looked for an update or different mode to allow students to control the period instead of it being a hidden variable. There is even a simulation in development which will allow students to control the transmitted amplitude and have the student try to send the right sequence of bits in the presence of noise.

The initial responses from the students has been received and will be discussed in detail in a future journal paper. Students have access to a Version 1.0 of the M-ary constellation diagram but no data has been gathered yet. Currently in development is an advanced mode meant to showcase the effects of non-idealities in the RF-front end and their effects on signal space representation and error rate statistics.

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