An Introductory Communication Systems Course with MATLAB/Simulink-Based Software-Defined Radio Laboratory

Dr. Cory J. Prust, Milwaukee School of Engineering

Dr. Cory J. Prust is an Associate Professor in the Electrical Engineering and Computer Science Department at Milwaukee School of Engineering (MSOE). He earned his BSEE degree from MSOE in 2001 and his Ph.D. from Purdue University in 2006. Prior to joining MSOE in 2009, he was a Technical Staff member at MIT Lincoln Laboratory. He teaches courses in the signal processing, communication systems, and embedded systems areas.

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Abstract

In recent years, software-defined radio (SDR) has become increasingly popular in electrical and computer engineering education as a tool for teaching communication systems, networking, and digital signal processing. Adoption of SDR has been enabled through decreasing hardware costs, mature and widely available software development tools, and educational resources aimed at effectively utilizing SDR in undergraduate education. A survey of the current engineering education literature shows that SDR technology has been widely adopted in advanced digital communications and networking courses, elective courses focusing on SDR technology itself, as an enabling technology in senior capstone or research projects, and as a demonstration and motivational tool supplementing existing courses or laboratories.

This paper presents an introductory physical-layer analog and digital communication systems course which has been designed to use modern SDR hardware and supporting software tools as an integral part of the course. Because the course prerequisites include only signals and systems analysis, Fourier Transform theory, and probability, it is a true first course in communication systems. Course topics include fundamental topics such as amplitude and angle modulation as well as modern communication topics such as orthogonal frequency division multiplexing. Each major course topic is accompanied by a laboratory module designed to reinforce that topic through simulation and hands-on experimentation. Students use MATLAB and Simulink software tools together with personal low-cost SDR hardware, allowing them to conduct experiments and investigations outside the traditional undergraduate laboratory setting. Through a balanced pedagogical approach involving in class experimentation and outside of class projects, the laboratory modules are designed to ensure strong understanding of foundational topics while simultaneously engaging and motivating students through investigation of real-world wireless communication signals and systems.

Details of the course approach, structure, and implementation are presented. Laboratory modules, their associated learning outcomes, and the use of MATLAB/Simulink and SDR hardware are described. The paper concludes with lessons learned and future improvements based on the initial offering of the course. The complete course materials, including all MATLAB and Simulink software and laboratory guides, are freely available.

I. Introduction

Advances in software-defined radio (SDR) systems has made this technology widely available to the engineering community. Electrical and computer engineering programs have been the beneficiary of reduced hardware costs and rapidly maturing software support tools, thus greatly reducing barriers to using SDR in the undergraduate classroom. Several textbooks aimed at teaching and utilizing SDR at the undergraduate level are now available [1]-[3].

A survey of recent publications in the engineering education literature shows many instances in which SDR is leveraged in electrical and computer engineering curricula. Common uses of SDR in the classroom include advanced elective-level coursework [4]-[6], courses focusing on teaching SDR technology itself [7][8], senior capstone [9] or other research projects, and SDR-based demonstrations used within existing courses [10] [11].

This paper presents an introductory communications systems course with an integrated MATLAB/Simulink-based SDR laboratory. The course covers introductory physical-layer analog and digital communication systems. The laboratory modules were designed to reinforce fundamental course topics, while engaging students through activities involving real-world communication systems and wireless signals. The overall approach leverages the fact that experimentation with wireless signal can be readily accomplished using low-cost SDR devices, some of which cost less than a typical textbook. Select portions of the laboratory modules can even be conducted outside the traditional laboratory setting, thus aligning with mobile studio approaches [12] [13].

The paper is organized as follows. Section II provides an overview of the course and outlines the key factors that motivated development of the SDR-based laboratory. The course and laboratory module design are described in Section III, followed by a detailed description of one of the laboratories in Section IV. Lessons learned from the first offering of the course are included in Section V, followed by conclusions and future work in Section VI.

II. Course Overview and Motivation for an SDR-based Laboratory

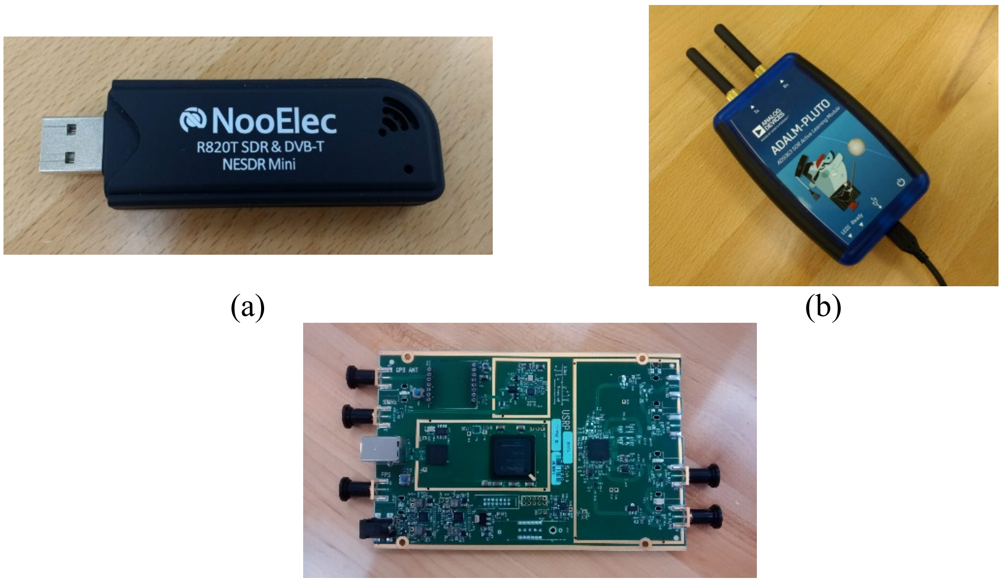
The electrical engineering program at the author's institution includes a senior-level undergraduate course covering introductory communication systems. The course covers the principles of analog and digital communications. Prerequisite topics include a signals and systems course covering both time-domain and frequency-domain analysis and a course covering basic probability and statistics. The course spans 10 weeks with 3 lecture hours and a 2-hour laboratory session each week. Students wanting to continue their study can take either or both of two follow-on elective courses covering advanced communication system topics.

For many years, the laboratory portion has been taught using the EMONA Telecommunication Instructional Modelling System [14]. Students typically complete 6 or 7 experiments covering analog amplitude and frequency modulation, digital modulation techniques, bit-error rates, and direct sequence spread spectrum. Laboratory experiments are usually completed in teams of two students per lab station. In recent years, a two-week laboratory involving software-defined radio was introduced in which students conduct brief experiments involving AM and FM communications using Ettus B200 USRPs.

The author's effort to transition this communication systems course to an SDR-based laboratory was motivated by several factors:

- Student response from the two-week exposure to SDR in the current version of the laboratory was strongly positive. Trends in student comments suggest that interaction with real-world wireless signals is particularly impactful. This student feedback, consistent with the author’s experiences in other courses where SDR has been used for student projects [5], suggests that such experiences may spark student interest and motivate further study in communication systems and related fields.

- SDR devices can be purchased for less than the cost of a typical course textbook. This allows students to purchase their own laboratory hardware and conduct experiments outside the typical laboratory setting. Figure 1 shows several examples of popular SDR devices offering a range of capabilities and price points.



(a) (b)

(c)

Figure 1: Software-defined radio devices. Commonly used SDR platforms used in engineering education include the RTL-SDR (panel (a), receive only, $20), ADALM PLUTO (panel (b), transmit and receive, $150), and ETTUS USRP B200 (panel (c), transmit and receive, $750)

- Mature software tools for interfacing to SDR devices provide a low-barrier to entry for undergraduate students. Development-focused packages such as GNU Radio [15] and MATLAB/Simulink [16] provide support for a wide range of SDR devices. Furthermore, some software packages provide graphical tools for constructing signal flow models which closely parallel the functional block diagram approach commonly used to describe communication systems.
- SDR represents a modern approach for designing and prototyping communication systems. Students who enter communications, networking, and related fields are likely to encounter SDR.
- An SDR-based laboratory can be leveraged for follow-on study in elective courses or other student projects.

III. Course and Laboratory Module Design

The course outline shown in Table 1 presents the major course topics. The most significant change in the outline compared to the previous version of the course (prior to the SDR-based laboratory) was the addition of complex-envelope representations. This topic was added since complex-envelope ideas provide valuable insight into understanding how SDR systems operate.

A series of MATLAB/Simulink simulations were also added to the lecture to aid in student understanding of the course material. In many cases, these simulations parallel those developed by students in the laboratory modules, and therefore provide templates to help guide their effort. For example, the double-sideband suppressed carrier simulation presented in Week 2 of the course is extended to a quadrature-amplitude modulated system by students as part of the AM laboratory module. These simulations are also unified with the SDR-based experiments in the sense that they share many of the same components and configurations.

Table 1: Weekly outline describing lecture topics in the introductory communications system course

Week	Topics
1	Course introduction; review prerequisite topics Introduction to elements of a communication system Concepts of baseband and passband signals, modulation, signal bandwidth
2	Introduction to amplitude modulation (AM) DSB-SC systems; modulators and demodulators; concept of coherent receivers DSB-LC systems; non-coherent receivers; modulation index and power efficiency ***MATLAB/Simulink Simulation – DSB-SC and DSB-LC***
3	Quadrature Amplitude Modulation (QAM) Complex-envelope representations for AM systems ***MATLAB/Simulink Simulation – I/Q and Complex Envelope for AM***
4	Introduction to angle modulation Concepts of frequency and phase modulation; modulators and demodulators Spectrum/Bandwidth of FM waveforms, Carson's Rule ***MATLAB/Simulink Simulation – FM Systems***
5	Complex envelope representations for FM/PM Case Study: Broadcast FM Radio Midterm Exam ***MATLAB/Simulink Simulation – I/Q and Complex Envelope for FM/PM***
6	Introduction to digital communications Digital carrier modulation: ASK, FSK, PSK M-ary digital communications
7	Optimum receiver structures; matched filtering; pulse shaping Concepts of random variables and stochastic processes ***MATLAB/Simulink Simulation – Matched filters, eye diagrams, signal constellations***
8	Bit-error rate performance of digital communication systems in the presence of noise ***MATLAB/Simulink Simulation – Bit Error Rates***
9	Introduction to spread spectrum; concepts of FHSS and DSSS DSSS modulation and demodulation Case Study: Global Positioning System
10	Introduction to orthogonal frequency division multiplexing (OFDM) OFDM modulation and demodulation Case Study: Wireless LAN Waveforms and IEEE 802.11 Standards
11	Final exam

The laboratory modules were designed to support the course learning outcomes and lecture topics. A balanced approach where students use both simulation and experimentation with real wireless signals was employed. The laboratory topics and their duration are as follows:

- Laboratory 1: Introduction to Software-Defined Radio Communications Systems Laboratory (1 week)
- Laboratory 2: Amplitude Modulation (2 weeks)
- Laboratory 3: Frequency Modulation (2 weeks)
- Laboratory 4: Digital Communications (2 weeks)
- Laboratory 5: Direct Sequence Spread Spectrum (1 week)
- Laboratory 6: Orthogonal Frequency Division Multiplexing (1 week)

The overall laboratory approach involves students using their own SDR device, referred to as the *personal SDR device*, throughout the course. To make this feasible, the laboratories were designed so that a low-cost SDR would suffice. In the initial course offering, each student was supplied with an RTL-SDR device, which costs just $20. For experiments involving SDR transmitters, Ettus B200 USRPs were supplied to the students. Although it was not used in the initial offering, the ADALM-PLUTO device, which costs $150, provides transmit and receive capability and is therefore an attractive alternative.

The choice of software package was carefully considered. Important factors included the complexity of the installation process and initial start-up time for students, ease of use, and student familiarity with the software from previous coursework. Ultimately, MATLAB/Simulink was chosen. The laboratories place greater emphasis on Simulink models since the graphical approach offers quick prototyping of models that closely resemble the block diagram approach used in lecture. In addition to MATLAB and Simulink, the Communications Toolbox, DSP Toolbox, and Signal Processing Toolbox are also required. An additional support package for interfacing to the personal SDR device is also needed. This package is easily installed directly through MATLAB, and the installation process is integrated into the introductory laboratory module.

An outline of the complete set of laboratory modules is presented in Table 2. The stated learning outcomes were derived to support the course learning outcomes and lecture topics.

Table 2: Learning outcomes for SDR-based laboratory modules

Laboratory Module	**Student Learning Outcomes** *Upon successful completion of this laboratory, the student will be able to:*
Laboratory 1: Intro to SDR Communication Systems Laboratory	- Describe the basic components of a SDR. - Compare and contrast an SDR with a traditional radio system. - Verify that their personal SDR device is properly communicating with the MATLAB/Simulink environment. - Construct a simple spectrum analyzer model in Simulink using their personal SDR device. - Identify and investigate a real-world radio frequency signal using their personal SDR device.
Laboratory 2: Amplitude Modulation	- Observe transmission of information using amplitude modulation over a wireless channel. - Describe and characterize DSB-LC and DSB-SC waveforms based on time-domain and frequency domain measurements. - Explain the concept of frequency-division multiplexing. - Utilize complex-envelope notation to describe amplitude modulated waveforms. - Simulate transmission of two independent messages using quadrature-amplitude modulation. - Construct a real-time DSB-LC receiver using their personal SDR device. - Construct a real-time DSB-LC transmitter and broadcast a waveform that meets a radio-frequency channel specification.
Laboratory 3: Frequency Modulation	- Describe the relationship between the instantaneous angle and the instantaneous frequency of a carrier signal. - Show how a message signal is used to modulate the frequency of the carrier signal. - Simulate FM communication systems using both passband and baseband models. - Explain the relationship between parameters of the modulating signal, such as its amplitude and bandwidth, to characteristics of the resulting frequency modulated signal. - Verify that Carson's rule is an accurate approximation of the bandwidth of a frequency modulated signal. - Compute the sideband amplitudes for tone-modulated FM signal as a function of the modulation index. - Compare the measured spectrum of a tone-modulated FM signal to the theoretical spectrum. - Implement a frequency demodulator using SDR hardware and verify its operation over a wireless channel.
Laboratory 4: Digital Communications	- Identify and characterize common forms of digital carrier modulation based on time-domain and frequency-domain measurements. - Explain the ideal receiver structure for digital communication systems. - Simulate the bit error performance of a digital communication system and compare to theoretical predictions. - Explain the influence of noise and interference on the performance of a digital communication system. - Explain the importance of carrier synchronization in a digital communication system. - Explain the importance of symbol synchronization (timing recovery) in a digital communication system. - Implement a digital communication system using SDR hardware and verify its operation over a wireless channel.
Laboratory 5: Spread Spectrum Communications	- Explain how spreading codes are used in DSSS communication systems. - Explain the importance of code synchronization in a DSSS communication system. - Simulate a DSSS communication system. - Simulate a multi-user communication system that uses code-division multiplexing. - Implement a DSSS receiver using SDR hardware and verify its operation over a wireless channel.
Laboratory 6: Orthogonal Frequency Division Multiplexing	- Explain the use of orthogonal carriers in a multicarrier communication system. - Simulate a multicarrier communication system. - Explain how FFT-based processing in used for OFDM modulation and demodulation. - Identify and explain key parameters and characteristics of a real-world communication system that utilizes OFDM.

Each laboratory module follows a similar format and uses similar activities. These activities can be characterized as follows:

- Investigations of wireless signals: Using either a signal broadcast by the instructor or a real-world signal of opportunity, students examine actual radio-frequency signals using their personal SDR device. In the case of instructor broadcasts, the signals can be carefully designed to align with a specific course learning outcome. For example, in the AM laboratory students examine an instructor broadcast that includes both DSB-LC and DSB-SC waveforms. Whenever possible, students examine real-world signals of opportunity such as in the FM laboratory where they examine broadcast FM radio signals. The activities include tasks meant to motivate students (e.g., demodulate the FM signal and listen to the radio broadcast) as well as reinforce theory presented during lecture (e.g., measure signal bandwidth and compare to Carson's Rule approximations).
- Simulations: Each laboratory module includes at least one simulation component. These simulations help reinforce lecture concepts and expose students to the power and importance of simulation. In some cases, simulations are used in lieu of a wireless experiment when that experiment is overly complex or cumbersome to achieve with an SDR-based system. One example is the bit-error rate simulation in the Digital Communications laboratory which, for a variety of reasons, is challenging to implement in an undergraduate laboratory.
- Student project: Each laboratory module ends with a student project. These projects are a culminating activity for that laboratory, and often reinforce topics from earlier labs. Projects incorporate elements of real-world communication systems and therefore show students how the course material is applied in actual systems.

The fact that each student has their own personal SDR device enables different learning modes to be used, and the laboratory design leverages these different modes. The learning modes, and examples of each, are as follows:

- Students receive a signal of opportunity: In this mode, students receive real-world wireless signals of opportunity using their personal SDR receiver. This mode is introduced in the very first laboratory module by asking students to investigate some of the many wireless signals that surround them. Using a simple model that implements an RF spectrum analyzer, they use their SDR device to examine RF signals such as broadcast FM radio, key fobs and other personal transmitters, HD television signals, and aircraft ADS-B broadcasts. In the student project portion of the lab, students must investigate a wireless signal of their choosing outside of laboratory, then report on their findings through both observation of the signal and researching its characteristics (e.g., modulation scheme, signal bandwidth).
- Students receive an instructor broadcast: In this mode, the instructor operates a transmit SDR and broadcasts an RF signal in the local area of the laboratory. In the first offering of the course, the author used an Ettus B200 USRP for broadcasting. This approach allows the instructor to carefully design the communication signal to support learning outcomes of the laboratory. This learning mode is used in the Digital Communication

laboratory to help students understand the importance of carrier and symbol synchronization. The instructor broadcasts a BPSK signal and students use their personal SDR device to view eye diagrams and signal constellations of the received signal. The exercise is made feasible by the robust carrier and symbol synchronizer blocks contained in the MATLAB/Simulink Communications Toolbox. Figures 3 and 4 show the Simulink model and signal visualizations seen by students, respectively.

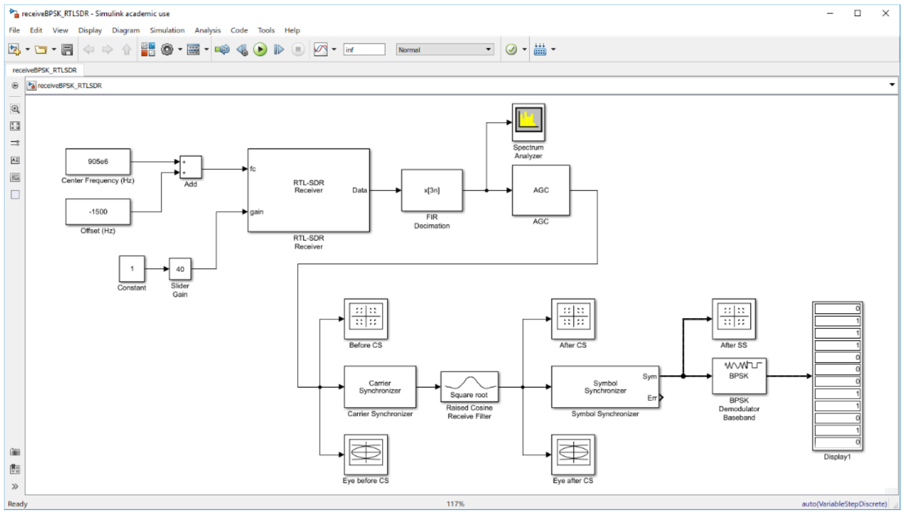
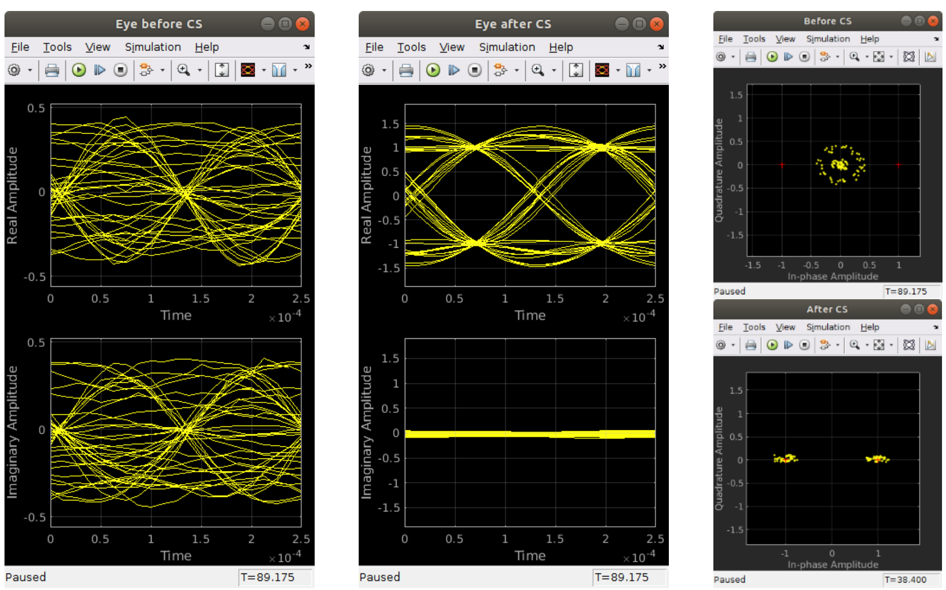


Figure 3: Simulink model for a BPSK receiver, including constellation and eye diagrams



(a) (b) (c)

Figure 4: Example visualizations seen by students using the BPSK receiver. Panels (a) and (b) show eye diagrams before and after carrier synchronization, respectively. Panel (c) shows constellations diagrams before (top) and after (bottom) carrier synchronization.

- <u>Students transmit and receive their own wireless signals</u>: In this mode, students work in pairs or small teams to operate a transmit capable SDR broadcasting their own communication signal and then use a personal SDR device to receive the broadcast. In the AM laboratory, each student team is provided a communication channel of a specified bandwidth and center frequency in the 900MHz band. Student teams are then responsible for creating a DSB-LC communication signal containing voice information that complies with the specifications. The final phase of the laboratory asks all student teams to broadcast their waveform simultaneously and then examine the frequency spectrum, thus allowing them to see each other's broadcasts and demodulating any of them they wish. The activity highlights concepts of frequency division multiplexing and the importance of responsible use of the spectrum. In the current revision of the laboratory modules, signal transmission is done only in the AM laboratory but could be incorporated into other laboratories.

IV. Example Laboratory: Frequency Modulation

To provide further insight into the laboratory module design, this section describes the FM laboratory in greater detail. The laboratory is composed of five distinct parts that are completed by each student over a roughly two-week time period. At the end of each part, a series of embedded questions are posed to the students through which they demonstrate proficiency in the learning outcomes.

1. Investigating a Broadcast FM Radio Signal
   Broadcast FM Radio is a particularly good signal of opportunity because it is available almost anywhere at almost any time. As a *pre-lab* exercise, students examine the broadcast FM signal of a radio station of their choosing, and then construct a Simulink model (Figure 5) to demodulate and listen to the mono (Left + Right) audio signal. Except for the "FM Demodulator Baseband" block, the students have utilized each of the blocks in previous laboratories, and thus have adequate experience to construct and debug the model on their own. The "FM Demodulator Baseband" block is eventually replaced by the student's own demodulator, which is fully developed and examined in a later part of the lab.

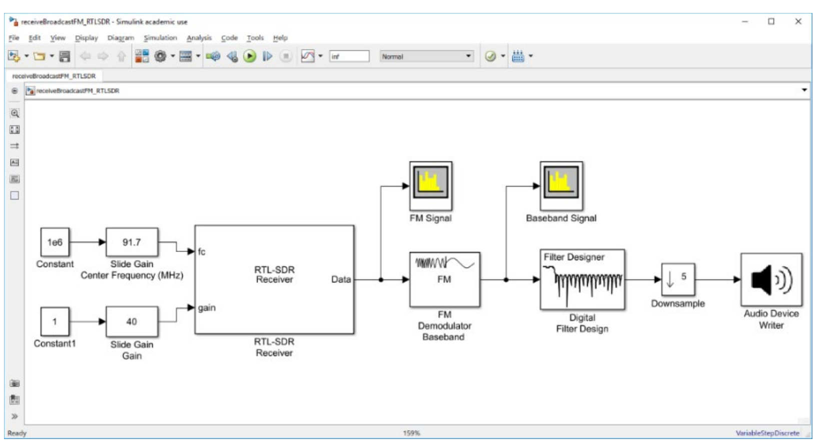


Figure 5: Simulink model for a receiving and listening to FM Radio (mono audio)

2. Simulation of a Passband FM Modulator

The lecture portion of the course presents the mathematical equations for describing FM communication signals. This simulation activity instructs students to build a Simulink model (Figure 6) that implements the standard FM equation given below.

$$s(t) \quad = \quad A\cos\left(2\pi f_c t + k_f \int_{-\infty}^{t} m(\lambda)d\lambda\right)$$

By adding visualization blocks (e.g., Time Scope and Spectrum Analyzer blocks) students can examine the "equation" in a step-by-step manner, and ultimately see how the FM waveform relates to the original message signal. The model is constructed in such a way that parameters of the system can be easily adjusted, and therefore students can strengthen their understanding through experimentation (e.g., students can see how the message amplitude can greatly impact the bandwidth of the communication signal).

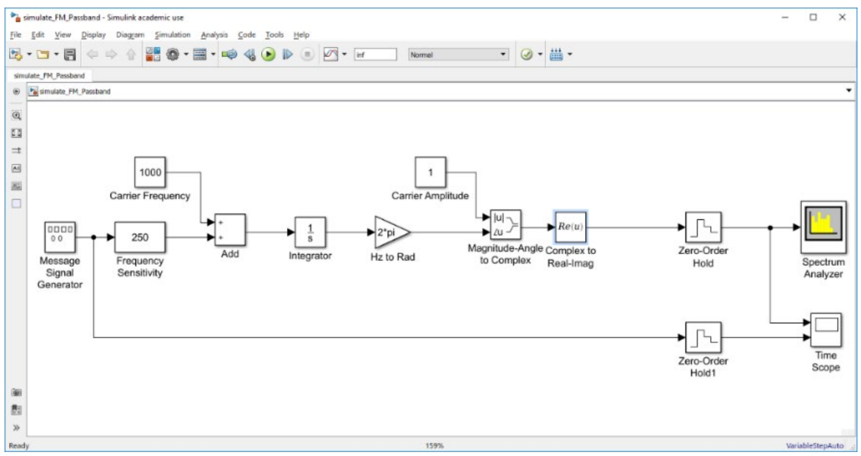


Figure 6: Simulink model for simulating passband FM waveforms

3. Simulation of a Baseband FM Communication System

In this portion of the laboratory, students construct a complete FM communication system (i.e., modulator and demodulator) in Simulink (Figure 7). The simulation serves multiple purposes. First, the example demonstrates the concept of baseband simulation using complex-envelope representations. Second, the model introduces an FM demodulator approach that operates using complex-envelope ideas. The demodulator is explained in detail and is then utilized in the remainder of the lab. Therefore, the simulation gives students the opportunity to experiment with and better understand the demodulator before using it with actual wireless signals. Third, the model shows how carrier frequency and phase offsets can be introduced in a baseband model, and students view the effect of these offsets on the recovered message signal. An embedded question asks students to mathematically derive the effect of such offsets, which should coincide with their observations from the model.

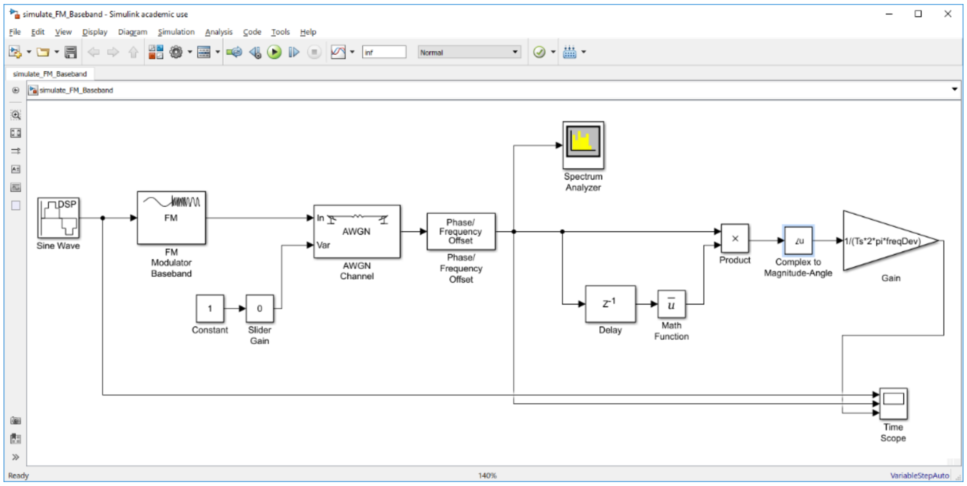


Figure 7: Simulink model for a simulating a baseband FM communication system.

4. Observing and Demodulating a Tone-Modulated FM Waveform
   Tone modulated FM (i.e., an FM waveform resulting from a sinusoidal message signal) is a classic example used in many introductory communication courses. In this portion of the laboratory, the instructor broadcasts a tone-modulated FM signal and the students use their personal SDR device to receive the broadcast. The student activity is then two-fold. First, based on the observed FM spectrum, students estimate the frequency of the message tone and then use that information, combined with knowledge of the peak frequency deviation used in the transmitter, to compare the observed FM spectrum to what is predicted by a theoretical calculation. Second, students use the FM demodulator they previously simulated to recover the sinusoidal message.

5. Student Project: Automatic Picture Transmission (APT) Receiver
   The final laboratory activity is the student project. In the current revision of the laboratory module, the project is based on the Automatic Picture Transmission (APT) system that is used to broadcast real-time weather satellite imagery to low-cost ground-based receiver stations [17]. The student's goal is to recover an image encoded into an actual wireless signal according to the APT standard. Doing so requires knowledge of both FM and AM communications. For simplicity, the APT signal is broadcast by the instructor in the laboratory. Students are guided to construct a Simulink model (Figure 8) that performs the demodulation process, however certain parameters (e.g., filter cut-off frequencies) must be decided by the students based on the provided information and/or their observations of the broadcast signal. The Simulink model then stores the demodulated signal into the MATLAB workspace, where students must write a few lines of MATLAB to form the final image. Figure 9 shows the APT image used in the initial course offering together with the image recovered by a student using their personal SDR device.

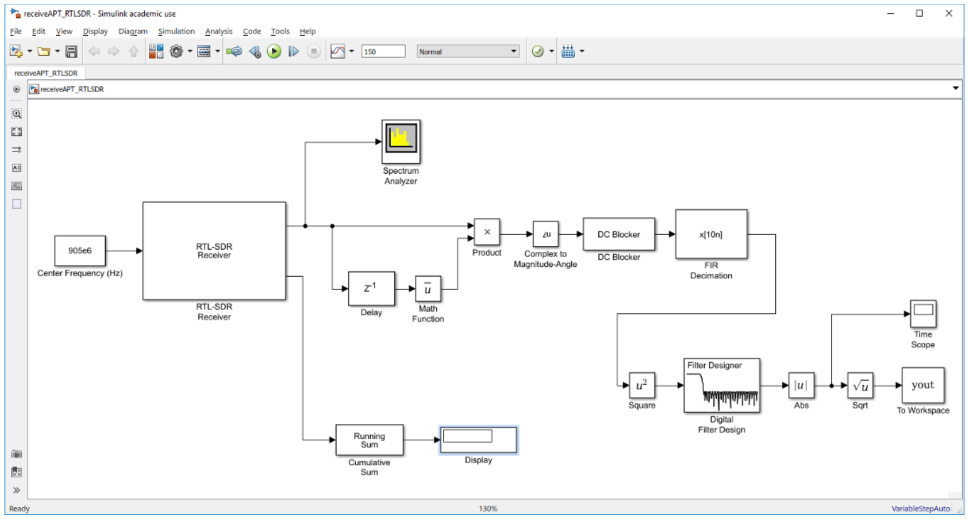
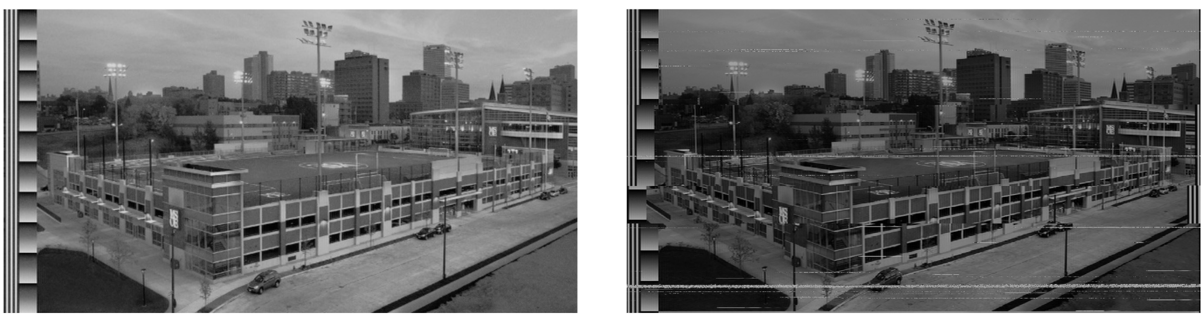


Figure 8: Simulink model for receiving and demodulating the APT broadcast.



(a) (b)

Figure 9: APT images used in FM laboratory student project. Panel (a) shows the original broadcast image and panel (b) shows the image recovered by a student.

V. Lessons Learned

The modified version of the course and the new SDR-based laboratories were offered for the first time in the Winter 2018-19 term to a group of 14 students. Each student had access to their own RTL-SDR throughout the term and utilized MATLAB R2018a running on a workstation-class laptop computer leased from the university. Lessons learned from the first offering include:

- The initial learning curve in utilizing personal SDR devices in MATLAB/Simulink was somewhat "steeper" than expected. While most students had prior experience with Simulink, several new features and concepts must be learned. For example, there is an inherent need for digital signal processing (DSP) operations (e.g., digital filters, decimation) when using SDR, and most students enrolled in the first offering had not taken a DSP course. The author believes this can be largely overcome through further improvements in the laboratory documentation, and these updates are underway.

- Many of the laboratory activities involve instructor broadcasts of wireless signals. These activities must be carefully managed from a time perspective. Since students work at different paces, dependence on the instructor broadcasts can create logistical challenges especially when some students are still working with the current broadcast while others are ready for the next one. It may be best to limit the number of instructor broadcasts throughout any one lab period, and then stagger the laboratory activities so that students can continue with other portions of the lab when they finish with any one broadcast.
- Interacting with real-world RF signals naturally sparked conversations surrounding use of the electromagnetic spectrum, wireless security, and ethical use of modern SDR technology. One particularly lively conversation stemmed from a student inquiring whether they could capture and reproduce the RF signal from key fobs used to unlock vehicle doors. The ensuing discussion ultimately transitioned to one of vulnerability of wireless systems and strategies to improve security. Instructors should be prepared for and welcome such discussions, as they present an opportunity to engage with students on topics of tremendous importance.

VI. Conclusion and Future Work

This paper presents an introductory communication systems course with an integrated SDR-based laboratory. The laboratory modules utilize low-cost SDR devices together with MATLAB/Simulink development tools to guide students through hands-on experimentation. Robust software tools provided in the MathWorks Communications Toolbox make experimentation with actual wireless communication systems accessible and highly engaging for students enrolled in a first course in communication systems.

Student feedback from the initial course offering suggested high satisfaction with the SDR-based laboratory. Future work involving a more detailed assessment and evaluation of the SDR-based approach, particularly as it impacts student achievement of learning outcomes, is under consideration.

All course resources, including complete laboratory documentation and Simulink models for use by instructors and students, are freely available by contacting the author or by downloading at https://www.mathworks.com/matlabcentral/fileexchange/69417-introductory-communication-systems-course-using-sdr.

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