An Undergraduate-level, Problem-based Introduction to Orthogonal Frequency-Division Multiplexing

Pranavi Boyalakuntla
Olin College of Engineering
Needham, MA, USA
pboyalakuntla@olin.edu

Mark Goldwater
Olin College of Engineering
Needham, MA, USA
mgoldwater@olin.edu

Utsav Gupta
Olin College of Engineering
Needham, MA, USA
ugupta@olin.edu

Whitney Q. Lohmeyer
Olin College of Engineering
Needham, MA, USA
wlohmeyer@olin.edu

Siddhartan Govindasamy
Department of Engineering
Boston College
Chestnut Hill, MA, USA
govindsi@bc.edu

***Abstract*—Principles of Wireless Communication (PWC) is an upper-level Electrical and Computer Engineering (ECE) elective taught at Olin College, an undergraduate-only engineering institution that is known for its small size and project-based learning (PBL) curriculum. PWC takes a top-down approach to teaching where students develop an understanding of wireless communications principles by transmitting and receiving data across physical and simulated channels. The course is run in a studio-like environment; class time is used collaboratively to complete three labs using MATLAB and software-defined radios (SDRs). After each lab is completed, teams write a report which details their implementation, the theory behind the algorithms they wrote, and relevant quantitative benchmarks like constellation plots, signal-to-noise ratio (SNR) calculations, and bit error rate calculations. Labs 1 and 2 entail implementations of binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) along with multiple-input multiple-output (MIMO) system simulations. Lab 3 culminates in students implementing orthogonal frequency-division multiplexing (OFDM) from first principles and communicating data over the air. OFDM is a standard multicarrier scheme used in WiFi and Long-Term Evolution (LTE) systems among others. By implementing OFDM according to the required specifications, students execute a real-world project and apply self-directed learning techniques to acquire the relevant technical skills much like one would in an industry or research position. Throughout this process, the students gain a deep familiarity with the OFDM algorithm while preparing data at specific points in the processing pipeline for meaningful visualization. While OFDM is often covered in an introductory graduate-level course, in this course offering, undergraduates are exposed to the OFDM algorithm with a top-down, problem-based learning approach that ties together fundamentals of electrical engineering with a real-world context.**

I. Introduction

Olin College of Engineering is a private undergraduate institution located in Needham, Massachusetts, known for its small size (approximately 390 total students), and project-based learning (PBL) curriculum. Olin offers three ABET accredited majors: Mechanical Engineering, Electrical and Computer Engineering (ECE), and General Engineering [2]. Principles of Wireless Communications (PWC), an elective course with recommended prerequisite Introduction to Analog and Digital Communication, is offered as a part of the ECE curriculum.

In its current form, Olin's PWC course was first offered in 2016 and was inspired by the instructors' experience developing multi-carrier modulation systems in industry and research. Classes are typically on the order of seven to ten students and held in a studio-like environment where students work on lab assignments in small teams, or individually, to achieve an understanding of the concepts and create functional systems. Students work closely with the professor to emphasize points of critical understanding. Since its inception, more than twenty students have completed the PWC course over three iterations. Additionally, twenty-two students completed a version of Lab 3 in an intensive one week course at Ahmedabad University in India.

Throughout the course, students are assessed on three primary learning objectives consistent with Olin College's Learning Objectives (OLOs): (1) Think Critically, (2) Develop and Apply Knowledge, Skills, Approaches and Methods, and (3) Communicate Effectively [3]. The course assignments comprise readings, three labs, and a final project. The final lab, over the course of three parts, culminates in the implementation of orthogonal frequency-division multiplexing (OFDM) on software-defined radios (SDRs) [4]. OFDM is a standard multi-carrier modulation scheme used in WiFi and Long-Term Evolution (LTE) systems. Olin's PWC course takes a top-down approach to teaching students the OFDM algorithm. Students learn the core technical material in the process of implementing an OFDM communications system as compared to a bottom-up approach, where students are taught the major aspects of an OFDM system prior to implementation. PWC's approach contextualizes the rationale behind various aspects of the modulation scheme and enables students to learn mathematical concepts like the Discrete Fourier Transform in context of a tangible application. In

Sponsored in part by the National Science Foundation under grant CNS 1618646.

industry and academia, engineering requires not only learning isolated discipline skills and competences, but also emphasizes learning as an integrated act which crosses disciplines. At the same time, graduates must be proficient in collaboration within project organizations. These factors motivate the application of project/problem-based learning in engineering courses [7].

PWC is novel in that it covers real-world algorithms such as Schmidl-Cox [8] timing synchronization in a problem-based approach at the undergraduate level and teaches foundational concepts in the context of implementing a communications system. This paper describes the three laboratory assignments in the PWC course. These labs culminate in students implementing the OFDM algorithm on software-defined radios (SDRs).

II. Course Breakdown

The PWC course is structured into three laboratory assignments, with the third assignment broken into three sub-assignments. Each assignment and sub-assignment has two deliverables – a successful implementation of the relevant algorithm to the Lab and a detailed write-up that connects the implementation to communication theory and electrical engineering concepts. In the case where a team is not able to successfully implement the lab algorithm, they must include next steps on how to improve their implementation as well as potential areas of concern they need help with. At the end of every Lab, teams provide peer feedback to each other and discuss any learnings, concepts they struggled with, and the performance of their implemented system. Furthermore, class discussions involve the difficulty of the assignment, any additional resources that the students used, and changes that could be made to improve the course content.

The subsections below provide a brief description of all the labs to contextualize the topics covered in Lab 3.

A. Lab 1: A Real-world Communications System

The goal of the first lab is to review the fundamental concepts of wireless communications by implementing a basic communications protocol in hardware using the B210 Universal Software Radio Peripherals (USRPs). In a prerequisite course, students learn about the two modulation schemes used in this lab, binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK). In PWC, students use these concepts to transmit and receive data over the USRPs. After completing this lab assignment, students gather in class to discuss their results and the performance of their system implementation as measured by data rate and bit error rate (BER).

Ettus Research, the manufacturer of the USRPs, provides a USRP hardware driver (UHD) [9] that includes command-line tools for transmitting (tx_samples_from_file.exe) and receiving (rx_samples_to_file.exe) data. The USRP interfaces with students' individual laptops over USB. Students develop code to generate a data file that is transmistted. With a separate USRP, student receive data to a file which they can then process in software. Using command-line tools to transmit and receive data means that students can use their preferred programming language to perform signal processing and modulation. It is recommended that students implement their code in MATLAB to standardize submissions and enable discussion between groups.

Lab 1 aims to introduce the USRP hardware to students and familiarize them with testing their implementations in hardware. This will prepare the students to successfully implement and test OFDM using the USRPs in Lab 3.

B. Lab 2: Multiantenna Systems

The second PWC lab introduces students to the advanced concept of multiantenna systems, specifically a multiple-input multiple-output (MIMO) system [10]. Lab 2 is divided into two parts which students complete in series. During Lab 2A, students are provided a MATLAB file that simulates a 2x2 MIMO channel. Students generate BPSK data for multiple transmitters and simulate transmission using the provided MIMO channel [11] [12]. The received data is then decoded according to the modulation scheme. Students develop an understanding of channel equalization techniques like zero-forcing (ZF) and minimum mean square error (MMSE) receivers through implementation.

In Lab 2B, students extend either the zero-forcing equalization or the MMSE equalization from a 2x2 MIMO system to a 4x4 MIMO system and implement channel parallelization using singular value decomposition (SVD) [11] [12]. For this portion of the lab, a simulated 4x4 MIMO channel is provided for transmitting the BPSK modulated data. After completing each part of Lab 2, students synthesize their work in a report which includes system analyses such as signal-to-noise ratio (SNR) as well as BER, and present their results to the class.

Frequently, MIMO and OFDM (MIMO-OFDM) is the prominent interface in communications systems [1]. Some well-known examples are 4G and 5G technologies as well as wireless Local Area Network (LAN) systems. By having students implement a MIMO system in simulation, a greater understanding of commonly used algorithms is achieved and a larger context for OFDM is introduced. This helps set the scene for OFDM in Lab 3.

C. Lab 3: OFDM

The fundamental goal of the third and final Lab in PWC is to learn about OFDM by implementing it as well as transmitting and receiving data using software-defined radios (SDRs) without using any specific built-in MATLAB functionality. Given that the students in this course are in their third or fourth year, they have developed sufficient technical and learning skills to execute a real-world project that one might encounter in an industry or research position. Ideally, after students have successfully completed Lab 3A to 3C, they should be able to work with analog and digital engineers to create a communications system from the ground up. The recommended general structure for the OFDM system (e.g. number of subcarriers, cyclic-prefix length, training symbols for timing synchronization, and pilot signals) that students use for this lab assignment loosely follow the 802.11g specification [6], giving students direct exposure to a system that resembles those that are used in everyday life.

Concepts from linear algebra such as orthogonality, the Discrete Fourier Transform (DFT), and the Fast Fourier Transform (FFT) algorithm are all fundamental topics for electrical engineers which are used in OFDM. Through implementing all aspects of OFDM from scratch, with the exception of lower-level utilities such as the FFT or cross-correlation, students are able to practice integrating these fundamentals into practical elements of wireless communications systems using a problem-based learning approach. In this manner, Lab 3 pushes students to use critical thinking to link together several intermediate-level electrical engineering concepts and develop a rudimentary approach for an advanced algorithm that underlies modern wireless systems. While implementing OFDM is a challenge in itself, the students are also assessed on the clarity and quality of their documentation, which directly reflects their understanding of the algorithm and their communication skills. Moreover, implementing OFDM in a problem-based learning setting helps students to develop skills for life-long learners and solve problems like one would do in an industry or research position. Gaining the confidence and skills to learn throughout one's career is helpful for long-term career success given the rapidly changing nature of high-technology [13].

III. Lab 3 Breakdown

A. Lab 3 Methodology

Labs 3A and 3B are simulated entirely in software: Lab 3A assumes a channel with a non-trivial frequency response while Lab 3B adds the complexity of carrier frequency offset (CFO). Lab 3C combines Lab 3A and 3B to send and receive OFDM data over the air using the B210 USRPs. These three parts are designed to build upon each other, with increasing complexity. As such, students build onto a persistent codebase for all portions of this Lab.

Once teams are ready to test their implementation on the USRPs, preprocessed data generated by students are transmitted and saved to a file on the receiving end. The data in the files are transmitted over the air using the UHD command line tool as used in Lab 1. On the receiver side, the samples from a second USRP are captured using the UHD command-line tool and saved into a binary data file. After the data is received, they can be loaded into MATLAB, or a different programming platform, and transformed back into a format for OFDM processing on the receiving end of the system. Students on a Unix platform can choose to use GNU radio, a tool used in the research community for transmission and reception, instead of the command-line utilities as a debugging tool.

Students test their implementation on an end-to-end USRP system in their own controlled environment and are able to configure carrier frequency and transceiver gain using functionality built into the UHD transmit and receive programs. Figures 1 and 2 illustrate the command line tools provided to students to send and receive data.

Figure 3 provides a schematic outlining the procedure required for each of the three parts of the third Lab.

B. Lab 3A: Fundamentals of OFDM

Lab 3A introduces students to the fundamental building blocks of the OFDM algorithm [4]. The main goal of this lab assignment is for students to transmit BPSK symbols using OFDM over a simulated channel without considering practical aspects like frequency offset and phase offset.

A simulated channel that incorporates a delay and a non-trivial impulse response is provided in MATLAB for students. Hence, students will have to perform synchronization, and implement channel estimation and equalization. As shown in Figure 3, students first generate BPSK symbols which are prepared for transmission using the OFDM algorithm. This data is then sent over a non-flat-fading channel (provided to students as a MATLAB function) with an SNR of 30 dB to simulate data transmission. The SNR of the channel is set to such a high value so that students can attribute any error to implementation rather than channel noise. Students retrieve the data by cross-correlating the portion of the data that is known to both the transmitter and receiver (i.e., the header) to find the start of the received data which is then decoded using the OFDM algorithm. Lastly, students compute the BER to validate their implementation. A BER of 0% is expected.

C. Lab 3B: Schmidl-Cox Frequency Correction Algorithm

Once students implement the fundamental building blocks of the OFDM algorithm, CFO is introduced as the first practical engineering hurdle. To account for this, students implement the Schmidl-Cox frequency correction algorithm. A non-flat-fading simulated channel including both a delay and frequency offset is provided as a MATLAB function. Further improving the codebase developed in Lab 3A, students generate a preamble per the Schmidl-Cox algorithm. This preamble is appended to the beginning of their generated BPSK data and then multiplexed as per the OFDM algorithm [8].

The cross-correlation of the Schmidl-Cox preamble and the received data is used to identify the beginning of the transmission. Next, CFO correction is performed using the Schmidl-Cox algorithm, and data is decoded using the OFDM algorithm. Finally, students compute the BER to validate their implementation. A BER of 0% is expected due to the high SNR of the simulated channel.

D. Lab 3C: OFDM Implementation in Hardware using SDRs

After implementing the Schmidl-Cox CFO correction algorithm with the OFDM carrier multiplexing scheme, students get one step closer to a real-world, over-the-air implementation of OFDM. In Lab 3C, students gain experience with engineering problems that arise when implementing OFDM on hardware: accounting for phase offset, utilizing guard bands, accounting for unusability of the direct current (DC)

```
./../UHD/examples/tx_samples_from_file --freq 915e6 --rate 2e6 --type float --ant "TX/RX" --args "serial=30
C628D" --subdev "A:A" --gain 150 --file tx.dat
```

Fig. 1: Example of the command line call to the UHD transmit tool.

```
./../UHD/examples/rx_samples_to_file --freq 915e6 --rate 2e6 --type float --ant "TX/RX" --args "serial=30CF
9C1" --subdev "A:A" --gain 150 --file rx.dat
```

Fig. 2: Example of a command line call to the UHD receive tool.

OFDM subcarrier (due to DC offset and the leakage of the local oscillator (LO) into the zeroth subcarrier), and setting appropriate transmit and receive gains [6] [5]. At this stage, a simulated channel is not provided as students test their implementation directly using the USRPs, although students can optionally modify a provided channel simulation to aid their development.

The specifications for transmission include a BER less than 0.1%, a data rate of at least 1 Mbps, and the use of BPSK symbols. Students are also encouraged, but not required, to implement OFDM using QPSK symbols.

The algorithm for Lab 3C builds onto the code-base developed in Lab 3A and Lab 3B. However, the procedure to create OFDM symbols in Lab 3C differs significantly. Here, pilot tones are added to assist phase-offset correction and guard bands are used to account for the roll-off of non-ideal filters in the USRPs. The subcarriers used for both the pilot tones and the guard-bands are identical to the 802.11g standard. After the symbols are prepared, the OFDM algorithm is used to encode the data and the Schmidl-Cox preamble is added for CFO correction.

At this point, the data is ready for transmission and is saved as a pre-processed data file. Students use the UHD driver to read and transmit the data over the air using the B210 USRP. This data is received by another B210 USRP and saved into a receive data file. The start of transmission is detected using a cross-correlation. CFO correction is then performed according to the Schmidl-Cox algorithm as described in Lab 3B. Next, phase-offset correction is performed using the pilot tones and the data is decoded using the OFDM algorithm. Finally, the BER is calculated to determine if the OFDM implementation was successful.

E. System Evaluation and Scientific Communication

The beginning of each class is used as a stand-up for teams to report progress on their algorithmic implementations, share obstacles that they are facing, and discuss any challenges that they have overcome. In this manner, students experience both intra-team and inter-team collaboration as they work within their team and learn from other teams' struggle and success. After completing each lab, teams write a report which details their approach to the implementation, the theory behind the implemented algorithms, and any quantitative benchmarks in the form of constellation plots, SNR calculations, and BER calculations. Student teams practice scientific communication skills and are evaluated on effective communication as they present these figures and a quantitative analysis of their implementation. Figure 4 shows a team's plots after testing their OFDM implementation on the B210 USRPs.

Figure 4a shows the received time domain signal, which demonstrates the Schmidl-Cox preamble. This team transmitted the Schmidl-Cox preamble at a higher power than the data so that the beginning of the signal could be easily identified using a cross-correlation-based method. Figure 4b shows the estimated frequency response of the channel that was used to equalize the received data. Figure 4c shows a constellation plot of received and decoded BPSK symbols after CFO correction. The effects of additive white Gaussian noise (AWGN) in the channel is made clear by the even distribution of decoded data around the ideal ±1 BPSK symbol values. Additionally, in Figure 4d, this student team decided to compare the first ten bits of the transmitted and received data to demonstrate exactly what the data looks like on the receiving end of the system. Through planning which figures to create, generating them, and presenting them to the class, students gain a deep familiarity with the OFDM algorithm.

Preparing figures also helps students to analyze and share aspects of their implementation that are not functioning as expected. Figure 5 depicts the constellation plot that was not properly corrected for CFO.

After creating 5a, it was clear that an improper correction for CFO was smearing the received signal across the complex plane. With this in mind, this team examined the frequency correction section of their code and was able to identify an indexing error which fixed the problem. This team also generated Figure 5b as they were testing their implementation. Using the real component of each BPSK symbol to determine whether its value is +/- 1, the two clusters of data produced a BER of zero despite the significant phase offset. Through creating this figure, the team identified an error which could potentially cause problems with longer transmissions or less ideal channels and corrected a mistake in their application of pilot tones to overcome the unwanted phase offset.

F. Course Survey and Evaluation

Olin instills learning outcomes in its graduates that represent key abilities, skills and mindsets necessary for success. These learning outcomes have been constructed through careful re-

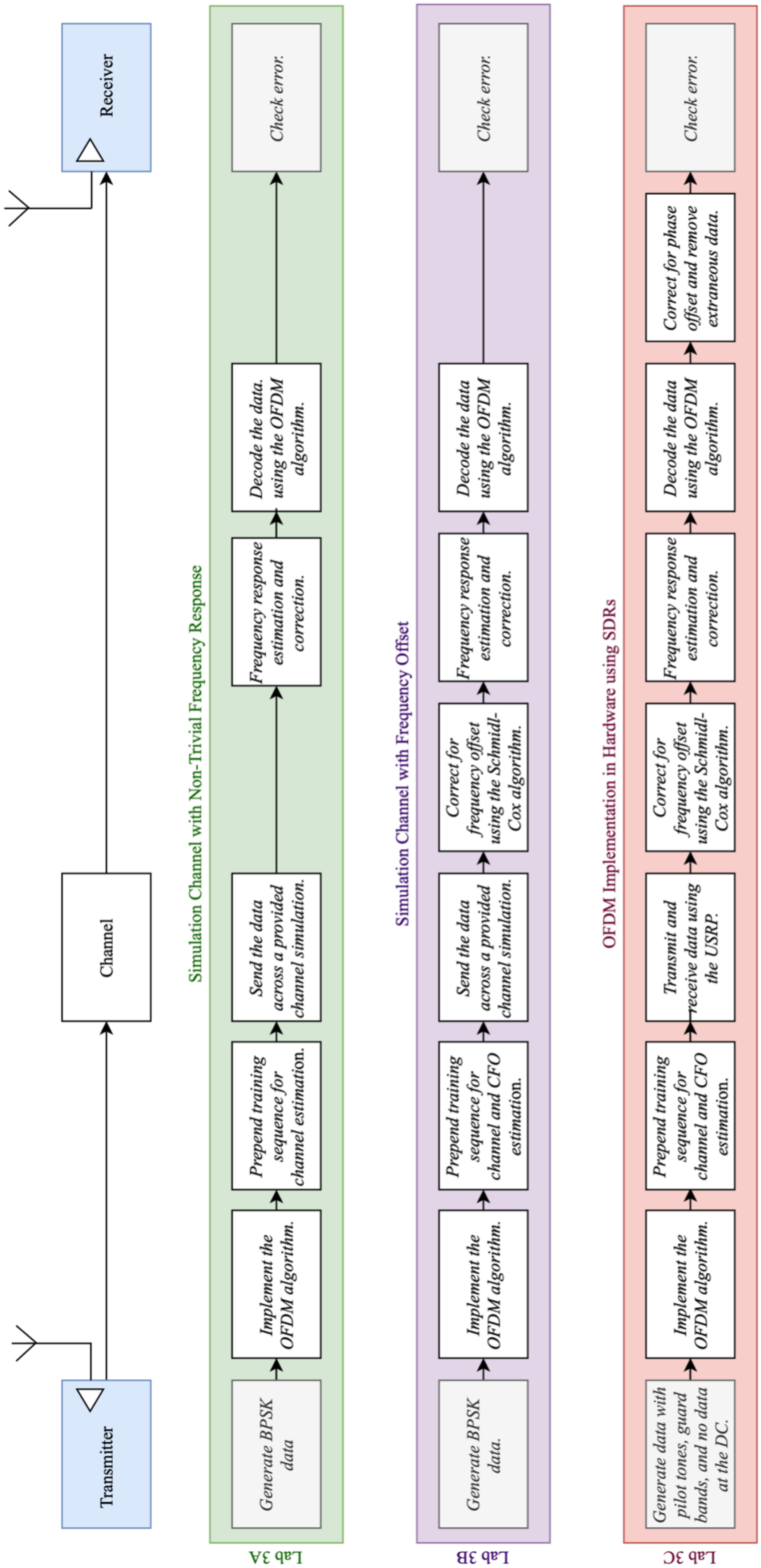
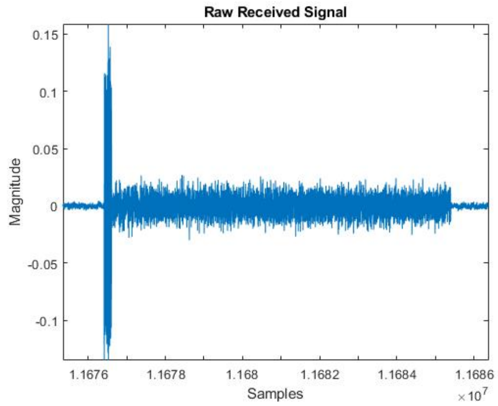
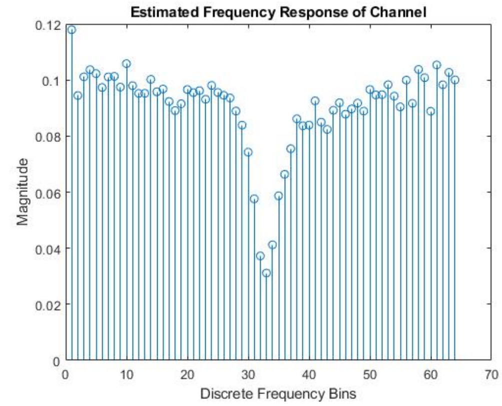


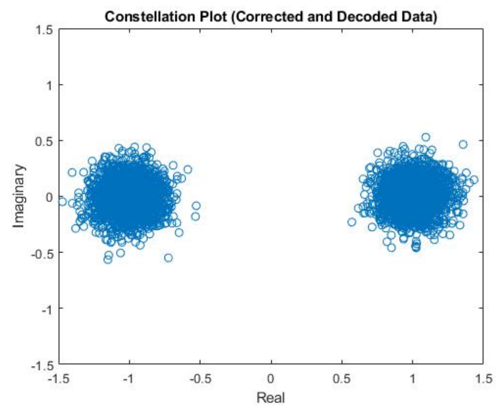
Fig. 3: Lab 3A - Lab 3C Procedure



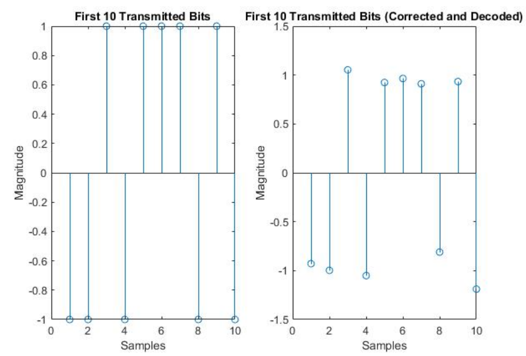
(a) Identified OFDM transmission in the time domain



(b) Channel frequency response estimation



(c) Constellation plot of the received BPSK symbols after Channel Frequency Offset correction



(d) Comparison of the first ten bits transmitted and received by the communications system

Fig. 4: Plots used to convey system performance and analysis

search into engineering practices required to tackle emerging technical, environmental and societal challenges on a global scale [3]. Of the eleven Olin Learning Outcomes (OLOs), the three most relevant for PWC are (1) Develop and Apply Knowledge, Skills, Approaches and Methods, (2) Think Critically, and (3) Communicate Effectively. At the end of the course, faculty review these OLOs and assess each student as to whether they are at a Novice (rated as one), Competent (rated as two), Proficient (rated as three) or Expert (rated as four) level for each. Students also self-assess their abilities through an end of course survey. The table below shows the end of course survey results for the OLOs for two semesters: Fall 2019 and Spring 2021. In Fall 2019, five of eight students responded. In Spring 2021, six of seven students responded. Half-point increments were allowed for student ratings in the Spring 2021 and is reflected in the table.

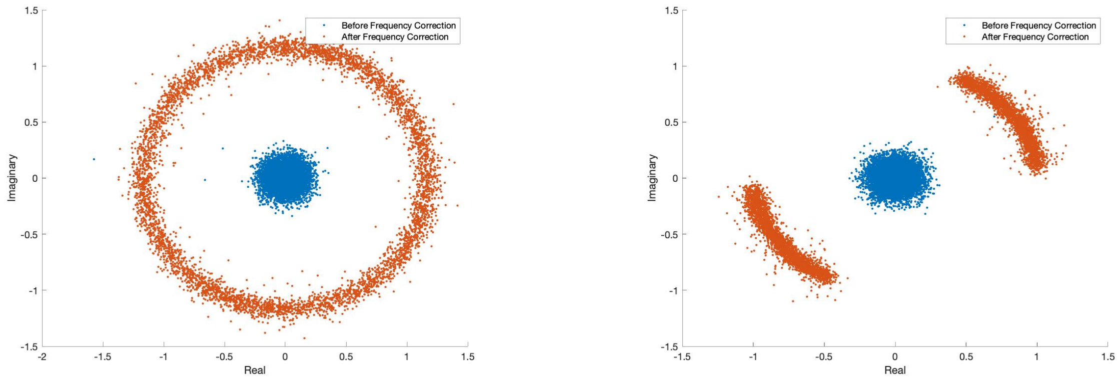
All students (five of eight total) who took the survey in Fall 2019, assessed that they (1) Developed and Applied Knowledge, Skills, Approaches and Methods and (2) Thought Critically (four out of four). Only four of five students evaluated their ability to (3) Communicate Effectively. In Spring 2021, six of seven total students completed the course survey.

TABLE I: Olin Learning Objectives (OLOs) survey results for PWC course.

Semester	OLO	Student Rating			
		2	3	3.5	4
		Competent	*Proficient*	-	*Expert*
Fall 2019	OLO 1	0%	0%	N/A	100%
	OLO 2	0%	0%	N/A	100%
	OLO 3	50%	25%	N/A	25%
Spring 2021	OLO 1	0%	0%	100%	0%
	OLO 2	0%	50%	17%	33%
	OLO 3	0%	33%	33%	33%

Six felt they were at a 3.5, between Proficient (rated as three) and Expert (rated as four) when it came to the first OLO. For the second OLO, Think Critically, three students felt they were Proficient (three out of four), two self-assessed as Experts, and one felt they were in between. When it came to the third OLO, Communicate Effectively, students were evenly distributed between Proficient and Expert (3-4).

In addition to the OLO assessment, students are requested to voluntarily complete an end of course survey. Of the twenty-three Olin undergraduates who took the course, more



(a) Improper correction for CFO

(b) Improper correction of channel-induced phase offset

Fig. 5: Both figures show the received data for Lab 3C with improper correction for channel-induced frequency and phase offset

than half completed an end of course survey. The survey is based on the 5-point Likert Scale and the responses include: strongly disagree, disagree, neutral, agree and strongly agree. All of these students agreed or strongly agreed that the PWC course included assignments that contributed effectively to their learning and stimulated their interest in the subject. Eleven out of fourteen either agreed or strongly agreed that the course helped them think creatively about the subject and twelve of the fourteen agreed or strongly agreed that the course made connections with other subjects, courses and disciplines. These results indicate that from the student perspective, PWC is effective at achieving the three most relevant learning outcomes of the eleven OLOs.

G. Comparison to Previous Practice

PWC is run studio-style without regularly scheduled lectures. Students are provided with required hardware and written documentation outlining the lab assignments. Furthermore, corresponding texts have been developed to help students self learn the theoretical material required to implement the project. As needed, the instructor provides mini-lectures on any points of confusion. This approach helps cultivate students' self-directed learning skills.

To the best knowledge of the authors, there are few, if any, other undergraduate-only courses which guide students through implementing OFDM from scratch and testing the implementation both in simulation and on SDRs. In the past, prepackaged simulators and exercises have been released [15], and undergraduate courses have reviewed the mathematics of OFDM and provide toy problems in which proposed systems are analyzed [16]. Although the plug-and-play simulators can provide students with insight as to how OFDM works end-to-end and the various steps involved in its implementation, it does not provide students with the opportunity to consider every detail of the algorithm from the exact positioning of the pilot signals to ensuring a hardware-ready implementation. On the other hand, existing courses that only provide a mathematical introduction to OFDM lack a real-world context. In contrast, the OFDM lab assignment in PWC is built around the fixed goal of implementing an OFDM system from the ground up, with over-the air transmission as the final goal.

IV. Conclusion

Advanced topics in wireless communications, like OFDM, are more often delivered in a traditional approach, if at all present in an undergraduate curriculum. PWC introduces a problem-based learning approach, allowing undergraduate students to learn about modern communication techniques through implementing theoretical concepts in hardware [17]. Lab 1 uses the understanding of fundamental ECE concepts like linear algebra and Fourier transforms, while exploring essential wireless communications concepts to implement a communications system across a physical medium. By providing a succinct introduction to multiantenna systems and the challenge of implementing 2x2 MIMO and 4x4 MIMO simulated channels, Lab 2 promotes self-directed learning among students, resulting in peer-to-peer learning on concepts like channel equalization and channel parallelization. Finally, Lab 3 combines all of the learnings from previous labs to a physical implementation of OFDM that is representative of what is specified in the IEEE 802.11g standard [6].

Split into three parts, Lab 3 addresses the intricacies of OFDM like guard bands, various channel constraints, CFO, and phase offset correction. In Lab 3, the challenge lies not only in delivering a working wireless link, but one that meets stringent benchmarks of at least a 1 Mbps data rate and less than a 0.1% BER in a noisy, real-world channel using SDRs. PWC aims to develop students' skills and knowledge such that they could implement a communications system given support in other areas like firmware, hardware, and RF technologies. By providing students a runway to explore methods of implementing algorithms, PWC aims to foster curiosity and develop life-long learners.

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