Sample-Based Understanding of Wireless Transceivers and Digital Transmission Via Software-Defined Radio

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Abstract

This paper presents an educational paradigm for the teaching of wireless transceiver design and digital transmission techniques from a sample-based perspective using compact form-factor software defined radio (SDR) technology. SDR has been extensively leveraged as an educational resource for the instruction of both undergraduate- and graduate-level digital communication courses for approximately a decade. Given decreasing SDR equipment costs coupled with increasing accessibility to communication system software design tools, SDR technology had been incorporated in numerous electrical and computer engineering curricula around the world. Although most of these SDR-based communication courses view the system from a bit-, frame-, or packet-based perspective and are constrained to laboratory environments, we present an educational framework where the curriculum is sample-based, *i.e.*, the entire communication system is viewed from the analog-to-digital converter (ADC) and the digital-to-analog converter (DAC), and the SDR platforms used are sufficiently compact that students can use them anywhere. The curriculum begins with the fundamentals of wireless communication systems engineering and the handling of complex-valued samples produced by and sent to the ADC and DAC, followed by exposure to several practical aspects of wireless transmission and transceiver implementations such as frequency offset, timing correction, and frame synchronization. Once these basic practical design considerations have been addressed, the course continues with the implementation of various modulation (*e.g.*, ASK, PSK, FSK) and coding (*e.g.*, BCH) schemes, with the objective of successfully transmitting ”hello world” and other messages wirelessly over-the-air within a classroom environment. Finally, several advanced topics such as multipath propagation, equalization, and multicarrier modulation are covered. Throughout the course, the students will be working in groups on a comprehensive course design project that synthesizes many of the concepts taught in class. Although this educational paradigm can use any SDR platform capable of handling complex-valued samples (*i.e.*, inphase samples and quadrature samples), the ADALM-PLUTO SDR platform by Analog Devices was used in this course due to its capabilities and compact form factor.

Introduction

In 2010, several of the authors of this paper presented an educational paradigm for teaching digital communications via a hands-on approach using software defined radio (SDR) technology[1]. At the time, SDR technology was only beginning to mature, the number of options were limited, access to the various features of the SDR platform was limited, and the cost of the hardware was relatively high (~$2000USD). Based on this proposed paradigm, the authors published an undergraduate textbook that presented a curriculum for teaching hands-on digital communications education using SDR[2]. This textbook commenced with several core theoretical concepts essential to the understanding of digital communications followed by a series of hands-on experiements were introduced to the student.

Given SDR technology at the time (both hardware and software), the student had limited access to the post-processed data from the SDR unit, and it was from this viewpoint that their understanding of real-world digital communication systems engineering began towards both the radio frequency front-end (RFFE) of the hardware as well as the digital processing side of the system where the digital communications and digital signal processing algorithms are executed. Other models for teaching digital communications via SDR technology experienced similar challenges and limitations with respect to the amount of access provided to the student with respect to the SDR hardware and software[3].

Figure 1: Photograph of ADALM PLUTO software defined radio unit by Analog Devices. The PLUTO SDR was extensively used during the undergraduate digital communications course on which this paper is based.

Over the past seven years, there have been significant advances in SDR hardware and software technologies[4]. SDR support in software packages such as MATLAB[5], Simulink[6], and GNU Radio[7] have evolved to a point where students can truly interact with real-world wireless signals over-the-air in real-time. At the same time, SDR hardware can now support both the transmission and reception of sophisticated waveforms such as Orthogonal Frequency Division Multiplexing (OFDM) and Mulitple Input Multiple Output (MIMO). In addition to these new capabilities, the cost of SDR hardware continues to decrease and is becoming more accessible to students, including the recent introduction of the ADALM-PLUTO SDR platform[8] by Analog Devices, which employs the AD9363[9] and costs approximately $100USD (see Figure 1). With these latest advances, SDR hardware and software are accessible to the larger student population and can be used not only for digital communications education but also employed in other educational and design activities, especially those with interdisciplinary aspects such as

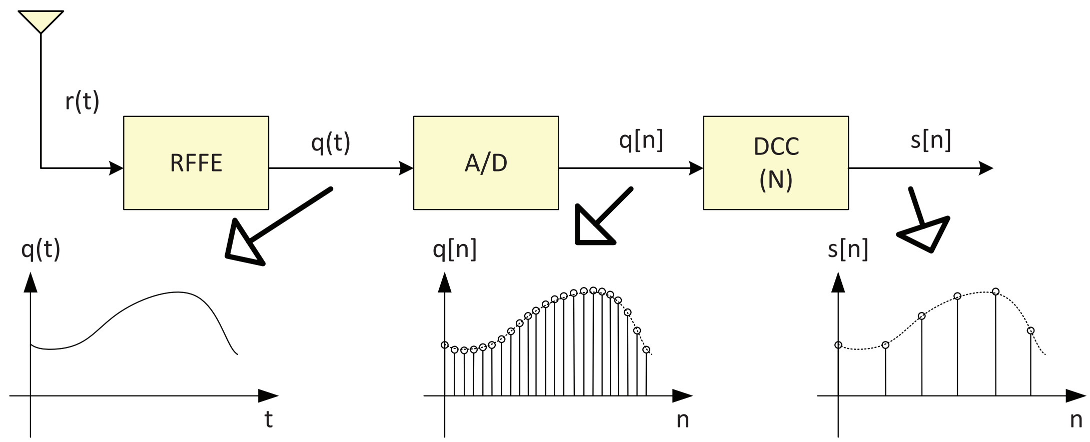

Figure 2: Illustration of the software defined radio receiver and its operation in converting an intercepted analog passband signal $r(t)$ to a digital baseband signal $s[n]$. The analog-to-digital converter (A/D) identified in the illustration is emphasized at the beginning of the course to highlight the importance of the translation between the analog and digital domains.

Cyber-Physical Systems (CPS) and Internet-of-Things (IoT).

In this paper, we present an educational paradigm for the teaching digital communication systems engineering using SDR from the perspective of the analog-to-digital converter (ADC) and the digital-to-analog converter (DAC). Based on our previously published approach[1] and the lessons learned over the past six years of instructing undergraduate and graduate students at Worcester Polytechnic Institute (WPI), the proposed paradigm views the sample as the fundamental unit of information within the SDR system rather than the bit, data packet, or data frame. Referring to the generic illustration of a digital communications receiver in Figure 2, the paradigm starts at the ADC and DAC, where the students related the raw digital baseband signal $q[n]$ with the analog baseband signal $q(t)$. After a brief explanation of how the radio frequency front-end (RFFE) converts an intercepted analog passband signal $r(t)$ to $q(t)$, the course progressively works it way through the system towards the digital communications and digital signal processing algorithms on the computing processor forming part of the SDR system (the downsampled digital signal $s[n]$ is ultimately what is processed by these algorithms). At the conclusion of the course, this hands-on paradigm provides the student with a holistic understanding of the communication system. At the same time, the student is exposed to many real-world issues and non-idealities at various stages of the system that would othewise never come up in a conventional digital communications course. Throughout the entire experience, the students are provided their own ADALM-PLUTO SDR platforms, enabling them to experiment and explore the wireless domain from anywhere around the world.

Table 1: Specification of the AD9363 RF Agile Transceiver[9].

Radio frequency 2x2 transceiver
Integrated 12-bit DACs and ADCs
325 MHz to 3.8 GHz bandwidth
Supports time division duplex and frequency division duplex
Tunable channel bandwidth of up to 20 MHz
6 differential or 12 single-ended inputs
Noise figure of 3 dB
Transmitter noise of ≤ -157 dBm/Hz noise floor
Transmitter monitor of 66 dB dynamic range with 1 dB accuracy

Methods

The theoretical groundwork for this hands-on course is based on the discrete-time approaches for digital communication systems education similar to those presented in several theoretical and simulation-based textbooks[10,11]. The undergraduate course that is currently employing this proposed hands-on digital communications educational paradigm at WPI, *ECE4305 Software Defined Radio Systems and Analysis*, leverages a flipped-classroom approach for instructing students in both SDR and digital communications. All lectures for this course are available from the ECE4305 YouTube channel[12], while the lecture periods are used to reinforce the theoretical concepts covered in class, discuss student experiences with the hands-on aspects of the course, and relate the corresponding theoretical and experiemental elements of the course.

Using the PLUTO SDR platform[8], which is based on the AD9363[9] (see Table 1 for specifications), the structure of the hands-on learning portion of the ECE4305 course using the proposed paradigm is as follows:

Laboratory 0 – SDR, FFT, SNR, and Signal Manipulation: The objective of this laboratory is to introduce the operations of SDR reception and transmission to the students, demonstrate some simple signal manipulation, and provide a discussion on signal power. Specifically, this laboratory experiment outlines radio connectivity in MATLAB and provides the student with an opportunity to design a simple test-bench where experiments can be repeated. The concepts of sample rate, decimation/interpolation, direct conversion, and complex baseband data are discussed, and signal scopes and other debugging tools are introduced. Connections to theoretical topics around power and power spectral densities are discussed. Note that this laboratory is used to bring up the entire class to the same starting point for the course with respect to foundational knowledge. Consequently, this laboratory does not count for credit, but it is a mandatory element of the course.

Laboratory 1 – Coarse and Fine Frequency Correction: The first of three for-credit experiments, the objective of this laboratory is to provide the student with an understanding of the various sources of frequency offset error that may potentially occur within a communication link, how it can be modeled, and finally how it can be corrected. An illustration of frequency offset error is shown in Figure 3. From this experiment, the students are expected to provide performance results of their designs, and produce a comparative study of simulations and SDR results. The students first model both large and small carrier mismatches between transmitting and receiving nodes. Then, the students implement algorithmic estimations and corrections for these offsets, as well as provide an analysis of the implementation performance with relative limits on algorithmic corrections. Once completed, the students are exposed to radio hardware and are tasked with conducting a comparative study with simulations. This hands-on experience builds upon the handware and software foundation established in Laboratory 0 by exposing the students to their first real-world challenge. By being able to identify, understand, and correct for frequency offsets, the students are now in a position to address the other real-world impairments that could potentially prevent them from transmitting and receiving wireless information.

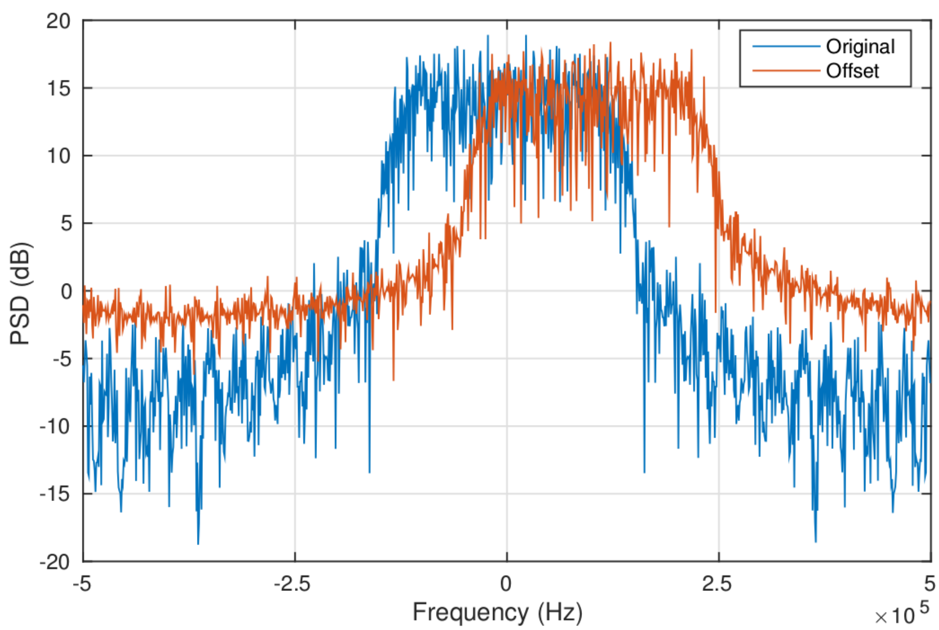

Figure 3: Center frequency offset experimental result. This center frequency offset is due to imperfections in the radio frequency front end at both the transmitter and receiver. Although relatively simple to identify, this is the first lesson in the course highlighting the difference between theory and practice.

Laboratory 2 – Timing Estimation and Matched Filtering: With frequency offset addressed in Laboratory 1, the next real-world challenge is timing error occurring from multiple sources within a communication link. In particular, the students learn in this laboratory how these timing error sources can be modeled and how they can be corrected. Furthermore, this laboratory presents a brief overview and implementation of transmit filtering. Given that frequency offset issues have been handled at this stage in the course, the students will be expected to provide some performance results with respect to their designs and produce a comparative study between computer simulations and SDR results. The students will explore models that describes the sample timing error and the carrier offset error between transmitting and receiving radios, as well as implement timing correction approaches and provide an analysis of the implementation performance with relative limits on the algorithmic correction. At the end of this laboratory, the students should have mastered solutions for correcting frequency offset and timing errors, as well as important tools such as eye diagrams (see Figure 4).

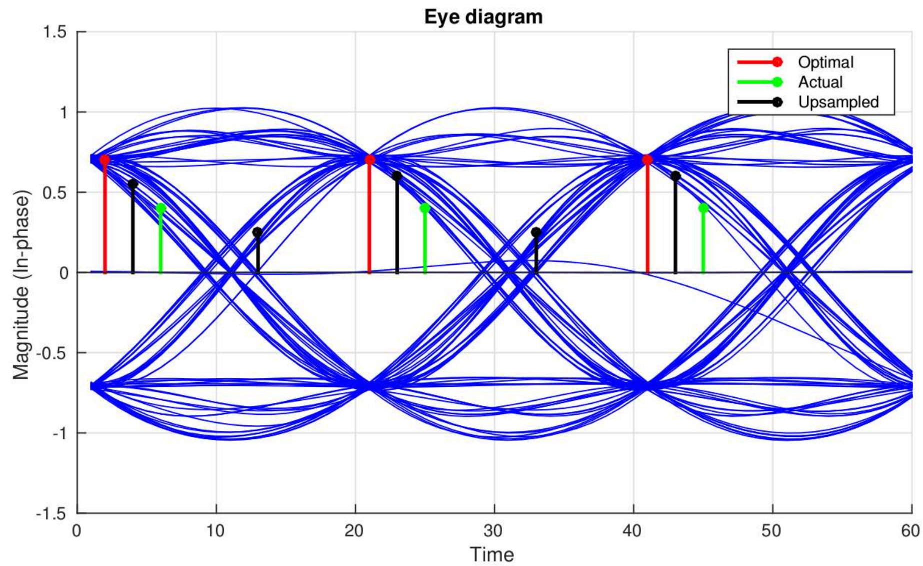

Figure 4: Example of an eye diagram possessing an initially unknown offset error. The eye diagram has been upsampled by twenty times so we can examine the transitions more closely and find the optimal sampling instant.

Laboratory 3 – Frame Synchronization, Message Decoding, and Source Coding: The final step in this hands-on educational paradigm for learning how to implement an end-to-end digital communication system is to determine the locations of the frames of data contained within an intercepted signal. Knowing how to correct for frequency offset and timing errors, the students will be tasked in this laboratory with generating framed data from a generic source, locating frames in a stream of demodulated data, and converting the data into the original source formatting. Additionally, the students will introduce source coding into their transmissions. In the first part of the laboratory experiment, the students will implement a packetized data stream and model frame offset in a source data stream. Then, the students will implement estimation techniques that will compensate for these offsets and handle multiple discontinuous frames. Previous synchronization errors will also be introduced along with their implemented corrections from the previous laboratory experiments to provide the students with a larger picture of how these different components are all intercopnnected with each other. Finally, channel coding will be included and will be evaluated with and without these synchronization errors. An illustration of how the students are expected to use tools such as correlation and sequences such as Barker Sequences to identify the starting location of frames is shown in Figure 5. Students will leverage the concept of correlation and apply it to a real-world signal intercepted by their SDR devices in order to extract the frame locations in the samples.

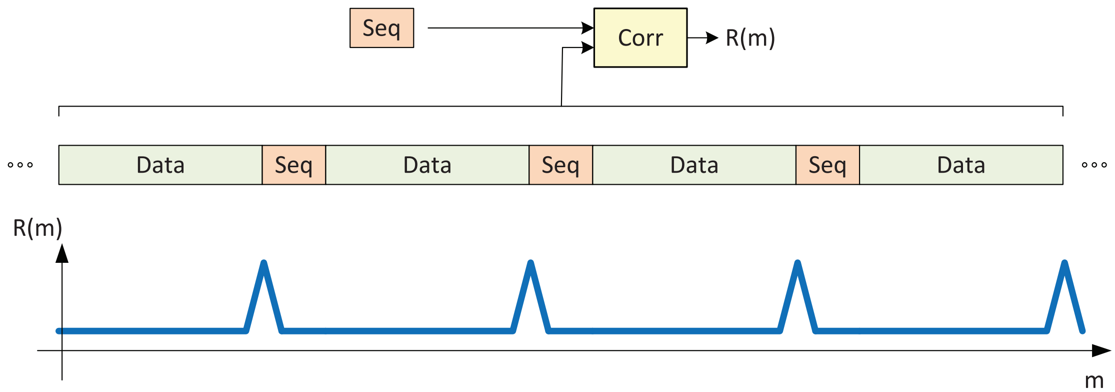

Figure 5: Leveraging a known sequence that is periodically inserted in a transmission, a receiver can be designed to exploit correlation characteristics in order to perform frame synchronization. This is the final fundamental lesson taught in the course prior to the students being expected to encode and decode binary data across the communication system end-to-end.

Results

The 2017 offering of ECE4305 consisted of eight WPI ECE undergraduate students, which was the first class to employ the proposed paradigm with the PLUTO SDR platforms. These students were paired up into four teams of two students each, and each team was responsible for working through each of the aforementioned laboratory experiments. Furthermore, given the small size of the class, all eight students worked on a single term-long comprehensive open-design project that synthesize all course concepts and the laboratory experiments in order to produce a functional prototype distributed spectrum sensing network that uploads spectrum measurements to the cloud. The open-ended course project leveraged the outcomes of the laboratory experiments, and utilized multiple coordinated PLUTO SDR units with each of them attached to a host computer installed with MATLAB. Note that several small quizzes were also conducted during the term in order to ensure that the students also mastered the theoretical concepts covered during the course.

Several results from the end-of-term student survey for the 2017 offering of ECE4305 are presented in Table 2. Based on these survey results, it is clear that the students found the experience in ECE4305 relatively rewarding. Although the students indicated that they had to spend approximately 16-20 hours per week on the SDR experimentation component of the course outside of regular lecture periods and supervised laboratory sessions, it is evident that the students found this SDR experimentation experience valuable based on the scores.

Although the students were able to design and implement sophisticated wireless communication networks based on SDR technology, there was some level of frustration with understanding the core fundamentals about how SDR technology should be setup and initialized. Although students have been exposed to wireless communications and networking before with previous course work, they did not have a solid understanding of how these concepts are connected to the device physics of the SDR platform itself, especially the radio frequency front end. For example, students were unaware that the transmit and receive paths of the SDR platforms should be assigned different center frequencies, thinking that when one path is not in use it would be

Table 2: Results of end-of-term student survey for 2017 offering of ECE4305.

Survey Question	Responses
"The educational value of the assigned work was ..." (Very poor = 1, Excellent = 5)	4.25/5
"Relative to other college courses I have taken, the amount I learned from the course was ..." (Much less = 1, Much more = 5)	4.5/5
"Relative to other college courses I have taken, the intellectual challenge presented by the course was ..." (Much less = 1, Much more = 5)	4.75/5
"On average, what were the total hours spent in each 7-day week outside of formally scheduled class time in work related to the course?"	16-20 hours/week
"Relative to other lab experiences, the intellectual challenge presented by the lab assignments was ..." (Much less = 1, Much more = 5)	4.75/5

effectively "off", which is not the case. Nevertheless, once the students eventually learned how SDR technology actually works, their usage of these platforms to design wireless communication systems and networks proceeded smoothly. An introduction to these SDR technology fundamentals will be further improved in subsequent offerings of ECE4305.

An attractive advantage of the using the PLUTO SDR in conjunction with MATLAB is that the students do not need to be confined to a laboratory setting. The compact design of the PLUTO SDR and the prevalence of MATLAB across the ECE student population makes this setup portable, allowing the students to work on wireless communication networks prototyping and design anywhere, from dorm rooms to coffee shops. This is a significant difference from SDR solutions from five years ago.

Discussion & Future Work

Student feedback from the students of the 2017 offering of ECE4305 at WPI was generally positive. It has been observed that the students are experiencing relatively less difficulty with respect to real-world issues such as frequency offset and timing errors when compared to previous offerings of the ECE4305 course employing the prior educational paradigm[1]. Furthermore, the amount of data available from the hardware observable from the different stages of the PLUTO SDR device, as well as the capabilities of the MATLAB and Simulink software pacakages, have been invaluable in providing the students will useful insight on the operation of the platform. Finally, although there are several non-ideal transmission characteristics associated with the SDR setup, this in itself is a very useful learning moment for the students since it highlights how the real-world can vary from the theory taught in a classroom.

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