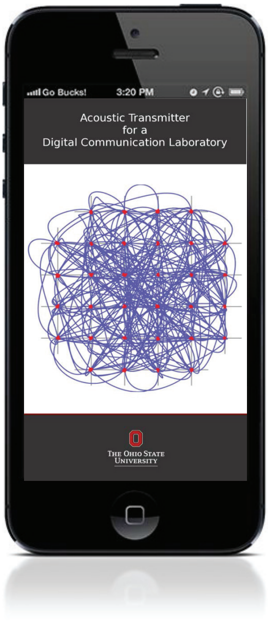
# A Digital Communication Laboratory

## Acoustic Explorations with a Software-defined Modem



Lee C. Potter and Yang Yang

2015

IBSN-10: x-xxxxxx-xx-x
IBSN-13: xxx-x-xxxxxx-xx-y

© 2015 LC Potter
All rights reserved.

Terms of Use: This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. It is attributed to Lee Potter and Yang Yang.
`http://creativecommons.org/licenses/by-nc-sa/4.0/legalcode`

This volume was typeset by the authors in LaTeX.

First edition, June 2015

Matlab and Simulink are trademarks of MathWorks. LabVIEW, USRP, Universal Software Radio Peripheral, and National Instruments are trademarks of National Instruments. Virtex is a trademark of Xilinx. Windows is a trademark of Microsoft. OpenStax CNX is a trademark of Rice University. iPhone, iPad, and iTunes are trademarks of Apple. GooglePlay and Android are trademarks of Google. PicoZed is a trademark of Avnet. Max2830 is a trademark of Maxim Integrated.

The routine `plottf.m` and Figures 1.5, 1.7, 2.1, 2.2, 4.2, and 4.4 are adapted from [Sch11] with permission from the author. Figure A.5 is provided courtesy of Aaron Wise; Figures A.6 and A.7 are used with permission.

This book is provided by the copyright holder and contributors “as is.” Any express or implied warranties, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose are disclaimed. In no event shall the authors be liable for any direct, indirect, incidental, special, exemplary or consequential damages (including, but not limited to, procurement of substitute goods or services; loss of use, data, or profits; or business interruption) however caused and on any theory of liability, whether in contract, strict liability, or tort (including negligence or otherwise) arising in any way out of the use of this book or any information, theories, or software contained or described in it, even if advised of the possibility of such damage.

Neither the name of The Ohio State University nor the names of its contributors may be used to endorse or promote products derived from this book, or the the software contained in it, without specific prior written permission.

# Contents

# Preface

This text is intended as a student guide for hands-on exploration of physical layer communication. Through a sequence of guided explorations, students design and implement a baseband digital communication system with modulation to an acoustic carrier frequency. The acoustic operation allows students to hear, see, and wirelessly transmit signals using readily available, low-cost hardware, such as a PC with sound card or a smartphone. Acoustic operation, while readily accessible, nonetheless presents a student with the channel impairments and synchronization issues encountered in radio frequency systems.

Our approach is based on experiences, both successful and disappointing, with several alternative pedagogical choices, including simulation-based laboratory instruction, direct digital conversion to a radio frequency carrier, and commercially-available radio-frequency platforms. Our preference for an acoustic modem derives from four goals. First, we seek a very low-cost pathway to provide laboratory experiences to students using ubiquitous equipment. An emphasis on cost is heightened by consideration of resource challenges encountered world-wide, and by Ohio State collaborations in Honduras and Columbia (`https://osuhe.engineering.osu.edu/`). Second, in order to provide meaningful student experiences in a short, seven-week format, we seek a balance between investing time in tools versus concepts. We choose to tilt the balance in favor of concepts, adopting familiar software tools for a rapid learning curve. Third, we seek to require students to engage in systems-level consideration of the full modem architecture, rather than week-by-week operate in a black-box world of single sub-steps. We are hopeful that we have achieved a proper balance in this regard. Fourth, we seek to develop instructional materials that are somewhat independent of specialized hardware platforms which inevitably experience rapid successions of updates or replacements.

At The Ohio State University, the text accompanies a laboratory course, ECE 5007, which meets three hours weekly during the second half of each semester. The laboratory course was introduced in conjunction with our university's transition from quarters to semesters. Undergraduate students enter the laboratory course with a semester-long introduction to signals and systems and corequisite enrollment in a digital communication lecture course. The laboratory course uses chapters 1 through 7 as guided learning exercises, reinforcing and exploring concepts abstractly presented in a typical digital communications lecture course. The second term schedule facilitates coordination of the laboratory topics with a lecture syllabus based on any of the many excellent digital communication textbooks, e.g., [Fit07, Mad08, Sch11, Pro01, JS04, Gal08]. The scope of each chapter is selected with the aim of students successfully implmenting a portion of an acoustic digital modem during a three hour session.

The text supports other learning experiences beyond the Ohio State course offering. First, the chapters are written with the intent of allowing self-study. A brief review of concepts is presented in each chapter, with emphasis on intuition and algorithmic implementation; more detailed and rigorous treatments of topics can be found in referenced sources. Second, the approach can be adopted for use in high school STEM education; pilot high school projects have been taught in Annandale-on-Hudson, New York and Seattle, Washington by Taylor Williams, a Knowles Science Teaching Foundation Fellow. Third, additional chapters are included in the text to accommodate a full semester laboratory course; additional topics include forward error correction coding, equalization of frequency-selective fading channels, and multi-carrier modulation. Further, the acoustic signal can provide an intermediate frequency signal for RF modulation; several RF options are discussed in Appendix A.

The guided explorations challenge students to design and implement a digital modem operating at audio frequencies. The computations for the software-defined radio are performed in a high-level language[1], such as MATLAB , Octave, Sci-Lab, or Sage. The exercises presented in the text have been run in MATLAB and Octave.

---

[1] See `http://www.mathworks.com/`, `http://octave.sf.net/`, `http://www.scilab.org/`, and `http://www.sagemath.org/`

The basis for our acoustic modem approach to a digital communication laboratory comes from a senior design project conducted some years ago at Ohio State. An undergraduate team was judged on communication system performance measured as bits per second per Hertz per dollar per decameter; transmission was at 918 MHz, an acceptable error rate was specified, and a laptop or smartphone was considered a zero-cost option for baseband processing. The open-ended design project elicited solutions ranging from high-gain directional antennas to merely radiating with paper clips, and students typically chose PSK or OFDM designs. The combination of systems-level design and detailed subroutine development was judged a strength in the experience.

The authors thankfully acknowledge the insights and contributions we have gathered from a variety of sources. The approach is heavily influenced by the digital communication textbook by Rick Johnson and Bill Setheras [JS04] and course notes by Phil Schniter [Sch11]. We have benefited from the laboratory courses taught by Steven Tretter [Tre08] and Robert Heath [Hea12]. We are grateful to the teaching assistants and students who embraced the senior design challenge of building a 918 MHz modem; particular thanks go to Adam Margetts, Aditi Kothiyal, Gene Whipps, Aaron Wise, Randy Askin, Michael Guirguis, Nathan Reed, Rob Brichler, Rich Kershaw, and Kevin Wells. We have learned much from Rohit Aggarwal's development of exercises for the National Instruments RF-RIO board. We thank Abigail Gillett and Adam Rich for development of an iPhone app for acoustic transmission.

Lee C. Potter
*Riverlea, Ohio*

Yang Yang
*San Diego, California*

# CHAPTER 1

# Introduction

The goals of this introductory exercise are to review basic concepts from signals and systems and to introduce the hardware and software tools to be used during the course. Concepts reviewed include sampling, aliasing, sinc reconstruction, low-pass filtering, frequency up-conversion and frequency down-conversion. The chapter begins with a survey of physical layer communication and discussion of the software-defined radio concept.

## 1.1 A Physical Layer Model

Figure 1.1 displays a complete digital communication processing chain for both the transmitter and receiver. In the seven layer Open Systems Interconnection model, the *physical layer* (PHY), or Layer 1, defines the means of transmitting raw bits over a physical link. For digital communication, the story begins and ends with a binary message; this binary message may represent, for example, speech, audio, an image, video, or high-definition television. At the transmitter, bits are encoded for error protection and converted to a sequence of discrete symbols. Symbols must be converted to a waveform suitable for transmission. In a process known as "pulse shaping," symbols are converted to a sampled-data baseband message; then, the sampled data are converted to an analog voltage signal through a digital-to-analog converter. This conversion often also entails a frequency shift to an intermediate frequency. The intermediate frequency signal is then modulated to a frequency that is matched to the desired transmission channel, such as a licensed band for commercial radio frequency transmission.

The receiver processing chain mirrors the transmission chain, but with added complexity to handle synchronization of the receiver to the transmitter and to accommodate signal distortions, or impairments, due to transmission and thermal noise at the receiver. Receiver design to mitigate these impairments is considered in Chapters 5, 6, and 8.

Symbols are illustrated in Fig. 1.2(a) for the case of the quadrature phase shift keying (QPSK) symbol constellation, also known as 4-ary quadrature amplitude modulation (4-QAM). In QPSK, pairs of bits are mapped to one of four equal energy symbols. The mapping of bits to symbols and the decoding of noisy symbols back to bits are considered in Chapter 3. A typical impulse response used for pulse shaping is illustrated in Fig. 1.2(b). The role of the pulse shaping filter and the associated design trade-offs are considered in Chapter 4. Moving down the transmission chain in Figure 1.1, the I channel of a 47-bit baseband message is shown in Figure 1.2(c), and the corresponding bandpass signal with acoustic carrier frequency 1800 Hz is shown in Figure 1.2(d).

In this laboratory course, students are guided through a sequence of directed explorations, culminating in the design and implementation of an acoustic modulator/demodulator (modem). The acoustic modem implemented in this course works much like a fax modem.

## 1.2 Software Radio

A radio is any kind of device that wirelessly transmits or receives signals at the radio frequency (RF) wavelengths of the electromagnetic spectrum. Radios are found in many products, such as cell phones, tablet computers, automobiles, televisions, spectrometers, and magnetic resonance imagers. A *software-defined radio* (SDR) can be defined as a radio in which some or all of the physical layer functions are implemented through modifiable software operating on programmable processing technologies [SDR, Fre].

Conventional hardware-based radio devices provide operational flexibility only by physically changing hardware components. In contrast, a SDR provides an inexpensive multi-mode, multi-functional, multi-protocol device that can be modified using software upgrades to provide new features to existing systems. The steady advancement

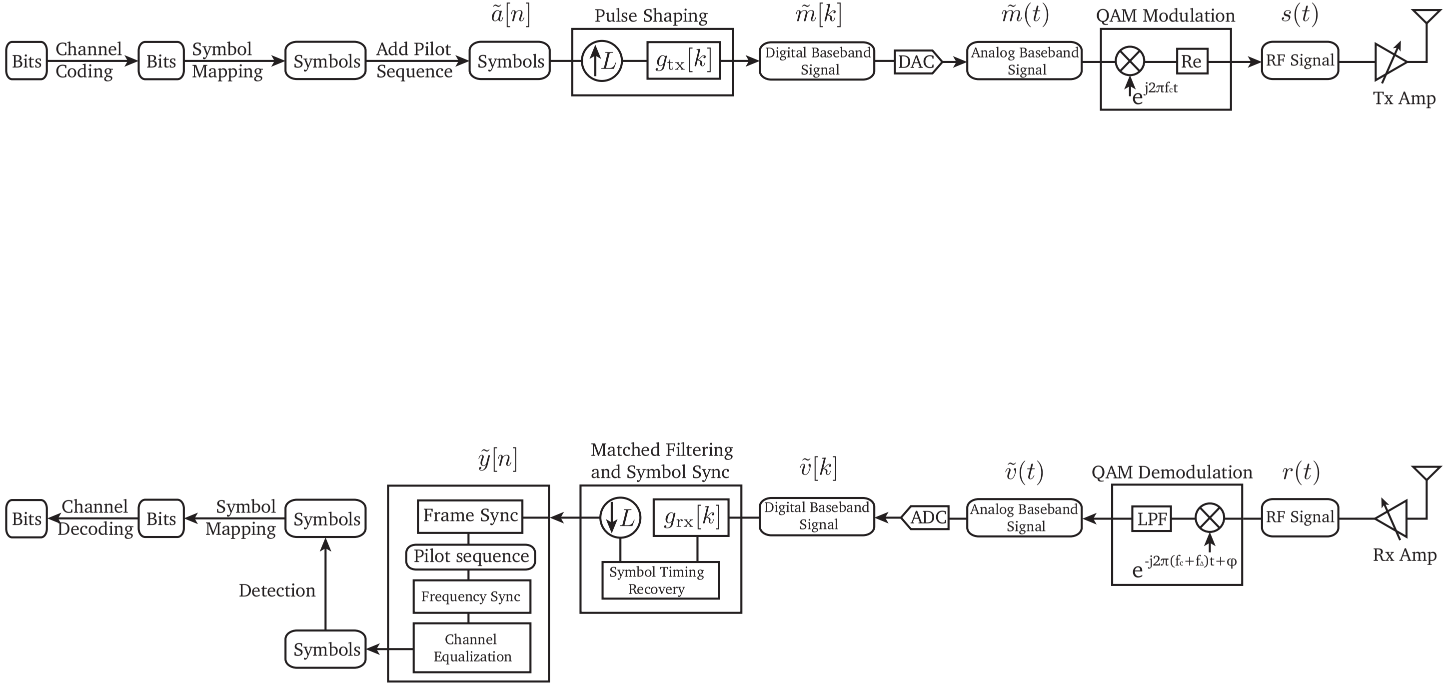
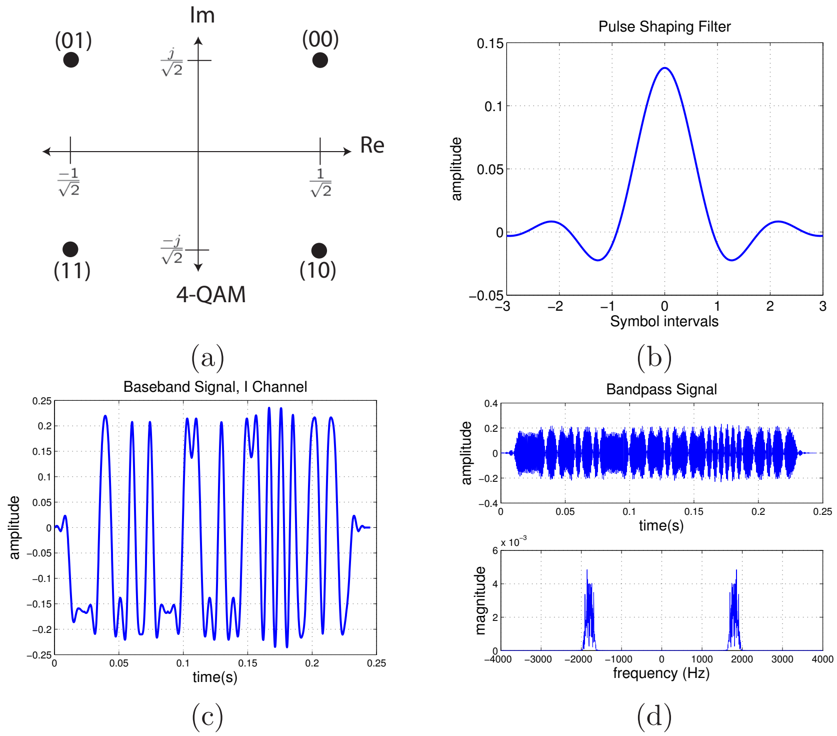


Figure 1.1: Physical layer communication processing chain for transmission and reception.

of digital technologies has provided digital sampling rates and processing speeds to process both baseband and intermediate frequency signals. SDR may soon provide interoperability of communication devices in public safety and emergency response scenarios.

A typical SDR architecture is shown in Figure 1.3. For operation at frequencies above the UHF band, current SDRs use mixers at the front end to perform analog up-conversion and down-conversion to and from the desired frequency band. On receive, the wireless signal induces on the antenna a current, which is boosted by a low-noise amplifier and filtered before down-conversion to in-phase (I) and quadra-



(a) (b)

(c) (d)

Figure 1.2: Illustrations of (a) an example symbol constellation; (b) pulse shaping filter impulse response; (c) baseband signal, I channel; and, (d) bandpass signal for $f_c = 1800$ Hz.

ture (Q) channels at an intermediate frequency (IF). The IF signal is then directly sampled at an analog-to-digital converter (ADC). Digital down-converters (DDCs) then further down-convert the signal via multiplication by a signal generated by a numerically controlled oscillator (NCO). Multiplication results in signals at the sum and difference of frequencies. The sum-of-frequencies signal is filtered out, and the difference-of-frequencies signal provides the baseband waveform, which is decimated, meaning only every $L^{th}$ sample is retained. The decimated signal lowers the sample rate to the baseband bandwidth, simplifying data processing yet retaining the information carried in the signal.

A similar set of steps occurs on transmission. Digital up-conversion (DUC) numerically mixes a baseband signal to an IF carrier frequency. The DUC, like the DDC at the receiver, is commonly packaged as a single integrated circuit. The IF signal signals in the I and Q channels feed an analog quadrature mixer that produces the RF signal, which is amplified and fed to the antenna.

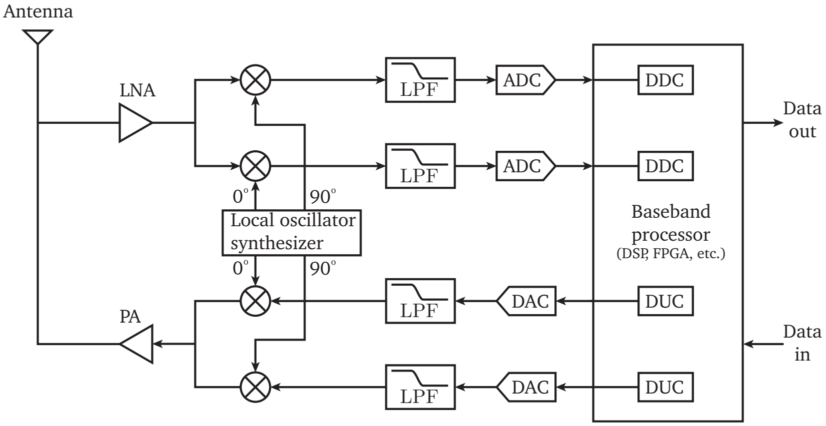


Figure 1.3: A typical SDR architecture.

## 1.3 Background

This section provides a brief review of concepts explored in the laboratory exercises. First, sampling and aliasing are reviewed. Second,