Modern Communications

Designed for a single-semester course, this concise and approachable text covers all of the essential concepts needed to understand modern communications systems. Balancing theory with practical implementation, it presents key ideas as a chain of functions for a transmitter and receiver, covering topics such as amplification, up- and down-conversion, modulation, dispersive channel compensation, error correcting codes, acquisition, multiple-antenna and multiple-input multiple-output antenna techniques, and higher-level communications functions. Analog modulations are also presented, and all of the basic and advanced mathematics, statistics, and Fourier theory needed to understand the concepts covered are included. Supported online with PowerPoint slides, a solutions manual, and additional MATLAB®-based simulation problems, it is ideal for a first course in communications for senior undergraduate and graduate students.

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"Strikes an elegant balance between fundamental concepts, their applications, and the depth of explanation. It's the kind of book that you want to hand to all beginners in wireless."
Ashutosh Sabharwal, Rice University

"An ideal introduction to modern communications systems. Theoretical principles and practical considerations are presented in an integrated fashion, and the material is introduced in an intuitive manner with a logical progression of ideas, making this the perfect text for a beginner with an interest in pursuing serious study of modern communications systems. This book should be on the required or recommended text list of all introductory communications courses."
Siddhartan Govindasamy, Boston College

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A Systematic Introduction

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Preface

It is a very sad thing that nowadays there is so little useless information.

Oscar Wilde

In writing this text, my aim is to provide a systematic and efficient introduction to the way in which modern communications systems are designed and analyzed. While there are many wonderful undergraduate texts on this topic (for example, [1–3]) that commonly employ a historically motivated structure, this textbook provides an alternative that is hopefully more efficient. I consciously chose to keep this text relatively short to encourage a linear reading of the entire text. I focus on wireless communications, but the ideas presented are applicable to other types of communications systems. This textbook will allow you to teach all the critical topics in a semester-length course.

The content of this textbook addresses the topics necessary to understand issues that are critical to building real-world communications systems. This focus differentiates my text from some that miss important practical topics while overemphasizing techniques that are now less important. The textbook is split into two parts. The first part is the essential portion of the text. The second part contains useful background information. I use notional transmitter and receiver radio chains to guide this introduction. I introduce the idea of channel capacity early in the textbook. This allows the reader to have a sense of the limits of performance that motivate the engineering choices we make. Additionally, I stress the effects of hardware limitations, such as noise figure, phase noise, analog-to-digital converter (ADC) and digital-to-analog converter (DAC) quantization, and linearity. I emphasize up- and down-conversion approaches that are currently used, such as direct conversion and digital intermediate frequency (IF). I provide a short introduction to forward error correction and draw the connection to capacity. I discuss the critical topics of acquisition and synchronization that are often overlooked. I discuss dispersive channels and emphasize approaches such as orthogonal frequency-division multiplexing (OFDM) and adaptive equalization to address these channels. I also introduce multiple-input multiple-output (MIMO) communications, and with an eye toward future systems I consider adaptive multiple-antenna processing. Finally, I review or introduce the mathematical tools, such as linear algebra and statistics, to perform the calculations required to understand communications systems.

Specifically, I organize this textbook into the following topics. In Chapter 1, “Notation,” I provide a quick overview of the mathematical notation used. In Chapter 2, “Basic Radio,” I provide a quick survey of concepts used in communications systems, focusing on wireless radio systems. These concepts include signal sources, channels (for example, the Friis equation for line-of-sight propagation), noise sources, signal-to-noise ratio, theoretical limits, nonidealities, antennas, waveforms, and representative transmit and receive processing chains. In Chapter 3, “Fundamental Limits on Communications,” I introduce the concepts of channel capacity and source compression, including the idea that there is a fundamental achievable bound on data rate (Shannon’s channel capacity) with a sketch of a proof of the bound. I also discuss how to use the Shannon limit to help in system design. In Chapter 4, “Amplifiers and Noise,” I present an overview of amplifiers and sources of noise, including an overview of low-noise amplifiers (LNAs) with a derivation of the Friis formula. I discuss nonidealities of amplifiers including nonlinearity with an explanation of the third-order input intercept point (IIP3). In Chapter 5, “Up- and Down-Conversion,” I introduce techniques to move signals between baseband and carrier frequencies, including multiple up- and down-conversion techniques. I connect the mathematical formulations with the basic block diagrams of various direct conversion and superheterodyne approaches. In this context, I discuss DACs and ADCs with a corresponding discussion of dynamic range. I also introduce how the combination of crystal oscillators and phase-locked loops (PLLs) are used to construct frequency synthesizers that are integral to the operation of up- and down-conversion techniques. In Chapter 6, “Modulation and Demodulation,” I present modulation and demodulation techniques to move between bits and in-phase and quadrature baseband voltages. I discuss various constellation approaches, including binary-phase-shift keying (BPSK), quadrature-phase-shift keying (QPSK), 8-phase-shift keying (8-PSK), 16-quadrature-amplitude modulation (16-QAM), and differential approaches. I compare hard decision and soft decision demodulation approaches. I also sketch the derivation of the modulation-specific capacity result. I provide a discussion of the relationship between pulse-shaping filters and spectral shapes. In Chapter 7, “Dispersive Channels,” I introduce the concept of propagation channels with delay spread and provide receiver and waveform techniques to compensate for these effects, including adaptive equalizers and OFDM. For OFDM, I motivate the idea of a cyclic prefix and discuss subcarrier spacing design. In Chapter 8, “Error Correcting Codes,” I present forward error correction approaches at an introductory level. While a proper treatment would take a semester, I do provide an overview of systematic linear block codes (Hamming codes, for example). I discuss generator matrices, parity check matrices, and syndromes. I also provide an introduction to convolutional codes with an explanation of Viterbi demodulation. In Chapter 9, “Acquisition and Synchronization,” I survey techniques for acquiring a communications link and synchronizing between radios. I introduce various acquisition and synchronization approaches such as energy, cross-correlation, and autocorrelation detector techniques. I discuss the receiver operating characteristic (ROC) curves for these approaches. I also derive the maximum likelihood

(ML) techniques for spectral and temporal synchronization. In Chapter 10, "Radio Duplex, Access, and Networks," I provide an introduction to how radios interact in terms of use of the channel. I introduce the ideas of time-division duplex (TDD) and frequency-division duplex (FDD) approaches. I also introduce various access control approaches, including Aloha and carrier-sense multiple access (CSMA), time-division multiple access (TDMA), frequency-division multiple access (FDMA), and code-division multiple access (CDMA). I provide simple examples of CDMA spreading and de-spreading. In Chapter 11, "Multiple-Antenna and Multiple-Input Multiple-Output Communications," I introduce theory and techniques for multiple-antenna and MIMO techniques. I introduce the concept of multiple-antenna receivers and MIMO communications systems, as well as spatially adaptive beamforming. I also discuss MIMO channel capacity and some simple space–time coding approaches. In Chapter 12, "Analog Radio Systems," I review analog radio techniques for historical completeness. I review amplitude and phase modulations and various carrier and sideband suppression approaches. To provide a mathematical background, I discuss the Hartley modulator and the associated Hilbert transform. I provide an analytical presentation of the spectrum of a sinusoidal phase modulation. Finally, I provide an analysis of how to use PLLs to demodulate angle-modulation techniques.

In Part II, "Mathematical Background," I review and introduce concepts that are useful in understanding communications systems. In Chapter 13, "Useful Mathematics," I provide a range of useful engineering mathematics, including complex variables, linear algebra, multivariate calculus, and special functions. In Chapter 14, "Probability and Statistics," I review basic probability, including the concepts of density functions, Bayes' theorem, maximum a posteriori (MAP) and ML estimators, change of variables and moments, and multivariate distributions. I also introduce a number of important distributions, including complex Gaussian, exponential, chi-square, and Rician distributions. I also discuss the concept of a random process. Finally, in Chapter 15, "Fourier Analysis," I review Fourier theory, including basic transforms, Fourier series, discrete-time Fourier transforms, and discrete Fourier transforms with a discussion of the usefulness of fast Fourier transforms (FFTs).

For an undergraduate semester class, I expect a typical presentation of the material would provide an overview of communications by using Chapter 2; quickly review the essential mathematic background by leveraging Chapters 13–15; and spend most of the class on Chapters 3–10. Depending upon the preparation of the class, I would include Chapter 11. Additionally, Chapter 12 might be presented for historical context. While some advanced concepts are introduced in Chapters 13–15, I provide these chapters primarily for review and reference, although the time dedicated to these chapters can be modulated depending upon the readiness of the students.

To support the classroom use of the textbook, I provide supplemental materials. These materials include a full set of slides for presentation, solutions for a subset of problems, and a rich set of supplemental simulation-focused problems. This material is available at www.cambridge.org/blisscomms.

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I would like to thank Cartel Coffee Lab, who helped fuel much of the writing of this text. The baristas are always friendly, and I still have not found a better espresso.

I would like to thank my parents, Daniel Bliss, Sr. and Nancy Bliss. I know that I got lucky because I still have not found better parents. I hope for my daughter's sake that I can be even a fraction of the parent that they were. Sure, I probably should have put them above the espresso, but, come on, espresso. I would also like to deeply thank Nadya and my daughter, Coco (who is fond of cats), for their love.