Introduction to Communication Systems

Showcasing the essential principles behind modern communication systems, this accessible undergraduate textbook provides a solid introduction to the foundations of communication theory.

- Carefully selected topics introduce students to the most important and fundamental concepts, giving them a focused, in-depth understanding of core material, and preparing them for more advanced study.
- Abstract concepts are introduced "just in time" and reinforced by nearly 200 end-of-chapter exercises, alongside numerous MATLAB code fragments, software problems, and practical lab exercises, firmly linking the underlying theory to real-world problems, and providing additional hands-on experience.
- An accessible lecture-style organisation makes it easy for students to navigate to key passages, and quickly identify the most relevant material.

Containing material suitable for a one- or two-semester course, and accompanied online by a password-protected solutions manual and supporting instructor resources, this is the perfect introductory textbook for undergraduate students studying electrical and computer engineering.

Upamanyu Madhow is Professor of Electrical and Computer Engineering at the University of California, Santa Barbara. His research interests broadly span communications, signal processing and networking, with current emphasis on next-generation wireless and bio-inspired approaches to networking and inference. He is a recipient of the NSF CAREER Award and the IEEE Marconi prize paper award in wireless communication, author of the graduate-level textbook *Fundamentals of Digital Communication* (2008), and a Fellow of the IEEE.

"Madhow does it again: *Introduction to Communication Systems* is an accessible yet rigorous new text that does for undergraduates what his digital communications book did for graduate students. It provides a superior treatment of not only the fundamentals of analog and digital communication, but also the theoretical underpinnings needed to understand them, including frequency domain analysis and probability. The book is unusual in that it also includes newer topics of pressing current relevance like multiple antenna communication and OFDM. I strongly recommend this book for faculty teaching senior level courses on communication systems."

Jeffrey G. Andrews
The University of Texas at Austin

"This is an excellent undergraduate text on analog and digital communications. It covers everything from classic analog techniques to recent wireless systems. Students will enjoy the inclusion of advanced topics such as channel coding and MIMO."

David Love
Purdue University

"*Introduction to Communication Systems* by Madhow is truly unique in the vast landscape of introductory books on communication systems. From the basics of signal processing, probability, and communications, to the advanced topics of coding, multipath mitigation, and multiple antenna systems, the book deftly interweaves abstract theory, design principles, and applications in a highly effective and insightful manner. This masterfully-written book will play a key role in teaching and inspiring the next generation of communication system engineers."

Andrea Goldsmith
Stanford University

"This is the textbook on communications I have wanted for a while. Crisply written, it forms the basis for an ideal two semester sequence. It nicely balances rigor, concepts and practice."

Saoura Dasgupta
University of Iowa

"This is a unique introduction to the basic principles of communication system design, with a remarkable combination of rigour and accessibility. The MATLAB exercises are expertly weaved together with theoretical principles making it an excellent textbook for training undergraduate communication systems engineers."

Suhas Diggavi
University of California, Los Angeles

"This is a valuable addition to the current set of textbooks on communication systems. It is comprehensive, and offers a modern perspective shaped by the author's research that has pushed the state of the art. The software labs enhance the practicality of the text and serve to illustrate more advanced material in an accessible way."

Michael Honig
Northwestern University

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To my family and students

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Preface

Progress in telecommunications over the past two decades has been nothing short of revolutionary, with communications taken for granted in modern society to the same extent as electricity. There is therefore a persistent need for engineers who are well-versed in the principles of communication systems. These principles apply to communication between points in space, as well as communication between points in time (i.e., storage). Digital systems are fast replacing analog systems in both domains. This book has been written in response to the following core question: what is the basic material that an undergraduate student with an interest in communications should learn, in order to be well prepared for either industry or graduate school? For example, some institutions teach only digital communication, assuming that analog communication is dead or dying. Is that the right approach? From a purely pedagogical viewpoint, there are critical questions related to mathematical preparation: how much mathematics must a student learn to become well-versed in system design, what should be assumed as background, and at what point should the mathematics that is not in the background be introduced? Classically, students learn probability and random processes, and then tackle communication. This does not quite work today: students increasingly (and, I believe, rightly) question the applicability of the material they learn, and are less interested in abstraction for its own sake. On the other hand, I have found from my own teaching experience that students get truly excited about abstract concepts when they discover their power in applications, and it is possible to provide the means for such discovery using software packages such as MATLAB. Thus, we have the opportunity to get a new generation of students excited about this field: by covering abstractions "just in time" to shed light on engineering design, and by reinforcing concepts immediately using software experiments in addition to conventional pen-and-paper problem solving, we can remove the lag between learning and application, and ensure that the concepts stick.

This textbook represents my attempt to act upon the preceding observations, and is an outgrowth of my lectures for a two-course undergraduate elective sequence on communication at UCSB, which is often also taken by some beginning graduate students. Thus, it can be used as the basis for a two-course sequence in communication systems, or a single course on digital communication, at the undergraduate or beginning graduate level. The book also provides a review or introduction to communication systems for practitioners, easing the path to study of more advanced graduate texts and the research literature. The prerequisite is a course on signals and systems, together with an introductory course on probability. The required material on random processes is included in the text.

A student who masters the material here should be well-prepared for either graduate school or the telecommunications industry. The student should leave with an understanding of baseband and passband signals and channels, modulation formats appropriate for these channels, random processes and noise, a systematic framework for optimum demodulation based on signal-space concepts, performance analysis and power–bandwidth tradeoffs for common modulation schemes, a hint of the power of information theory and channel coding, and an introduction to communication techniques for dispersive channels and multiple antenna systems. Given the significant ongoing research and development activity in wireless communication, and the fact that an understanding of wireless link design provides a sound background for approaching other communication links, material enabling hands-on discovery of key concepts for wireless system design is distributed throughout the textbook.

I should add that I firmly believe that the utility of this material goes well beyond communications, important as that field is. Communications systems design merges concepts from signals and systems, probability and random processes, and statistical inference. Given the broad applicability of these concepts, a background in communications is of value in a large variety of areas requiring "systems thinking," as I discuss briefly at the end of Chapter 1.

The goal of the lecture-style exposition in this book is to clearly articulate a selection of concepts that I deem *fundamental* to communication system design, rather than to provide comprehensive coverage. "Just in time" coverage is provided by organizing and limiting the material so that we get to core concepts and applications as quickly as possible, and by sometimes asking the reader to operate with partial information (which is, of course, standard operating procedure in the real world of engineering design). However, the topics that we do cover are covered in sufficient detail to enable the student to solve nontrivial problems and to obtain hands-on involvement via software labs. Descriptive material that can easily be looked up online is omitted.

Organization

- Chapter 1 provides a perspective on communication systems, including a discussion of the transition from analog to digital communication and how it colors the selection of material in this text.
- Chapter 2 provides a review of signals and systems (biased towards communications applications), and then discusses the complex-baseband representation of passband signals and systems, emphasizing its critical role in modeling, design, and implementation. A software lab on modeling and undoing phase offsets in complex baseband, while providing a sneak preview of digital modulation, is included. Chapter 2 also includes a section on wireless-channel modeling in complex baseband using ray tracing, reinforced by a software lab that applies these ideas to simulate link time variations for a lamppost-based broadband wireless network.
- Chapter 3 covers analog communication techniques that remain relevant even as the world goes digital, including superheterodyne reception and phase-locked loops. Legacy analog modulation techniques are discussed to illustrate core concepts, as well as in

recognition of the fact that suboptimal analog techniques such as envelope detection and limiter–discriminator detection may have to be resurrected as we push the limits of digital communication in terms of speed and power consumption. Software labs reinforce and extend concepts in amplitude and angle modulation.

- Chapter 4 discusses digital modulation, including linear modulation using constellations such as pulse amplitude modulation (PAM), quadrature amplitude modulation (QAM), and phase-shift keying (PSK), and orthogonal modulation and its variants. The chapter includes discussion of the number of degrees of freedom available on a bandlimited channel, the Nyquist criterion for avoidance of intersymbol interference, and typical choices of Nyquist and square-root Nyquist signaling pulses. We also provide a sneak preview of power–bandwidth tradeoffs (with detailed discussion postponed until the effect of noise has been modeled in Chapters 5 and 6). A software lab providing a hands-on feel for Nyquist signaling is included in this chapter.

The material in Chapters 2 through 4 requires only a background in signals and systems.

- Chapter 5 provides a review of basic probability and random variables, and then introduces random processes. This chapter provides detailed discussion of Gaussian random variables, vectors and processes; this is essential for modeling noise in communication systems. Examples giving a preview of receiver operations in communication systems, and computation of performance measures such as error probability and signal-to-noise ratio (SNR), are provided. A discussion of the circular symmetry of white noise, and noise analysis of analog modulation techniques, are placed in an appendix, since this is material that is often skipped in modern courses on communication systems.
- Chapter 6 covers classical material on optimum demodulation for M-ary signaling in the presence of additive white Gaussian noise (AWGN). The background on Gaussian random variables, vectors, and processes developed in Chapter 5 is applied to derive optimal receivers, and to analyze their performance. After discussing error probability computation as a function of SNR, we are able to combine the materials in Chapters 4 and 6 for a detailed discussion of power–bandwidth tradeoffs. Chapter 6 concludes with an introduction to link-budget analysis, which provides guidelines on the choice of physical link parameters such as transmit and receive antenna gains, and distance between transmitter and receiver, using what we know about the dependence of error probability as a function of SNR. This chapter includes a software lab that builds on the Nyquist signaling lab in Chapter 4 by investigating the effect of noise. It also includes another software lab simulating performance over a time-varying wireless channel, examining the effects of fading and diversity, and introduces the concept of differential demodulation for avoidance of explicit channel tracking.

Chapters 2 through 6 provide a systematic lecture-style exposition of what I consider core concepts in communication at an undergraduate level.

- Chapter 7 provides a glimpse of information theory and coding whose goal is to stimulate the reader to explore further using more advanced resources such as graduate courses and textbooks. It shows the critical role of channel coding, provides an initial exposure to information-theoretic performance benchmarks, and discusses belief propagation in detail, reinforcing the basic concepts through a software lab.

- Chapter 8 provides a first exposure to the more advanced topics of communication over dispersive channels, and to multiple antenna systems, often termed space–time communication, or multiple-input, multiple-output (MIMO) communication. These topics are grouped together because they use similar signal processing tools. We emphasize lab-style "discovery" in this chapter using three software labs, one on adaptive linear equalization for single-carrier modulation, one on basic orthogonal frequency-division multiplexing (OFDM) transceiver operations, and one on MIMO signal processing for space–time coding and spatial multiplexing. The goal is for students to acquire hands-on insight that should motivate them to undertake a deeper and more systematic investigation.
- Finally, the epilogue contains speculation on future directions in communications research and technology. The goal is to provide a high-level perspective on where mastery of the introductory material in this textbook could lead, and to argue that the innovations which this field has already seen set the stage for many exciting developments to come.

The role of software. Software problems and labs are integrated into the text, with "code fragments" implementing core functionalities provided in the text. While code can be provided online, separate from the text (and, indeed, sample code is made available online for instructors), code fragments are integrated into the text for two reasons. First, they enable readers to immediately see the software realization of a key concept as they read the text. Second, I feel that students learn more by putting in the work of writing their own code, building on these code fragments if they wish, rather than using code that is easily available online. The particular software that we use is MATLAB, because of its widespread availability, and because of its importance in design and performance evaluation both in academia and in industry. However, the code fragments can also be viewed as "pseudocode," and can be easily implemented using other software packages or languages. Block-based packages such as Simulink (which builds upon MATLAB) are avoided here, because the use of software here is pedagogical rather than aimed at, say, designing a complete system by putting together subsystems as one might do in industry.

Suggestions for using this book

I view Chapter 2 (complex baseband), Chapter 4 (digital modulation), and Chapter 6 (optimum demodulation) as core material that *must* be studied to understand the concepts underlying modern communication systems. Chapter 6 relies on the probability and random processes material in Chapter 5, especially the material on jointly Gaussian random variables and white Gaussian noise (WGN), but the remaining material in Chapter 5 can be skipped or covered selectively, depending on the students' background. Chapter 3 (analog communication techniques) is designed such that it can be completely skipped if one wishes to focus solely on digital communication. Finally, Chapter 7 and Chapter 8 contain glimpses of advanced material that can be sampled according to the instructor's discretion. The qualitative discussion in the epilogue is meant to provide the student with perspective, and is not intended for formal coverage in the classroom.

In my own teaching at UCSB, this material forms the basis for a two-course sequence, with Chapters 2–4 covered in the first course, and Chapters 5 and 6 covered in the second course, with the dispersive channels portion of Chapter 8 providing the basis for the labs in the second course. The content of these courses is constantly being revised, and it is expected that the material on channel coding and MIMO may displace some of the existing material in the future. UCSB is on a quarter system, hence the coverage is fast-paced, and many topics are omitted or skimmed. There is ample material here for a two-semester undergraduate course sequence. For a one-semester course, one possible organization is to cover Chapter 2 (focusing on the complex envelope), Chapter 4, a selection of Chapter 5, Chapter 6, and, if time permits, Chapter 7.

The slides accompanying the book are intended not to provide comprehensive coverage of the material, but rather to provide an example of selections from the material to be covered in the classroom. I must comment in particular on Chapter 5. While much of the book follows the format in which I lecture, Chapter 5 is structured as a reference on probability, random variables, and random processes that the instructor must pick and choose from, depending on the background of the students in the class. The particular choices I make in my own lectures on this material are reflected in the slides for this chapter.

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This book is an outgrowth of lecture notes for an undergraduate elective course sequence in communications at UCSB, and I am grateful to the succession of students who have used, and provided encouraging comments on, the evolution of the course sequence and the notes. I would also like to acknowledge faculty in the communications area at UCSB who were kind enough to give me a "lock" on these courses over the past few years, as I was developing this textbook.

The first priority in a research university is to run a vibrant research program, hence I must acknowledge the extraordinarily capable graduate students in my research group over the years during which this textbook was developed. They have done superb research with minimal supervision from me, and the strength of their peer interactions and collaborations is what gave me the mental space, and time, needed to write this textbook. Current and former group members who have directly helped with aspects of this book include Andrew Irish, Babak Mamandipoor, Dinesh Ramasamy, Maryam Eslami Rasekh, Sumit Singh, Sriram Venkateswaran, and Aseem Wadhwa.

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