Channel Codes

Channel coding lies at the heart of digital communication and data storage, and this detailed introduction describes the core theory as well as decoding algorithms, implementation details, and performance analyses.

Professors Ryan and Lin, known for the clarity of their writing, provide the latest information on modern channel codes, including turbo and low-density parity-check (LDPC) codes. They also present detailed coverage of BCH codes, Reed–Solomon codes, convolutional codes, finite-geometry codes, and product codes, providing a one-stop resource for both classical and modern coding techniques.

The opening chapters begin with basic theory to introduce newcomers to the subject, assuming no prior knowledge in the field of channel coding. Subsequent chapters cover the encoding and decoding of the most widely used codes and extend to advanced topics such as code ensemble performance analyses and algebraic code design. Numerous varied and stimulating end-of-chapter problems, 250 in total, are also included to test and enhance learning, making this an essential resource for students and practitioners alike.

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Channel Codes

Classical and Modern

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Preface

The title of this book, *Channel Codes: Classical and Modern*, was selected to reflect the fact that this book does indeed cover both classical and modern channel codes. It includes BCH codes, Reed–Solomon codes, convolutional codes, finite-geometry codes, turbo codes, low-density parity-check (LDPC) codes, and product codes. However, the title has a second interpretation. While the majority of this book is on LDPC codes, these can rightly be considered to be both classical (having been first discovered in 1961) and modern (having been rediscovered circa 1996). This is exemplified by David Forney's statement at his August 1999 IMA talk on codes on graphs, "It feels like the early days." As another example of the classical/modern duality, finite-geometry codes were studied in the 1960s and thus are classical codes. However, they were rediscovered by Shu Lin *et al.* circa 2000 as a class of LDPC codes with very appealing features and are thus modern codes as well. The classical and modern incarnations of finite-geometry codes are distinguished by their decoders: one-step hard-decision decoding (classical) versus iterative soft-decision decoding (modern).

It has been 60 years since the publication in 1948 of Claude Shannon's celebrated *A Mathematical Theory of Communication*, which founded the fields of channel coding, source coding, and information theory. Shannon proved the existence of channel codes which ensure reliable communication provided that the information rate for a given code did not exceed the so-called capacity of the channel. In the first 45 years that followed Shannon's publication, a large number of very clever and very effective coding systems had been devised. However, none of these had been demonstrated, in a practical setting, to closely approach Shannon's theoretical limit. The first breakthrough came in 1993 with the discovery of turbo codes, the first class of codes shown to operate near Shannon's capacity limit. A second breakthrough came circa 1996 with the rediscovery of LDPC codes, which were also shown to have near-capacity performance. (These codes were first invented in 1961 and mostly ignored thereafter. The state of the technology at that time made them impractical.) Because it has been over a decade since the discovery of turbo and LDPC codes, the knowledge base for these codes is now quite mature and the time is ripe for a new book on channel codes.

This book was written for graduate students in engineering and computer science as well as research and development engineers in industry and academia. We felt compelled to collect all of this information in one source because it has been scattered across many journal and conference papers. With this book, those entering the field of channel coding, and those wishing to advance their knowledge, conveniently have a single resource for learning about both classical and modern channel codes. Further, whereas the archival literature is written for experts, this textbook is appropriate for both the novice (earlier chapters) and the expert (later chapters). The book begins slowly and does not presuppose prior knowledge in the field of channel coding. It then extends to frontiers of the field, as is evident from the table of contents.

The topics selected for this book, of course, reflect the experiences and interests of the authors, but they were also selected for their importance in the study of channel codes – not to mention the fact that additional chapters would make the book physically unwieldy. Thus, the emphasis of this book is on codes for binary-input channels, including the binary-input additive white-Gaussian-noise channel, the binary symmetric channel, and the binary erasure channel. One notable area of omission is coding for wireless channels, such as MIMO channels. However, this book is useful for students and researchers in that area as well because many of the techniques applied to the additive white-Gaussian-noise channel, our main emphasis, can be extended to wireless channels. Another notable omission is soft-decision decoding of Reed–Solomon codes. While extremely important, this topic is not as mature as those in this book.

Several different course outlines are possible with this book. The most obvious for a first graduate course on channel codes includes selected topics from Chapters 1, 2, 3, 4, 5, and 7. Such a course introduces the student to capacity limits for several common channels (Chapter 1). It then provides the student with an introduction to just enough algebra (Chapter 2) to understand BCH and Reed–Solomon codes and their decoders (Chapter 3). Next, this course introduces the student to convolutional codes and their decoders (Chapter 4). This course next provides the student with an introduction to LDPC codes and iterative decoding (Chapter 5). Finally, with the knowledge gained from Chapters 4 and 5 in place, the student is ready to tackle turbo codes and turbo decoding (Chapter 7). The material contained in Chapters 1, 2, 3, 4, 5, and 7 is too much for a single-semester course and the instructor will have to select a preferred subset of that material.

For a more advanced course centered on LDPC code design, the instructor could select topics from Chapters 10, 11, 12, 13, and 14. This course would first introduce the student to LDPC code design using Euclidean geometries and projective geometries (Chapter 10). Then the student would learn about LDPC code design using finite fields (Chapter 11) and combinatorics and graphs (Chapter 12). Next, the student would apply some of the techniques from these earlier chapters to design codes for the binary erasure channel (Chapter 13). Lastly, the student would learn design techniques for nonbinary LDPC codes (Chapter 14).

As a final example of a course outline, a course could be centered on computer-based design of LDPC codes. Such a course would include Chapters 5, 6, 8, and 9. This course would be for those who have had a course on classical channel codes, but who are interested in LDPC codes. The course would begin with an introduction to LDPC codes and various LDPC decoders (Chapter 5). Then, the student would learn about various computer-based code-design approaches, including Gallager codes, MacKay codes, codes based on protographs, and codes based on accumulators (Chapter 6). Next, the student would learn about assessing the performance of LDPC code ensembles from a weight-distribution perspective (Chapter 8). Lastly, the student would learn about assessing the performance of (long) LDPC codes from a decoding-threshold perspective via the use of density evolution and EXIT charts (Chapter 9).

All of the chapters contain a good number of problems. The problems are of various types, including those that require routine calculations or derivations, those that require computer solution or computer simulation, and those that might be characterized as a semester project. The authors have selected the problems to strengthen the student's knowledge of the material in each chapter (e.g., by requiring a computer simulation of a decoder) and to extend that knowledge (e.g., by requiring the proof of a result not contained in the chapter).

We wish to thank, first of all, Professor Ian Blake, who read an early version of the entire manuscript and provided many important suggestions that led to a much improved book.

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We also acknowledge the talented Mrs. Linda Wyrgatsch whose painting on the back cover was created specifically for this book. We note that the paintings on the front and back covers are classical and modern, respectively.

Finally, we would like to give special thanks to our wives (Stephanie and Ivy), children, and grandchildren for their continuing love and affection throughout this project.

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Web sites for this book:
www.cambridge.org/9780521848688
http://www.ece.arizona.edu/~ryan/ChannelCodesBook/