Communication Networks

Communication Networks blends control, optimization, and stochastic network theories with features that support student learning to provide graduate students with an accessible, modern approach to the design of communication networks.

- Covers a broad range of performance analysis tools, including important advanced topics that are made accessible to graduate students for the first time.
- Taking a top-down approach to network protocol design, the authors begin with the deterministic model and progress to more sophisticated models.
- Network algorithms and protocols are tied closely to the theory, engaging students and helping them understand the practical engineering implications of what they have learnt.
- The background behind the mathematical analyses is given before the formal proofs and is supported by worked examples, enabling students to understand the big picture before going into the detailed theory.
- End-of-chapter exercises cover a range of difficulties; complex problems are broken down into several parts, many with hints to guide students. Full solutions are available to instructors.

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AN OPTIMIZATION, CONTROL, AND STOCHASTIC NETWORKS PERSPECTIVE

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To Amma, Appa, Susie, Katie, and Jenny
RS

To my parents, Lingfang and Ethan
LY

"This book by Srikant and Ying fills a major void – an analytical and authoritative study of communication networks that covers many of the major advances made in this area in an easy-to-understand and self-contained manner. It is a must read for any networking student, researcher, or engineer who wishes to have a fundamental understanding of the key operations of communication networks, from network dimensioning and design to congestion control, routing, and scheduling. Throughout the book, the authors have taken pains to explain highly mathematical material in a manner that is accessible to a beginning graduate student. This has often required providing new examples, results, and proofs that are simple and easy to follow, which makes the book attractive to academics and engineers alike. A must have networking book for one's personal library!"

Ness B. Shroff
The Ohio State University

"*Communication Networks* provides a deep, modern and broad yet accessible coverage of the analysis of networks. The authors, who made many original contributions to this field, guide the readers through the intuition behind the analysis and results. The text is ideal for self-study and as a basis for a graduate course on the mathematics of communication networks. Students in networking will benefit greatly from reading this book."

Jean Walrand
University of California, Berkeley

"*Communication Networks*, by Srikant and Ying, provides a mathematically rigorous treatment of modern communication networks. The book provides the essential mathematical preliminaries in queueing theory, optimization and control, followed by a rigorous treatment of network architectures, protocols and algorithms that are at the heart of modern-day communication networks and the Internet. It is the best textbook on communication networks from a theoretical perspective in over 20 years, filling a much needed void in the field. It can be an excellent textbook for graduate and advanced undergraduate classes, and extremely useful to researchers in this rapidly evolving field."

Eytan Modiano
Massachusetts Institute of Technology

"This book presents a view of communication networks, their architecture and protocols, grounded in the theoretical constructs from optimization and queuing theory that underpin the modern approach to the design and analysis of networks. It is a superb introduction to this approach."

Frank Kelly
University of Cambridge

"This textbook provides a thoughtful treatment of network architecture and network protocol design within a solid mathematical framework. Networks are required to provide good stable behavior in random environments. This textbook provides the tools needed to make this happen. It provides needed foundations in optimization, control, and probabilistic techniques. It then demonstrates their application to the understanding of current networks and the design of future network architectures and protocols. This is a 'must' addition to the library of graduate students performing research in networking, and engineers researching future network architectures and protocols."

Donald F. Towsley
University of Massachusetts Amherst

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PREFACE

Why we wrote this book

Traditionally, analytical techniques for communication networks discussed in textbooks fall into two categories: (i) analysis of network protocols, primarily using queueing theoretic tools, and (ii) algorithms for network provisioning which use tools from optimization theory. Since the mid 1990s, a new viewpoint of the architecture of a communication network has emerged. Network architecture and algorithms are now viewed as slow-time-scale, distributed solutions to a large-scale optimization problem. This approach illustrates that the layered architecture of a communication network is a natural by-product of the desire to design a fair and stable system. On the other hand, queueing theory, stochastic processes, and combinatorics play an important role in designing low-complexity and distributed algorithms that are viewed as operating at fast time scales.

Our goal in writing this book is to present this modern point of view of network protocol design and analysis to a wide audience. The book provides readers with a comprehensive view of the design of communication networks using a combination of tools from optimization theory, control theory, and stochastic networks, and introduces mathematical tools needed to analyze the performance of communication network protocols.

Organization of the book

The book has been organized into two major parts. In the first part of the book, with a few exceptions, we present mathematical techniques only as tools to design algorithms implemented at various layers of a communication network. We start with the transport layer, and then consider algorithms at the link layer and the medium access layer, and finally present a unified view of all these layers along with the network layer. After we cover all the layers, we present a brief introduction to peer-to-peer applications which, by some estimates, form a significant portion of Internet traffic today.

The second part of the book is devoted to advanced mathematical techniques which are used frequently by researchers in the area of communication networks. We often sacrifice generality by making simplifying assumptions, but, as a result, we hope that we have made techniques that are typically found in specialized texts in mathematics more broadly accessible. The collection of mathematical techniques relevant to communication networks is vast, so we have perhaps made a personal choice in the selection of the topics. We have chosen to highlight topics in basic queueing theory, asymptotic analysis of queues, and scaling laws for wireless networks in the second part of the book.

We note that two aspects of the book are perhaps unique compared to other textbooks in the field: (i) the presentation of the mathematical tools in parallel with a top-down view of communication networks, and (ii) the presentation of heavy-traffic analysis of queueing models using Lyapunov techniques.

The background required to read the book

Graduate students who have taken a graduate-level course in probability and who have some basic knowledge of optimization and control theory should find the book accessible. An industrious student willing to put in extra effort may find the book accessible even with just a strong undergraduate course in probability. Researchers working in the area of communication networks should be able to read most chapters in the book individually since we have tried to make each chapter as self contained as possible. However, occasionally we refer to results in earlier chapters when discussing the material in a particular chapter, but this overlap between chapters should be small. We have provided a brief introduction to the mathematical background required to understand the various topics in the book, as and when appropriate, to aid the reader.

How to use the book as an instructor

We have taught various graduate-level courses from the material in the book. Based on our experience, we believe that there are two different ways in which this book can be used: to teach either a single course or two courses on communication networks. Below we provide a list of chapters that can be covered for each of these options.

- A two-course sequence on communication networks.
  - Course 1 (modeling and algorithms): Chapters 1–6 except Section 3.5, and Sections 7.1, 7.2, 7.4.1, and Chapter 8. The mathematical background, Sections 2.1 and 2.3, can be taught as and when necessary when dealing with specific topics.
  - Course 2 (performance analysis): Chapters 9 (cover Section 8.2 before Section 9.14), 10, and 11. We recommend reviewing Chapter 3 (except Section 3.5), which would have been covered in Course 1 above, before teaching Chapter 10.
- A single course on communication networks, covering modeling, algorithms, and performance analysis: Chapters 1–6 except Section 3.5, Sections 9.1–9.10 of Chapter 9, and Chapters 10 and 11.

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This book grew out of courses offered by us at the University of Illinois at Urbana-Champaign, Iowa State University, and Arizona State University. The comments of the students in these courses over the years have been invaluable in shaping the material in the book. We would like to acknowledge Zhen Chen, Javad Ghaderi, Juan Jose Jaramillo, Xiaohan Kang, Joohwan Kim, Siva Theja Maguluri, Chandramani Singh, Weina Wang, Rui Wu, Zhengyu Zhang, and Kai Zhu in particular, who read various parts of the book carefully and provided valuable comments. We also gratefully acknowledge collaborations and/or discussions with Tamer Başar, Atilla Eryilmaz, Bruce Hajek, Frank Kelly, P. R. Kumar, Sean Meyn, Sanjay Shakkottai, Srinivas Shakkottai, Ness Shroff, and Don Towsley over the years, which helped shape the presentation of the material in this book.