Cambridge University Press book proposal

Working book title:

Stochastic Networks

Rationale and scope:

This book uses stochastic models to shed light on important issues in the design and control of communication networks. Randomness arises in communication systems at many levels: for example, the initiation and termination times of calls in a telephone network, or the statistical structure of the arrival streams of packets at routers in the Internet. How can routing, flow control and connection acceptance algorithms be designed to work well in uncertain and random environments?

Each chapter will contain a brief technological motivation of the mathematical techniques. In discussing the mathematical techniques, a clear distinction will be made between self-contained proofs, proofs based on some external fact, and mere sketches of plausibility (which may require large amounts of work to be turned into rigorous proofs).

Chapters 1-6 describe a variety of classical models that can be used to help understand the performance of large-scale communication networks. Queueing and loss networks are studied, as well as random access schemes. Parallels are drawn with models from physics, and with models of traffic in road networks.

Chapters 7 and 8 study congestion control algorithms in the Internet. This is an area of some practical importance, with network operators, hardware and software vendors, and regulators actively seeking ways of delivering new services reliably and effectively. The interplay between end-systems and the network has attracted the attention of economists as well as mathematicians and engineers.

Appendices will contain self-contained discussions of mathematical techniques used in the course: Lagrange multipliers, derivation of Little's Law from renewal theory, a more in-depth treatment of large deviations, and Foster-Lyapunov criteria for positive recurrence of Markov chains.

The book will be developed from a Part III (final-year undergraduate and master's level) course given at Cambridge University; lecture notes from this course are provided as indicative material. The material will be reorganized as needed and cleaned up, and transitional narrative will be added at the start of chapters and sections; however, we will retain the informal feel of the course. The intention is to give a compact, highly motivated introduction to the central questions that arise in the study of communication networks and to build a basic toolbox of mathematical ideas and results used to address these questions. Each chapter will end with further reading and exercises.

Readership:

The book is intended for advanced undergraduate and beginning graduate students in mathematics, engineering and computer science. Readers are assumed to know basic optimization at least to the level of Lagrange multipliers, and probability to the level of discrete-time Markov chains. Some familiarity with the theory of continuous-time Markov chains would be helpful but is not essential.

Competing/related books:

1. B. Hajek, Communication Network Analysis.
   This set of lecture notes is very similar in both content and style to the book, although it is aimed at an electrical engineering rather than mathematical audience. To the best of the authors' knowledge, B. Hajek is not planning to extend his notes to book format.

2. P. Robert, Stochastic Networks and Queues. Springer-Verlag, 2003.

3. H. Chen and D.D. Yao, Fundamentals of Queueing Networks. Springer-Verlag, 2001.

4. S. Asmussen, Applied Probability and Queues - second edition. Springer-Verlag, 2003.
   The above three books are written for more advanced students of mathematics; they explore the theory of queueing systems in much greater depth, with relatively fewer applications.

5. R. Srikant, The Mathematics of Internet Congestion Control. Birkhauser, 2004.

6. S. Shakkottai and R. Srikant, Network Optimization and Control. Foundations and Trends in Networking, NoW Publishers, 2007.
   The above two books are more in-depth treatments of the last section of the book.

7. O. Ibe, Fundamentals of Stochastic Networks, Wiley, 2011.
   This book is also aimed at a higher level, and explores the structure of the network (random graph etc.) and the potential effects on performance. There is very little overlap between topics covered, beyond basic queueing theory.

Detailed table of contents:

Introduction

1. Warm-up with Markov chains

Review of definitions and notation. Time reversal. Erlang's formula. Further reading. Exercises.

2. Queueing networks

A/B/C notation. M/M/1 queue. Series of M/M/1 queues. Close migration process. Open migration process. Generalizations (communication network; processor sharing). Little's law. Linear migration process. Further reading. Exercises.

3. Loss networks

Motivating examples. Network model. Intuition behind Erlang fixed point. Truncating reversible processes. Loss probabilities. Maximum probability. A limiting regime. Limit theorems. Erlang fixed point. Further reading. Exercises.

4. Decentralized optimization

Example: electron movement and current. Extremal characterization. Braess's paradox. Wardrop equilibrium. Gallagher's algorithm. Further reading. Exercises.

5. Random access networks

ALOHA model. Acknowledgement-based schemes. Further reading. Exercises.

6. Effective bandwidth

Bandwidth profile. Effective bandwidth and effective capacity. Chernoff bound. Queue with buffering. Further reading. Exercises.

7. Internet congestion control

Control of elastic network flows. A few notions of fairness. A primal algorithm (TCP). MulTCP (congestion avoidance). Current implementation of TCP. Cache location. A dual algorithm. Time delays. Further reading. Exercises.

8. Flow-level internet models

Behavior across the network. What can go wrong? Examples of instability. Further reading. Exercises.

Appendix A. Lagrange multipliers.

Basics about Lagrange multipliers, including strong duality and KKT conditions.

Appendix D. Renewal theory and Little's Law.

Derivation of Little's Law from the renewal-reward theorem (stated, with reference to proof).

Appendix B. Large deviations.

Proof of the Chernoff bound, with some extra discussion.

Appendix C. Foster-Lyapunov criteria.

A proof that a Lyapunov function for a Markov chain implies positive recurrence.

References

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Special features:

None.

Description of any ancillary material:

None.

Proposed length of book and proposed completion date:

150 pages. September 2012.

Brief credentials of the author(s):

Frank Kelly is professor of the Mathematics of Systems in the University of Cambridge. His main research interests are in random processes, networks and optimization. He is especially interested in applications to the design and control of networks and to the understanding of self-regulation in large-scale systems.

Elena Yudovina is a PhD candidate in the Department of Pure Mathematics and Mathematical Statistics, University of Cambridge. Her research interests include models for analysis and control of transport, service and electricity networks.