Preface

**Raison d’être**

The field of study popularly known as “networking” is concerned with the science and technology for building communication networks that provide reliable and timely information transport services to distributed applications over a physical network of communication links. Thus communication networks are engineering systems, and, as with other engineering systems, an analytical approach can be brought to bear on their study and design. Although qualitative heuristics can be used for simple networks, for high-speed integrated services networks the analytical approach can yield more efficient solutions. With rapidly expanding link bandwidths, increasing memory densities, frequent releases of ever more powerful microprocessors, and shrinking time to market, there is often little time to determine optimal implementations. Nevertheless the analytical approach yields important insights that can drive good heuristics. Furthermore, in the design of high-speed wide area networks, we are faced with physical limits (such as the speed of light and geographical distances) and technological limits (such as the lag between transmission speeds and memory access speeds), and an approach based on quantitative evaluation of alternatives is indispensable in handling these limits.

The analytical approach has played an important role in the engineering of circuit-multiplexed telephone networks (e.g., for network sizing and for improving adaptive routing strategies) and is making a significant impact on the design of high-speed packet networks that carry a variety of traffic, each with its own service requirements. Some examples of such impact are the design of high-performance routers, the routing of bandwidth guaranteed paths, and traffic controls for Web transfers. In networks that offer only store-and-forward services, the technology has been driven more by an effort to develop a best-effort data transport that would work under diverse conditions (links with widely different bit rates and bit error rates and nonhomogeneous hosts and operating systems). Among the best-effort transport technologies, the Internet protocols have by far the largest installed base. With the Internet rapidly becoming the vehicle of choice for transporting all kinds of information, modeling and analysis are proving invaluable in understanding the limitations of the Internet protocols and for improving them so that the Internet evolves into an integrated services packet network that can provide some level of quality of service assurance to each type of traffic it carries. Indeed this effort is
strongly influenced by the analytical research that has gone into the development of ATM (Asynchronous Transfer Mode) networking technology.

**About This Book**

In this book we take a fresh view to the teaching of the quantitative aspects of communication networking. We view networking in terms of the elements required to build a communication network out of the basic “plumbing” of communication links. We identify these elements as multiplexing, switching, routing, and network management. This book is about the first three elements and has one part devoted to each of these elements. Thus, from the point of view of communications engineering, the material presented in this book can be seen as a natural progression from physical layer engineering, which yields communication links, to the engineering of communication networks built out of these links.

The approach in this book is to raise various engineering issues in multiplexing, switching, and routing and to provide analysis and design techniques to address them via mathematical models. Yet this is *not* a book on mathematical tools for networking (specialized monographs are available on such topics), but one on network engineering via mathematical models and their analyses. The mathematical analyses are developed when they are needed as the discussion unfolds. This helps in emphasizing and consequently developing the structure of the right performance questions to be asked during the engineering of network subsystems. In some cases the models attempt to capture the details of particular implementations (e.g., adaptive windowing in TCP); in many cases the models abstract one or more important issues arising in a system architecture, thus permitting the study of various alternatives (e.g., input queueing in packet switches). In each case we show how the models and their analyses can also yield important insights into the underlying phenomena. To the extent possible, the presentation of the material is generic and not tied to specific networking technologies. The latter are discussed as examples or applications. The Internet’s Transmission Control Protocol (TCP) is an important exception; this class of adaptive window-based congestion control algorithms is so important that several pages have been devoted to its analysis.

The coverage in this book includes material from recent literature on the modeling, analysis, control, and optimization of communication networks so as to systematically address the issues in multiplexing, switching, and routing. For example, recent advances in the following topics have been covered:

- Deterministic and stochastic network calculus
• Congestion control for elastic traffic: TCP modeling and performance and utility optimization models
• Wireless access networks and multihop ad hoc networks
• Queueing in packet switches
• Input processing in packet switches, such as route lookups and classification
• Routing for quality of service

The book draws heavily on research literature, and each chapter is accompanied by extensive notes on the literature. Inline exercises (that may require providing simple proofs, analyzing simple cases, or carrying out a calculation) help the reader to better appreciate the material. A large number of supplementary problems are provided at the end of all but the introductory chapters. There are about two hundred exercises and problems in the book. Extensive use of schematic figures helps to illustrate the discussions.

Target Audience for This Book
This book has come out of courses taught by us at the Indian Institute of Science and the Indian Institute of Technology, primarily to final-year undergraduate and first-year graduate students. In reading this book, it will be useful to have a familiarity with the “big picture” of networking through at least a descriptive-level knowledge of networking concepts and technologies. To make this book as self-contained as possible, we provide a descriptive overview of the principles and practice of networking before delving into the analytical aspects. Also, a first course in probability and random processes would be useful background for reading this book. We invoke some results from probability theory, linear and nonlinear optimization, discrete event random processes, and queueing theory. An appendix that summarizes the results we use is also provided.

This book is first of all intended as a text to accompany an analytical course in networking for final-year undergraduate and first-year graduate students (in electrical engineering or computer science). The book is also targeted at networking professionals whose work is primarily architecture definition and implementation and who would like to obtain a quantitative understanding of the comparisons between design choices. This book will also be useful to performance modeling and analysis experts who would like to get a better understanding of how
models arise from the physical problems, so that the models they analyze can be better tuned to represent more realistic situations.

**Outlines of the Chapters**

The book is organized into four parts along with five appendices. Some chapters have their own appendices, containing proofs that are technical in nature and that need not be read inline.

The preamble part contains Chapters 1 and 2. Chapter 1 (Introduction: Two Examples) motivates the role of analytical models via examples of a packet voice multiplexing system and a fast packet switch. Chapter 2 (Networking: Functional Elements and Current Practice) first describes networking as being concerned with the problem of sharing the resources of a physical network of communication links. The basic functional elements of networking are then identified and discussed. A description of current network technologies provides the “big picture” understanding of communication networks.

Part I is on multiplexing and contains Chapters 3–8. The discussion on multiplexing begins in Chapter 3 (Multiplexing: Performance Measures and Engineering Issues) with classification of traffic into two types—stream and elastic traffic—and a discussion on the performance and engineering issues associated with each of these traffic types.

Chapter 4 (Stream Sessions: Deterministic Network Analysis) develops the end-to-end network calculus based on worst-case traffic bounds and the characterization of network elements by service curves, and then discusses packet scheduling. The theory developed in the chapter is tied to practice by showing how the RSVP protocol is used to set up a guaranteed delay connection in the Internet’s IntServ architecture. In Chapter 5 (Stream Sessions: Stochastic Analysis), we make a natural progression to develop packet multiplexer capacity designs based on probabilistic models and asymptotic results such as the central limit theorem, Chernoff’s bound, and Cramer’s theorem. The technique of effective bandwidths is covered in detail in this chapter. The chapter ends with a glimpse of why these techniques are not useful for long-range-dependent traffic. While Chapters 4 and 5 are concerned with in-call performance of stream traffic, models for call-level performance are considered in Chapter 6 (Circuit-Multiplexed Networks). Here we first present the analysis of circuit multiplexed links in a multiclass network and then discuss blocking analysis in a network using the Erlang fixed point approach. Applications of the techniques from the chapter to a cellular system and to a WDM optical network are also discussed.
Elastic traffic is discussed in detail in Chapter 7 (Adaptive Bandwidth Sharing for Elastic Traffic) from the point-of-view of dynamic sharing of links among the elastic flows. We begin by using o.d.e. techniques to analyze generic rate-controlled (as in ATM/ABR) and window-controlled (as in TCP) flows through a single bottleneck link. TCP is described and analyzed under various situations: a wide area connection with random loss, multiple connections with random drop, and randomly arriving finite volume connections. Fairness for elastic flows in a network is studied in detail using utility optimization techniques. We also study the long range dependence of TCP controlled traffic.

Chapter 8 (Multiple Access: Wireless Networks) is the last chapter in Part I and details the multiplexing issues in the emerging area of wireless networks. A taxonomy of wireless networks is followed by a discussion on the physical layer issues. There is a brief discussion of cross-layer techniques. The performance of TCP over lossy wireless links is discussed. An extensive discussion on Aloha and IEEE 802.11 random access networks follows. Multihop ad hoc wireless networks are also discussed; the topics covered include connectivity, link scheduling, and capacity scaling laws for dense ad hoc networks.

Chapters 9–12 constitute Part II on switching and are primarily concerned with packet switches. Chapter 9 (Performance and Architectural Issues) is an introduction to switching with a discussion on performance measures for switches and the architectural choices for packet switches. In Chapter 10 (Queueing in Packet Switches), we treat the nonblocking switch fabric as a blackbox and first discuss saturation throughput and queueing delays. Virtual output queuing, switch scheduling for increased throughput, and output queue emulation are also discussed. In Chapter 11 (Switching Fabrics), we progress to designing the switch fabric. We first describe elementary switching structures and then develop the design of switching networks including Clos networks and self-routing networks. The design of a self-routing broadcast network and the multicast switch are also presented. Finally, in Chapter 12 (Packet Processing), the design of fast packet processing (IP address lookup and packet classification) and general issues in packet switch design are discussed. A brief overview of network processors is also provided.

Chapters 13–16 form Part III, which focuses on routing. Chapter 13 (Routing: Engineering Issues) is an introduction to this part. In this chapter, we discuss general issues and terminology that appear in the study of routing. Chapter 14 (Shortest Path Routing of Elastic Aggregates) is about shortest path routing in networks. We formulate and analyze an optimal routing problem for routing a given set of elastic traffic demands that can be arbitrarily split across multiple routes. Then we explore the idea of realizing optimal routes
by setting appropriate link weights and then using shortest paths according to these link weights. Finally, we discuss well-known shortest path algorithms and their generalizations, as well as two standard routing protocols. Chapter 15 (Virtual-Path Routing of Elastic Aggregates) is motivated by the issue of routing MPLS paths. We consider the generalized problem of on-demand routing, where prior information about the demands is not known. We also assume the constraint that demands cannot be split across multiple routes and study minimum interference routing formulations and heuristics. Chapter 16 (Routing of Stream-Type Sessions) considers the problem of routing stream traffic sessions so as to satisfy their end-to-end performance requirements. We consider nonadditive and additive performance metrics, as well as networks with rate-based and non-rate-based multiplexers, and study algorithms to obtain feasible routes.

Appendix A is a glossary of the acronyms and the mathematical notation used in the book. Appendices B–E provide a review of some of the mathematical techniques used in the book.

**Using the Book**

We have made the book self-contained by providing all the advanced concepts used in the book in the appendices. There are some “starred” sections (numbered or unnumbered and indicated by the symbol (⋆) in the heading) that deal with specialized or more advanced material and can be skipped on a first reading without losing the continuity of the presentation. The dependencies between the different parts of the book are shown in Figure 1. Thus, for example, Chapters 3, 4, and 5 must be read in sequence, and these can be followed by Chapter 7, but it is also possible to develop a course that uses Chapters 3, 7, and 8, with the instructor filling in some material from Chapter 5 as needed in Chapter 7.

There are many ways in which the book can be used to teach an analytical course in networking. The material in Chapters 1 and 2 can be given as a reading assignment at the beginning of the course or covered in 3–5 lecture hours. One lecture hour each on the introductory chapters to the three parts—Chapters 3, 9, and 13—may be useful to explain the issues in each of the components. The ideal way to use the book would be in a two-semester course with Part I being covered in the first semester and Parts II and III in the second semester. A one-semester course based on parts of Chapters 4–8, 10, and 14 has been taught by one of the authors. A course based on Chapter 4, Part II (except Chapter 10), and Part III, along with a summary of the results from Chapters 5–8
and Chapter 10, will be accessible to graduate students who do not have a strong background in stochastic analysis.

Our experience in conveying some of the seemingly difficult probability concepts to students with possibly limited exposure to such material has been very positive and we recommend that an instructor bravely try it.

The web site for the book is at books.elsevier.com/mk/?ISBN=0124287514. This web site contains errata, additional problems, PostScript files of the figures used in the book, and other instructional material. An instructor’s manual containing detailed course plan alternatives and solutions to all the exercises and problems is also available via password protected access (see web site for details).
Acknowledgments
We are grateful to Vivek S. Borkar, Bharat T. Doshi, P. R. Kumar, Steven Low, David McDysan, Galen Sasaki, and Don Towsley for the patience with which they read the manuscript and for the detailed comments and critique they provided. These comments have helped to smooth many rough edges in the presentation.
Sanjay Bose, A. Chockalingam, Supratim Deb, Madhav Desai, Munish Goyal, N. Hemachandra, Koushik Kar, Akshay Kashyap, Nilesh Khude, P. Mathivanan, Harish Pillai, and Amol Sahasrabudhe read many of the draft chapters and provided valuable feedback. We are thankful to them. We thank the many students who pointed out errors and omissions when parts of the books were used in our courses.
In the planning and preparation of this book the authors have had useful and encouraging discussions with Gustavo De Veciana, Sanjay Shakkottai, and Pramod Viswanath. We are grateful to them for sparing their time for these discussions.
Parts of this book were class tested by Alhoussein Abouzeid (Rensselaer Polytechnic Institute), Steven Low (California Institute of Technology), Armand Makowski (University of Maryland, College Park), Utpal Mukherji (Indian Institute of Science), Catherine Rosenberg (Purdue University), Saswati Sarkar (University of Pennsylvania), Rajeev Shorey (National University of Singapore), Biplab Sikdar (Rensselaer Polytechnic Institute), and Joseph Thomas (University of Maryland, Baltimore County). We thank them for their confidence in the book and the valuable feedback they have given us.
The team at Morgan Kaufmann and Elsevier were a pleasure to work with. Our thanks are due to Rick Adams and Karyn Johnson for providing excellent support during the development of the book and for quick responses to all our questions and concerns, to Betsy Hardinger for the pain staking copy editing, to Marcy Barnes-Henrie and Simon Crump for efficiently managing the production, to Gopinath Iyengar for a superb job of compositing the material, to Eric DeCicco for patiently discussing the cover design with us, and to Brent dela Cruz for managing the publicity.
Finally we express our gratitude to our families for their love, support, and patience during the preparation of the book. Anurag Kumar thanks his wife, Pamela, for her constant encouragement, his mother for her ever present support, and his children, Anupama and Siddhartha, for their patience during his long periods of preoccupation with this project. D. Manjunath thanks ManjulaRani for maintaining sanity at home during the many times the timelines of her thesis and this book were in phase and AmruthaVarshini (more than half her life has
been spent in the shadow of this book) for bearing his absence and supporting KMK. Joy Kuri thanks his parents, Nanda Kumar and Bela, his wife, Manjula, and his daughter, Ushnaa, for their love, support, and encouragement.

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