

# Preface

The purpose of this book is to give the reader two things, to paraphrase Mark Twain: Roots to know the basics of modeling networks and Wings to fly away and attempt modeling other proposed systems of interest.

The Internet phenomenon is affecting us all in the way we communicate, conduct business, and access information and entertainment. More unforeseen applications are still to come. All of this is due to the existence of an efficient global high-performance network that connects millions of users and moves information at a high rate with small delay.

## High-Performance Networks

A high-performance network is characterized by two performance measures *bandwidth* and *delay*. Traditional network design focused mainly on bandwidth planning; the solution to network problems was to add more bandwidth. Nowadays, we have to consider message delay particularly for delay-sensitive applications such as voice and real-time video. Both bandwidth and delay contribute to the performance of the network. Bandwidth can be easily increased by compressing the data, by using links with higher speed, or by transmitting several bits in parallel using sophisticated modulation techniques. Delay, however, is not so easily improved. It can only be reduced by the use of good scheduling protocols, very fast hardware and switching equipment throughout the network. The increasing use of optical fibers means that the transmission channel is close to ideal with extremely high bandwidth and low delay (speed of light). The areas that need optimization are the interfaces and devices that connect the different links together such as hubs, switches, routers, and bridges. The goal of this book is to explore the design and analysis techniques of these devices. There are indications, however, that the optical fiber channel is becoming less than ideal due to the increasing bit rates. Furthermore, the use of wireless mobile networking is becoming very popular. Thus new and improved techniques for transmitting across the noisy, and band-limited, channel become very essential. The work to be done to optimize the physical level of communication is devising algorithms and hardware for adaptive data coding and compression. Thus digital signal processing is finding an increasing and pivotal role in the area of networking.

## Scope

The three main building blocks of high-performance networks are the links, the switching equipment connecting the links together, and the software employed at the nodes and switches. The purpose of this book is to provide the basic techniques for modeling and analyzing the last two components: the software and the switching equipment. The book also reviews the design options used to build efficient switching equipment. For this purpose, different topics are covered in the book such as Markov chains and queuing analysis, traffic modeling, interconnection networks, and switch architectures and buffering strategies.

There are many books and articles dealing with continuous-time Markov chains and queuing analysis. This is because continuous-time systems are thought to be easily modeled and analyzed. However, digital communications are discrete in nature. Luckily, discrete-time Markov chains are simple, if not even easier, to analyze. The approach we chose to present Markov chains and queuing analysis is to start with explaining the basic concepts, then explain the analytic and numerical techniques that could be used to study the system. We introduce many worked examples throughout to get a feel as to how to apply discrete-time Markov chains to many communication systems.

We employ MATLAB ® throughout this book due to its popularity among engineers and engineering students. There are many equally useful mathematical packages available nowadays on many workstations and personal computers such as Maple ® and Mathematica ®.

## Organization

This book covers the mathematical theory and techniques necessary for analyzing telecommunication systems. Queuing and Markov chain analyses are provided for many protocols that are used in networking. The book then discusses in detail applications of Markov chains and queuing analysis to model over 15 communications protocols and hardware components. Several appendices are also provided that round up the discussion and provide a handy reference for the necessary background material.

*Chapter 1* discusses probability theory and random variables. There is discussion of sample spaces and how to count the number of outcomes of a random experiment. Also discussed is probability density function and expectations. Important distributions are discussed since they will be used for describing traffic in our analysis. The Pareto distribution is discussed in this chapter, which is usually not discussed in standard engineering texts on probability. Perhaps what is new in this chapter is the review of techniques for generating random numbers that obey a desired probability distribution. Inclusion of this material rounds up the chapter and helps the designer or researcher to generate the network traffic data needed to simulate a switch under specified conditions.

*Chapter 2* discusses random processes and in particular Poisson and exponential processes. The chapter also discusses concepts associated with random processes such as ensemble average, time average, autocorrelation function, and cross-correlation function.

*Chapter 3* discusses discrete-time Markov chains. Techniques for constructing the state transition matrix are explored in detail as well as how the time step is determined since all discrete-time Markov chains require awareness of the time step value. The chapter also discusses transient behavior of Markov chains and explains the various techniques for studying it such as diagonalization, expansion of the initial distribution vector, Jordan canonic form, and using the z-transform.

*Chapter 4* discusses Markov chains at equilibrium, or steady state. Analytic techniques for finding the equilibrium distribution vector are explained such as finding the eigenvalues and eigenvectors of the state transition matrix, solving difference equations, and the z-transform technique. Several numerical techniques for finding the steady-state distribution are discussed such as use of forward- and backward-substitution, and iterative equations. The concepts of balance equations and flow balance are also explained.

*Chapter 5* discusses reducible Markov chains and explains the concept of closed and transient states. The transition matrix for a reducible Markov chain is partitioned into blocks and the closed and transient states are related to each partitioning block. An expression is derived for the state of a Markov chain at any time instant  $n$  and also at equilibrium. The chapter also discusses how a reducible Markov chain could be identified by studying its eigenvalues and eigenvectors. It is shown that the eigenvectors enable us to identify all sets of closed and transient states.

*Chapter 6* discusses periodic Markov chains. Two types of periodic Markov chains are identified and discussed separately. The eigenvalues of periodic Markov chains are discussed and related to the periodicity of the system. Transient analysis of a periodic Markov chain is discussed in detail and asymptotic behavior is analyzed.

*Chapter 7* discusses discrete-time queues and queuing analysis. Kendall's notation is explained and several discrete-time queues are analyzed such as the infinite-sized  $M/M/1$  queue and the finite-sized  $M/M/1/B$  queue. Equally important queues encountered in this book are also considered such as  $M^m/M/1/B$  and  $M/M^m/1/B$  queues. The important performance parameters considered for each queue are the throughput, delay, average queue size, loss probability, and efficiency. The chapter also discusses how to analyze networks of queues using two techniques: the flow balance approach and the merged approach.

*Chapter 8* discusses the modeling of several flow control protocols using Markov chains and queuing analysis. Three traffic management protocols are considered: leaky bucket, token bucket, and the virtual scheduling (VS) algorithm.

*Chapter 9* discusses the modeling of several error control protocols using Markov chains and queuing analysis. Three error control using automatic repeat request

algorithms are considered: stop-and-wait (SW ARQ), go-back- $N$  (GBN ARQ), and selective repeat protocol (SRP ARQ).

*Chapter 10* discusses the modeling of several medium access control protocols using Markov chains and queuing analysis. Several media access protocols are discussed: IEEE Standard 802.1p (static priority), pure and slotted ALOHA, IEEE Standard 802.3 (CSMA/CD, Ethernet), Carrier sense multiple access with collision avoidance (CSMA/CA), IEEE Standard 802.4 (token bus) & 802.5 (Token ring), IEEE Standard 802.6 (DQDB), IEEE Standard 802.11 distributed coordination function for ad hoc networks, and IEEE Standard 802.11 point coordination function for infrastructure networks (1-persistent and  $p$ -persistent cases are considered).

*Chapter 11* discusses the different models used to describe telecommunication traffic. The topics discussed deal with describing the data arrival rates, data destinations, and packet length variation. The interarrival time for Poisson traffic is discussed in detail and a realistic model for Poisson traffic is proposed. Extracting the parameters of the Poisson traffic model is explained given a source average and burst rates. The interarrival time for Bernoulli sources is similarly treated and a realistic model is proposed together with a discussion on how to determine the Bernoulli model parameters. Self-similar traffic is discussed and the Pareto model is discussed. Extracting the parameters of the Pareto traffic model is explained given a source average and burst rates. Modulated Poisson traffic models are also discussed such as the on-off model and the Markov modulated Poisson process. In addition to modeling data arrival processes, the chapter also discusses the traffic destination statistics for uniform, broadcast, and hot-spot traffic types. The chapter finishes by discussing packet length statistics and how to model them.

*Chapter 12* discusses scheduling algorithms. The differences and similarities between scheduling algorithms and media access protocols are discussed. Scheduler performance measures are explained and scheduler types or classifications are explained. The concept of max-min fairness is explained since it is essential for the discussion of scheduling algorithms. Twelve scheduling algorithms are explained and analyzed: first-in/first-out (FIFO), static priority, round robin (RR), weighted round robin (WRR), processor sharing (PS), generalized processor sharing (GPS), fair queuing (FQ), packet-by-packet GPS (PGPS), weighted fair queuing (WFQ), frame-based fair queuing (FFQ), core-stateless fair queuing (CSFQ), and finally random early detection (RED).

*Chapter 13* discusses network switches and their design options. Media access techniques are first discussed since networking is about sharing limited resources using a variety of multiplexing techniques. Circuit and packet-switching are discussed and packet switching hardware is reviewed. The basic switch components are explained and the main types of switches are discussed: input queuing, output queuing, shared buffer, multiple input queue, multiple output queue, multiple input and output queue, and virtual routing/virtual queuing (VRQ). A qualitative discussion of the advantages and disadvantages of each switch type is provided. Detailed quantitative analyses of the switches is discussed in Chapter 15.

*Chapter 14* discusses interconnection networks. Time division networks are discussed and random assignment time division multiple access (TDMA) is analyzed. Several space division networks are studied: crossbar network, generalized cube network (GCN), banyan network, augmented data manipulator network (ADMN), and improved logical neighborhood network (ILN). For each network, a detailed explanation is provided for how a path is established and, equally important, the packet acceptance probability is derived. This last performance measure will prove essential to analyze the performance of switches.

*Chapter 15* discusses modeling techniques for input buffer, output buffer, and shared buffer switches. Equations for the performance of each switch are obtained to describe packet loss probability, average delay within the switch, the throughput, and average queue size.

*Chapter 16* discusses the design of two next-generation high-performance network switches. The first Promina 4000 switch developed by N.E.T. Inc. The second is the VRQ switch which was developed at the University of Victoria and is being continually improved. The two designs are superficially similar and a comparative study is reported to show how high-performance impacted the design decisions in each switch.

*Appendix A* provides a handy reference for many formulas that are useful while modeling the different queues considered here. The reader should find this information handy since it was difficult to find all the formulas in a single source.

*Appendix B* discusses techniques for solving difference equations or recurrence relations. These recurrence relations crop up in the analysis of queues and Markov chains.

*Appendix C* discusses how the z-transform technique could be used to find a closed-form expression for the distribution vector  $s(n)$  at any time value through finding the z-transform of the transition matrix  $\mathbf{P}$ .

*Appendix D* discusses vectors and matrices. Several concepts are discussed such as matrix inverse, matrix nullspace, rank of a matrix, matrix diagonalization, and eigenvalues and eigenvectors of a matrix. Techniques for solving systems of linear equations are discussed since these systems are encountered in several places in the book. Many special matrices are discussed such as circulant matrix, diagonal matrix, echelon matrix, Hessenberg matrix, identity matrix, nonnegative matrix, orthogonal matrix, plane rotation, stochastic (Markov) matrix, substochastic matrix, and tridiagonal matrix.

*Appendix E* discusses the use of MATLAB in engineering applications. A brief introduction to MATLAB is provided since it is one of the more common mathematical packages used.

*Appendix F* discusses design of databases. A database is required in a switch to act as the lookup table for important properties of transmitted packets. Hashing and B-trees are two of the main techniques used to construct the fast routing or lookup

tables used in switches and routers. The performance of the hashing function and average lookup delay are analyzed. The B-tree data structure is discussed and the advantages of B-trees over regular binary trees and multiway trees are explained.

## Advanced Topics

I invested special effort in making this book useful to practicing engineers and students. There are many interesting examples and models throughout the book. However, I list here some interesting topics:

- Chapter 1 discusses heavy-tailed distribution in Section 1.20 and generation of random numbers in Section 1.35.
- Chapter 3 discusses techniques for finding higher powers for Markov chain state transition matrix in Sections 3.13 and 3.14.
- Chapter 5 discusses reducible Markov chains at steady state in Section 5.7 and transient analysis of reducible Markov chains in Section 5.6. Also, there is a discussion on how to identify a reducible Markov chain by examining its eigenvalues and eigenvectors.
- Chapter 6 discusses transient analysis of periodic Markov chains in Section 6.15 and asymptotic behavior of periodic Markov chains in Section 6.15. Also, there is a discussion on how to identify a periodic Markov chain and how to determine its period by examining its eigenvalues.
- Chapter 7 discusses developing performance metrics for the major queue types.
- Chapter 8 discusses how to model three flow control protocols dealing with traffic management.
- Chapter 9 discusses how to model three flow control protocols dealing with error control.
- Chapter 10 discusses how to model three flow control protocols dealing with medium access control.
- Chapter 11 discusses developing realistic models for source traffic using Poisson description (Section 11.3.2), Bernoulli (Section 11.4.3), and Pareto traffic (Section 11.8). There is also discussion on packet destination and length modeling.
- Chapter 12 discusses 12 scheduling algorithms and provides Markov chain analysis for many of them.
- Chapter 13 discusses seven types of switches based on their buffering strategies and the advantages and disadvantages of each choice.
- Chapter 14 discusses many types of interconnection networks and also provides, for the first time, analysis of the performance of each network.

## Web Resource

The website <http://www.ece.uvic.ca/~fayez/Book>, [www.springer.com/978-0-387-74437-7](http://www.springer.com/978-0-387-74437-7) contains information about the textbook and any related web resources.

## Errors

This book covers a wide range of topics related to communication networks and provides an extensive set of analyses and worked examples. It is “highly probable” that it contains errors and omissions. Other researchers and/or practicing engineers might have other ideas about the content and organization of this book. We welcome receiving any constructive comments and suggestions for inclusion in the next edition. If you find any errors, we would appreciate hearing from you. We also welcome ideas for examples and problems (along with their solutions if possible) to include in the next edition with proper citation.

You can send your comments and bug reports electronically to [fayez@uvic.ca](mailto:fayez@uvic.ca), or you can fax or mail the information to

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