Communication Networks
Fundamental Concepts and Key Architectures
Second Edition

通信网
基本概念与主体结构
（第2版）

Alberto Leon-Garcia
Indra Widjaja

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- In Chapter 2 the discussion on how all the layers work together has been improved by introduc using Ethereal packet captures. The section on application layer protocols has been expanded section provides an introduction to network protocol analyzers.

- PCM speech coding has been moved from Chapter 12 to Chapter 3.

- Chapter 4 provides more detail on SONET and optical transport networks. Satellite cellular netw been dropped.

- Chapter 5 now consists of two parts. The first part deals with peer-to-peer protocols using reliab transfer protocols as an example. The first part also includes TCP reliable byte stream service. part focuses on data link layer protocols and now includes a section on framing.

- Chapter 6 has also been divided into the principles of medium access control protocols (Part I) (Part II). We have simplified the mathematical discussion of medium access controls and provid separate section.

- In Chapter 7 we have streamlined the discussion of packet networks, and we have separated c advanced discussion of traffic management.

- Chapter 8 makes extensive use of packet ca ples to illustrate the operation of TCP/IP

- Chapter 10 on advanced network architectur n revised extensively. The discussion of has been replaced by a discussion of the ov er models to network interconnection. now contains discussion on virtual networks and GMPLS. The material on RTP and SIP has be and moved from Chapter 12 to this chapter.

- Chapter 11 has been updated with brief discussions of the Advanced Encryption Standard and security.

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内 容 简 介

本书内容大致分为三部分。

第一部分为综述，由前两章组成。主要通过广泛应用的网络业务介绍网络的变革与发展；并通过网络提供的服务讨论网络协议的分层模型和不同层之间的交互作用。

第二部分以电话网、局域网、分组交换网这些基础网络为例，介绍网络体系结构的基本概念和低层协议的主要技术。这部分包含第 3 章至第 7 章，其中，第 3 章介绍数字传输技术的基础知识，内容有不同媒体信息的数字化描述、数字调制、编码、检错、纠错、信道特性及各种传输媒质特性等。第 4 章介绍电路交换网络中的几种复用和交换技术，重点是 SONET。第 5 章讨论对等层协议，主要讨论数据链路层的 ARQ 差错控制协议，滑动窗机理，以及实用的 PPP 协议和 HDLC 协议。第 6 章首先详细讨论媒质访问控制技术，包括随机访问、预约访问、信道化访问，然后对以太网、令牌环、FDDI 和无线局域网的基本知识和协议作了简要介绍。第 7 章讨论分组交换网，介绍了几种常用的路由算法，并对不同类型的流量管理机制作了较为深入的分析。

第三部分讨论 TCP/IP 和 ATM 这两种主体网络，并进一步阐明基本的网络概念如何体现在这两种主体网络之中。此外，对当前某些热点课题也作了必要介绍。这部分由 5 章组成，其中，第 8 章讨论 TCP/IP 网络的结构和相关协议，包括 IP、IPv6、TCP、UDP、内部路由协议和组播路由协议等。第 9 章讨论 ATM 网络，主要介绍 ATM 层和 ATM 适配层，并对信令和 PNNI 路由选择作了基本介绍。第 10 章介绍现代网络结构中的基本概念和主要协议，包括综合服务、区分服务、互连模型以及 RSVP、MPLS、RTTP、SCP 等协议。第 11 章介绍网络安全协议和加密算法。第 12 章讨论网络中的多媒体技术和相关标准，包括数据压缩、信号编码以及分别用于图像和视频编码的 JPEG、MPEG 标准。

本书是第 2 版，除对第 1 版内容进行了更新外，还广泛引入了网络协议分析仪分析各种协议的操作过程。

概括而言，本书取材广泛，内容新颖，结合实际，既有基本的介绍，又有较为深入的分析，还有大量的习题，可作为计算机、电子等专业本科生、研究生的教学用书，或作为各行业网络技术人员、服务人员的参考读物。

计算机科学与技术学科研究生系列教材

序

未来的社会是信息化的社会，计算机科学与技术在其中占据了最重要的地位，这对高素质创新型计算机人才的培养提出了迫切的要求。计算机科学与技术已经成为一门基础技术学科，理论性和技术性都很强。与传统的数学、物理和化学等基础学科相比，该学科的教育工作者既要培养学科理论研究和基本系统的开发人才，还要培养应用系统开发人才，甚至是应用人才。从层次上来讲，则需要培养系统的设计、实现、使用与维护等各个层次的人才。这就要求我们的计算机教育按照定位的需要，从知识、能力、素质三个方面进行人才培养。

硕士研究生的教育需突出"研究"，要加强理论基础的教育和科研能力的训练，使学生能够站在一定的高度去分析研究问题、解决问题。硕士研究生要通过课程的学习，进一步提高理论水平，为今后的研究和发展打下坚实的基础；通过相应的研究及学位论文撰写工作来接受全面的科研训练，了解科学研究的艰辛和科研工作者的奉献精神，培养良好的科研作风，锻炼攻关能力，养成协作精神。
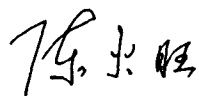
高素质创新型计算机人才应具有较强的实践能力，教学与科研相结合是培养实践能力的有效途径。高水平人才的培养是通过被培养者的高水平学术成果来反映的，而高水平的学术成果主要来源于大量高水平的科研。高水平的科研还为教学活动提供了最先进的高新技术平台和创造性的工作环境，使学生得以接触最先进的计算机理论、技术和环境。高水平的科研也为高水平人才的素质教育提供了良好的物质基础。

为提高高等院校的教学质量，教育部最近实施了精品课程建设工程。由于教材是提高教学质量的关键，必须加快教材建设的步伐。为适应学科的快速发展和培养方案的需要，要采取多种措施鼓励从事前沿研究的学者参与教材的编写和更新，在教材中反映学科前沿的研究成果与发展趋势，以高水平的科研促进教材建设。同时应适当引进国外先进的原版教材，确保所有教学环节充分反映计算机学科与产业的前沿研究水平，并与未来的发展趋势相协调。

中国计算机学会教育专业委员会在清华大学出版社的大力支持下，进行了计算机科学与技术学科硕士研究生培养的系统研究。在此基础上组织来自多所全国重点大学的计算机专家和教授们编写和出版了本系列教材。作者们以自己多年来丰富的教学和科研经验为基础，认真研究和结合我国计算机科学与技术学科硕士研究生教育的特点，力图使本系列教材对我国计算机科学与技术学科硕士研究生的教学方法和教学内容的改革起到引导作用。本系列教材的系统性和理论性强，学术水平高，反映科技新发展，具有合

适的深度和广度。同时本系列教材两种语种（中文、英文）并存，三种版权（本版、外版、合作出版）形式并存，这在系列教材的出版上走出了一条新路。

相信本系列教材的出版，能够对提高我国计算机硕士研究生教材的整体水平，进而对我国大学的计算机科学与技术硕士研究生教育以及培养高素质创新型计算机人才产生积极的促进作用。

陈火旺

2003 年 9 月

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PREFACE

OBJECTIVE

Communication networks are in a period of transition from networks that are based on telephone architecture and standards to networks based on the Internet Protocol (IP) architecture. The main reason for this change is that new services and applications can be deployed with unprecedented speed over an Internet that has attained the global reach of the telephone network. Many of these new applications and services are quite visible to the student. For example, in addition to e-mail and web surfing, there is buying/selling over the Internet (eBay), MP3 and other file exchanges (Napster, KaZaA), interactive games (Counterstrike), video streaming (CNN), and voice-over-IP (Net-Meeting, ICQ). Many other applications and services are having profound impact on business, manufacturing, international commerce, medicine, and government.

The infrastructure of communication networks is undergoing dramatic change under pressure from the new services and enabled by technology innovation. A new generation of wireless devices combines aspects of cellular phones, personal digital assistants, and even digital cameras and is enabling new modes of mobile communication such as short text messaging, event notification, e-mail, and web browsing. These wireless services are blazing a trail away from traditional telephony to new modes of IP-based multimedia communications. Inevitably the signaling system that enables all of the functionality of the cellular and telephone network will be replaced by more versatile signaling based on Internet protocols. A new generation of IP-based protocols will control and manage the resources in the next generation of networks.

It is in this exciting context of new services and emerging next-generation network architecture that we offer this second edition of our textbook. The purpose of this book is to provide an introduction to fundamental network architecture concepts and their application in existing and emerging networks. We emphasize the pivotal role of Internet protocols in future network architecture and at the same time provide a broad coverage of fundamental network concepts. Our view is that the student will be best prepared for a future of constant change through exposure to network design alternatives.

TARGET COURSES

The book is designed for introductory courses in computer networks and in communication networks at the upper-level undergraduate and first-year graduate programs in electrical engineering, computer engineering, and computer science. The book contains all the basic material covered in typical one-semester first courses in computer networks and in communication networks. The book also provides additional material in each chapter as well as advanced topics in the later chapters so that the book can be used in a two-semester course sequence. The book is up-to-date in its coverage of emerging network architecture and can also be used by engineering and computer professionals.

As prerequisites the book assumes a general knowledge of computer systems. In certain optional parts of the text, knowledge of programming, elementary probability, or elementary calculus is required. These sections are clearly indicated and can be skipped.

APPROACH AND CONTENT

The book is organized into three parts. In Part I we trace the evolution of networks and identify the key concepts and functions that form the basis for layered architectures. We introduce examples of services and applications that are familiar to the student (web browsing, e-mail, and telephone), and we explain how these services are supported by networks. This *big picture view of networks* helps the student to see how the various parts of a network architecture fit into one whole.

Part I. The big picture of networks (Chapters 1–2):
- Evolution of network concepts in telegraph, telephone, and computer networks
- How services and applications drive network architecture evolution
- How layers work together to deliver services
- Application layer, transport layer, and sockets
- Preparation for experimentation: network protocol analyzer, IP utilities, and socket programming

The second part presents fundamental concepts of network architecture and focuses on the lower four layers of the protocol stack. Our approach is to develop the fundamental concepts first and then to show their application in concrete examples. For example, we develop ARQ in detail as an example of a peer-to-peer protocol and then we discuss its application in TCP reliable stream service and flow control. We cover the essential computer network topics, but we also have extensive discussion of access and transport networks, telephone and cellular services and signaling. This additional material is organized so that it is optional, but we include it because we believe that much of network architecture evolution in the near future will involve the extension of Internet protocols to traditional networks and services.

Part II. Fundamental concepts in network architecture (Chapters 3–7):
- Digital transmission; copper, cable, radio, and optical media
- SONET and optical networking
- Circuit switching, signaling, telephone services, mobility
- Peer-to-peer protocol design; PPP, HDLC, POS, and GFP
- Medium-access control; Ethernet and 802.11 wireless LANs
- Voice and data cellular networks
- Packet switching, routing, congestion control, and QoS

The third and final part deals with key network architectures, advanced topics, and next generation networks. We present the protocols and standards that are likely to shape the next generation networks.

Part III. Key architectures, advanced topics, and next generation networks
(Chapters 8–12 and Appendices):
- IPv4 and IPv6; TCP, UDP; RIP, OSPF, BGP; DHCP and mobile IP
- ATM networks
- New Architectures: IntServ, RSVP, DiffServ, Peer vs. Overlay Interconnection, MPLS and GMPLS, RTP, SIP, and H.323
- Network Security: DES and AES, RSA, IPSec, SSL and TLS, 802.11
- Multimedia standards: JPEG, MPEG, Audio, MP3, voice-over-IP
- Network management and performance modeling

The book attempts to provide a *balanced view of all important elements of networking.* This is a very big challenge in the typical one-semester introductory course that has limited time available. We have organized the book so that all the relevant topics can be covered at some minimum essential level of detail. Additional material is provided that allows the instructor to cover certain topics in greater depth. Dependencies between sections are discussed later in the Preface.

CHANGES FROM THE FIRST EDITION

The most important change in the second edition is the extensive use of the open-source Ethereal network protocol analyzer in the teaching of network protocols. Ethereal allows any PC to capture live network traffic and to analyze the headers and payloads of the stream of captured traffic at layers 2 and above at any level of detail. We use Ethereal in the following ways:

- Examples of Ethereal packet captures demonstrate the operation of protocols such as HTTP, SMTP, Telnet, SIP, RSVP, RTP, DNS, TCP, UDP, OSPF, IP, ARP, Ethernet, 802.11, PPP, LCP, IPCP, SSL, and TLS.
- We provide instructors with Ethereal packet capture files that allow them to interactively demonstrate the operation of protocols in class.
- Exercises in the problem section require the students to carry out their own packet captures to examine and analyze the operation of protocols using real traffic.
- The book website contains experiments that involve the use of Ethereal in Linux-based router networks.

The second edition also contains various organizational and content changes. The following lists the key content and organizational changes from the first edition:

- The material in the book has been rearranged so that optional sections can be skipped without a disruption in the topic flow. The sections that contain optional material are indicated by a diamond (♦) in the heading. The optional sections that contain detailed mathematics are now indicated by a sidebar.
- Chapter 1 has been shortened and the discussion of network evolution has been simplified. The functions associated with each layer are introduced along with the discussion on network evolution.

- In Chapter 2 the discussion on how all the layers work together has been improved by introducing examples using Ethereal packet captures. The section on application layer protocols has been expanded and a new section provides an introduction to network protocol analyzers.
- PCM speech coding has been moved from Chapter 12 to Chapter 3.
- Chapter 4 provides more detail on SONET and optical transport networks. Satellite cellular networks have been dropped.
- Chapter 5 now consists of two parts. The first part deals with peer-to-peer protocols using reliable data transfer protocols as an example. The first part also includes TCP reliable byte stream service. The second part focuses on data link layer protocols and now includes a section on framing.
- Chapter 6 has also been divided into the principles of medium access control protocols (Part I) and LANs (Part II). We have simplified the mathematical discussion of medium access controls and provide details in a separate section.
- In Chapter 7 we have streamlined the discussion of packet networks, and we have separated clearly the more advanced discussion of traffic management.
- Chapter 8 makes extensive use of packet capture examples to illustrate the operation of TCP/IP protocols.
- Chapter 10 on advanced network architectures has been revised extensively. The discussion of ATM over IP has been replaced by a discussion of the overlay and peer models to network interconnection. The chapter now contains discussion on virtual networks and GMPLS. The material on RTP and SIP has been updated and moved from Chapter 12 to this chapter.
- Chapter 11 has been updated with brief discussions of the Advanced Encryption Standard and 802.11 security.

CHAPTER DEPENDENCIES

The book was designed to support a variety of introductory courses on computer and communication networks. By appropriate choice of sections, the instructor can provide a desired focus or make adjustments to account for the background of the students. Figure 1 contains a flow chart of the dependencies between sections in the book. The solid black line indicates the sequence of topics that forms the core of most introductory courses. The dashed lines show sections that can be added to provide greater depth in various topic areas. Section numbers in parentheses indicate dependencies that involve only subsections. After Chapter 8, the chapters are less interdependent. Chapter 11 depends on Chapter 8 only in regards to the header structure of IPv4 and IPv6. Chapter 12 depends only on Sections 3.1 and 3.2. Appendix A on queueing models provides supporting material for Sections 4.7, 5.7, and 6.5, which deal with performance modeling.

1.1–1.2 Network Evolution	1.3 Evolution Factors

2.1–2.3 Layered Architecture Overview of TCP/IP	2.5 Application Layer and Utilities

2.4 Sockets

3.1–3.2 Digital Information and Digital Transmission	3.6–3.7 Line Coding and Modems

3.3–3.5 Digital Information, Channels, and Digital Transmission

3.8 Transmission Media

3.9 Error Detection

4.8 Cellular Networks

4.4–4.6 Circuit Switching and Telephone Networks

4.1 Multiplexing

4.7 Telephone Traffic

4.2–4.3 SONET and Transport Networks

5.1–5.5 Peer-to-Peer Protocol; ARQ, Flow control TCP Reliable Stream Service; Framing, PPP

5.6 HDLC

5.7 Link Sharing

6.1–6.2 Multiple Access, Random Access

6.4 Channelization

6.5 MAC Performance

6.3 Scheduling

6.8–6.9 Ring LANs

6.6–6.7 LAN protocols Ethernet

6.11 LAN Bridges

(6.11.2)

6.10 Wireless LANs

7.1–7.5 Packet Switching, Routing, Shortest Paths

7.6 ATM

7.7–7.8 Traffic Management

8.1–8.6 TCP/IP Architecture

8.7–8.8 Multicast Routing, DHCP, Mobile IP

9. ATM Architecture

(8.2–8.3)

(10.4)

11. Network Security

10. Advanced Architectures

12. Multimedia Information

Appendix A Queueing Models

Appendix B Network Management

FIGURE 1   Chapter dependencies (solid arrows show sequence of core topics).

PEDAGOGICAL ELEMENTS

We have improved the pedagogical elements of the first edition and offer several new elements.

- *Ethereal Virtual Lab.* Lab experiments are the most effective means for reinforcing the concepts taught in lectures. At the physical layer a rich set of instruments (for example, oscilloscopes, spectrum analyzers, bit error rate sets) is available in the field to troubleshoot systems and can be used in the lab to teach and demonstrate the application of concepts in real systems. The tcpdump program written by Jacobson, Leres, and McCanne has formed the basis for many network protocol analyzers that are now used to troubleshoot protocols in network systems in the field and in the lab. The Ethereal open-source tool is one such network protocol analyzer that supports a very broad array of protocols and that is continuously updated by a large community of developers. We have used Ethereal to teach protocols in lectures and in experiments and have found it to be very effective in bringing the protocol concepts to life.

Figure 2 shows an Ethereal screenshot of a packet capture that a student can readily capture from a PC at home. The top pane shows the sequence of packets that transpire
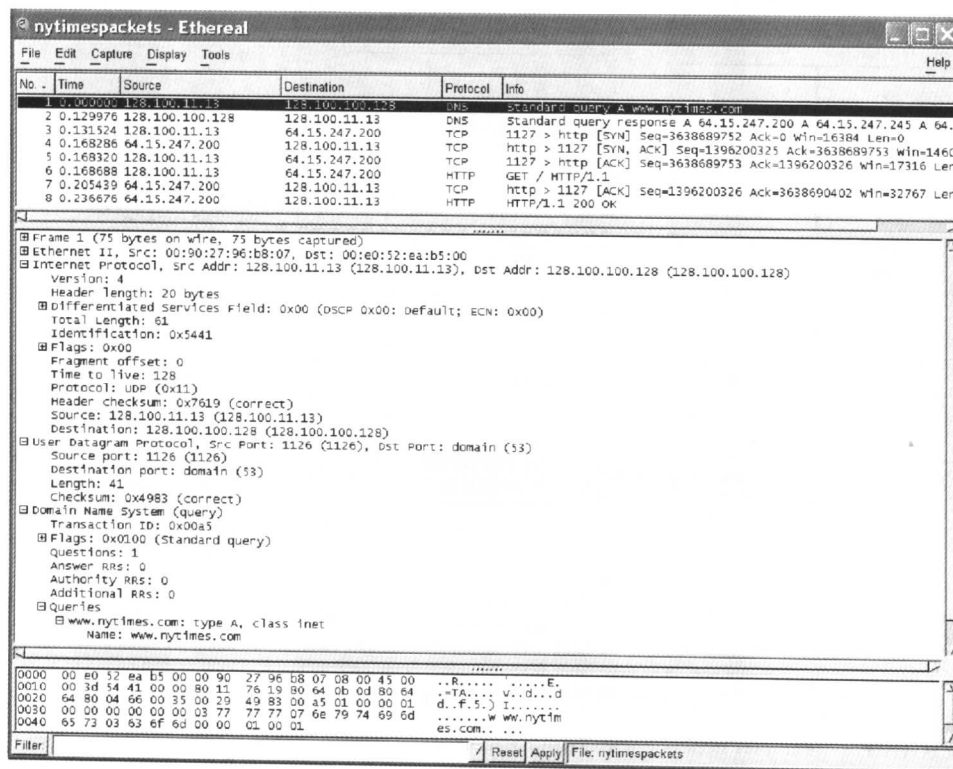
FIGURE 2   Sample Ethereal display.

after the student clicks on a web link: A DNS query and response; A TCP three-way connection setup; an HTTP request, followed by a TCP acknowledgment, and then the beginning of the HTTP response. The sequence of packets exchanged for various types of protocols can be analyzed in this fashion. The middle pane allows the user to delve into the details in the headers of any of the protocol data units at layer 2 and above. The middle pane in the figure shows some of the details of the IP, UDP, and DNS headers. The bottom pane allows the user to zoom into the bits and bytes of the header as well as the payload. This rich set of capabilities was developed within Ethereal for use in troubleshooting protocols in development labs as well as in the field. These same capabilities make Ethereal an extremely powerful teaching tool.

We use Ethereal to examine PPP, HDLC, Ethernet, MPLS, IP, IPv6, OSPF, UDP, TCP, DNS, HTTP, RTP, SIP, H.323, SSL, and TLS. We provide the instructors with packet capture files that allow them to demonstrate protocols interactively in the classroom. Most of the examples can be readily reproduced and examined in greater detail by the student. We also introduce networks utilities such as PING, IPconfig, netstat, and traceroute, which can be used in exercises that involve Ethereal packet captures.

- *Numerous figures.* Network diagrams, time diagrams, performance graphs, state transition diagrams are essential to effectively convey concepts in networking.
- *Lecture charts.* We have prepared approximately 500 MS PowerPoint® charts for use in lecture presentations. We have also prepared approximately 50 presentation charts that use animation to demonstrate certain key concepts more effectively. All of these charts are available to instructors in the book web site.
- *Numerous examples.* The discussion of fundamental concepts is accompanied with examples illustrating the use of the concept in practice. Numerical examples are included in the text wherever possible.
- *Text boxes.* Commentaries in text boxes are used to discuss network trends and interesting developments, to speculate about future developments, and to motivate new topics.
- *Problems.* The authors firmly believe that learning must involve problem solving. The book contains approximately 600 problems. Each chapter includes problems with a range of difficulties from simple application of concepts to exploring, developing, or elaborating various concepts and issues. Quantitative problems range from simple calculations to brief case studies exploring various aspects of certain algorithms, techniques or networks. Programming exercises involving sockets and TCP/IP utilities are included where appropriate.
- *Chapter introductions.* Each chapter includes an introduction previewing the material covered in the chapter and in the context of the "big picture."
- *Chapter summaries and checklist of important terms.* Each chapter includes a summary that reiterates the most important concepts. A checklist of important terms aids the student in reviewing the material.
- *Mathematical sections.* In general key mathematical results are summarized in the main text. A sidebar indicates (optional) mathematical sections that contain more detailed mathematical discussion or derivation of these results.
- *References.* Each chapter includes a list of references. Given the introductory nature of the text, references concentrate on pointing to more advanced materials. Reference

to appropriate Internet Engineering Taskforce (IETF) RFCs and research papers is made where appropriate, especially with more recent topics.

- *A website.* The following website www.mhhe.com/leon-garcia contains links to the following teaching resources:
  - An *Instructor's Solutions Manual*
  - Additional problems, exercises and experiments for instructors
  - Answers to selected problems for students
  - Animated PowerPoint lectures and presentations
  - Chapter pointers to useful and interesting websites

ACKNOWLEDGMENTS

With the help of the many reviewers, professors, and students who have used previous versions of this book, we have tried to make the complex and fluid topic of network architecture as approachable, up-to-date, and error-free as possible. We welcome all comments and suggestions on how to improve the text. Please contact us via the text's website with any ideas you may have.

<div style="text-align: right">

Alberto Leon-Garcia
Indra Widjaja

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ABOUT THE AUTHORS

Alberto Leon-Garcia is a Professor in the Department of Electrical and Computer Engineering at the University of Toronto where he holds the Jeffrey Skoll Chair in Computer Networks and Innovation. He was also Chief Technical Officer and co-founder of AcceLight Networks Inc. where he led the development of a terabit multi-service optical switch. In 1999 Dr. Leon-Garcia became an IEEE fellow for "*For contributions to multiplexing and switching of integrated services traffic.*"

At the University of Toronto, Dr. Leon-Garcia was the first holder of the Nortel Institute Chair in Network Architecture and Services. In 1998 he founded the Master of Engineering in Telecommunications program. Dr. Leon-Garcia has proudly supervised more than sixty graduate and postgraduate students.

Dr. Leon-Garcia is the author of the textbooks *Probability and Random Processes for Electrical Engineering* (Addison-Wesley), and *Communication Networks: Fundamental Concepts and Key Architectures* (McGraw-Hill), coauthored with Dr. Indra Widjaja.

Indra Widjaja received his Ph.D. degree in electrical engineering on high-speed packet switching architectures from the University of Toronto in 1992. Since 2001, he has been a researcher at Bell Laboratories, Lucent Technologies.

Dr. Widjaja's current research interests include traffic engineering, architectures for cost-effective transport networks, and high-speed packet switching. He has extensive publication in technical journals and conferences and holds several patents in switching architectures. He is also an active member of IETF and IEEE.

In 1993, Dr. Widjaja performed research on traffic management at the Teletraffic Research Center in Adelaide, Australia. From 1994 to 1997, he was Assistant Professor of Electrical and Computer Engineering at the University of Arizona where he taught courses in Computer Networking, Computer Architecture, and Digital Telephony, and conducted research in communication networks. He was also a Technical Consultant to Motorola and Lucent Technologies. From 1997 to 2001, he was with Fujitsu Network Communications where he worked on the architecture definitions and requirements for core switch, access switch, and transport products.