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DATA AND COMPUTER COMMUNICATIONS

FIFTH EDITION

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PREFACE

Objectives

This book attempts to provide a unified overview of the broad field of data and computer communications. The organization of the book reflects an attempt to break this massive subject into comprehensible parts and to build, piece by piece, a survey of the state of the art. The book emphasizes basic principles and topics of fundamental importance concerning the technology and architecture of this field, as well as providing a detailed discussion of leading-edge topics.

The following basic themes serve to unify the discussion:

- *Principles:* Although the scope of this book is broad, there are a number of basic principles that appear repeatedly as themes and that unify this field. Examples are multiplexing, flow control, and error control. The book highlights these principles and contrasts their application in specific areas of technology.
- *Design Approaches:* The book examines alternative approaches to meeting specific communication requirements. The discussion is bolstered with examples from existing implementations.
- *Standards:* Standards have come to assume an increasingly important, indeed dominant, role in this field. An understanding of the current status and future direction of technology requires a comprehensive discussion of the role and nature of the related standards.

Plan of the Text

The book is divided into four parts:

I *Data Communications:* This part is concerned primarily with the exchange of data between two directly-connected devices. Within this restricted scope, the key aspects of transmission, interfacing, link control, and multiplexing are examined.

II *Wide-Area Networks:* This part examines the internal mechanisms and technologies that have been developed to support voice, data, and multimedia communications over long-distance networks. The traditional technologies of packet switching and circuit switching are examined, as well as the more recent frame relay and ATM.

III *Local Area Networks:* This part explores the quite different technologies and architectures that have been developed for networking over shorter distances. The transmission media, topologies, and medium access control protocols that are the key ingredients of a LAN design are explored and specific standardized LAN systems examined.

IV *Communications Architecture and Protocols:* This part explores both the architectural principles and the mechanisms required for the exchange of data among computers, workstations, servers, and other data processing devices. Much of the material in this part relates to the TCP/IP protocol suite.

In addition, the book includes an extensive glossary, a list of frequently-used acronyms, and a a bibliography. Each chapter includes problems and suggestions for further reading.

The book is intended for both an academic and a professional audience. For the professional interested in this field, the book serves as a basic reference volume and is suitable for self-study.

As a textbook, it can be used for a one-semester or two-semester course. It covers the material in the Computer Communication Networks course of the joint ACM/IEEE Computing Curricula 1991. The chapters and parts of the book are sufficiently modular to provide a great deal of flexibility in the design of courses. The following are suggestions for course design:

- *Fundamentals of Data Communications*: Part I, Chapters 8 (circuit switching), 9 (packet switching), 12 (protocols and architecture).
- *Communications Networks*: If the student has a basic background in data communications, then this course could cover Parts II and III, and Appendix A.
- *Computer Networks*: If the student has a basic background in data communications, then this course could cover Chapters 5 (data communication interface), 6 (data link control), and Part IV.

In addition, a more streamlined course that covers the entire book is possible by eliminating certain chapters that are not essential on a first reading. Chapters that could be optional are: Chapters 2 (data transmission) and 3 (transmission media), if the student has a basic understanding of these topics, Chapter 7 (multiplexing), Chapter 10 (frame relay), Chapter 14 (bridges), and Chapter 18 (network security).

INTERNET SERVICES FOR INSTRUCTORS AND STUDENTS

There is a web page for this book that provides support for students and instructors. The page includes links to relevant sites, transparency masters of figures in the book in PDF (Adobe Acrobat) format, and sign-up information for the book's internet mailing list. The mailing list has been set up so that instructors using this book can exchange information, suggestions, and questions with each other and with the author. The web page is at http://www.shore.net/~ws/DCC5e.html.

As soon as any typos or other errors are discovered, an errata list for this book will be available at http://www.shore.net/~ws/welcome.html.

WHAT'S NEW IN THE FIFTH EDITION

This fifth edition is seeing the light of day less than a dozen years after the publication of the first edition. Much has happened during those years. Indeed, the pace of change, if anything, is increasing. The result is that this revision is more comprehensive and thorough than any of the previous ones. As an indication of this, about one-half of the figures (233 out of 343) and one-half of the tables (48 out of 91) in this edition are new. Every chapter has been revised, new chapters have been added, and the overall organization of the book has changed.

To begin this process of revision, the fourth edition of this book was extensively reviewed by a number of professors who taught from that edition. The result is that, in many places, the narrative has been clarified and tightened and illustrations have been improved. Also, a number of new "field-tested" problems have been added.

Beyond these refinements to improve pedagogy and user-friendliness, there have been major substantive changes throughout the book. Highlights include

- *ATM*: The coverage of ATM has been significantly expanded. There is now an entire chapter devoted to ATM and ATM congestion control (Chapter 11). New to this edition is the coverage of ATM LANs (Sections 13.4 and 14.3).
- *IPv6 (IPng) and IPv6 Security*: IPv6, also known as IPng (next generation), is the key to a greatly expanded use of TCP/IP both on the Internet and in other networks. This new topic is thoroughly covered. The protocol and its internetworking functions are discussed in Section 16.3, and the important material on IPv6 security is provided in Section 18.4.
- *Wireless and Spread Spectrum*: There is greater coverage of wireless technology (Section 3.2) and spread spectrum techniques (Section 4.5). New to this edition is treatment of the important topic of wireless LANs (Sections 12.5 and 13.6).
- *High-speed LANs*: Coverage of this important area is significantly expanded, and includes detailed treatment of leading-edge approaches, including Fast Ethernet (100BASE-T), 100VG-AnyLAN, ATM LANs, and Fibre Channel (Sections 13.1 through 13.5).
- *Routing*: The coverage of internetwork routing has been updated and expanded. There is a longer treatment of OSPF and a discussion of BGP has been added.
- *Frame Relay*: Frame relay also receives expanded coverage with Chapter 10 devoted to frame relay and frame relay congestion control.
- *Network Security*: Coverage of this topic has been expanded to an entire chapter (Chapter 18).
- *Network Management*: New developments in the specification of SNMPv2 are covered (Section 19.2).
- *SMTP and MIME*: Multimedia electronic mail combines the basic functionality of the Simple Mail Transfer Protocol with the Multi-purpose Internet Mail Extension.

- *HTTP*: (Hypertext Transfer Protocol): HTTP is the foundation of the operation of the worldwide web (www). Section 19.3 covers HTTP.
- *TCP/IP*: TCP/IP is now the focus of the protocol coverage in this book. Throughout the book, especially in Part IV, there is increased discussion of TCP/IP and related protocols and issues.

In addition, throughout the book, virtually every topic has been updated to reflect the developments in standards and technology that have occurred since the publication of the fourth edition.

ACKNOWLEDGMENTS

This new edition has benefited from review by a number of people, who gave generously of their time and expertise. Kitel Albertson (Trondheim College of Engineering), Howard Blum (Pace University), Mike Borella (DePaul University), William Clark (University of Alaska, Anchorage), Joe Doupnik (Utah State University), Doug Jacobson (Iowa State University), Dave Mallya, Biswath Mukherjee (University of California, Davis), and Mark Pullen (George Mason University) reviewed all or part of the manuscript.

Steve Deering of Xerox PARC reviewed the material on IPv6. Ted Doty of Network Systems Corporation reviewed IP security. Henrik Nielson reviewed HTTP.

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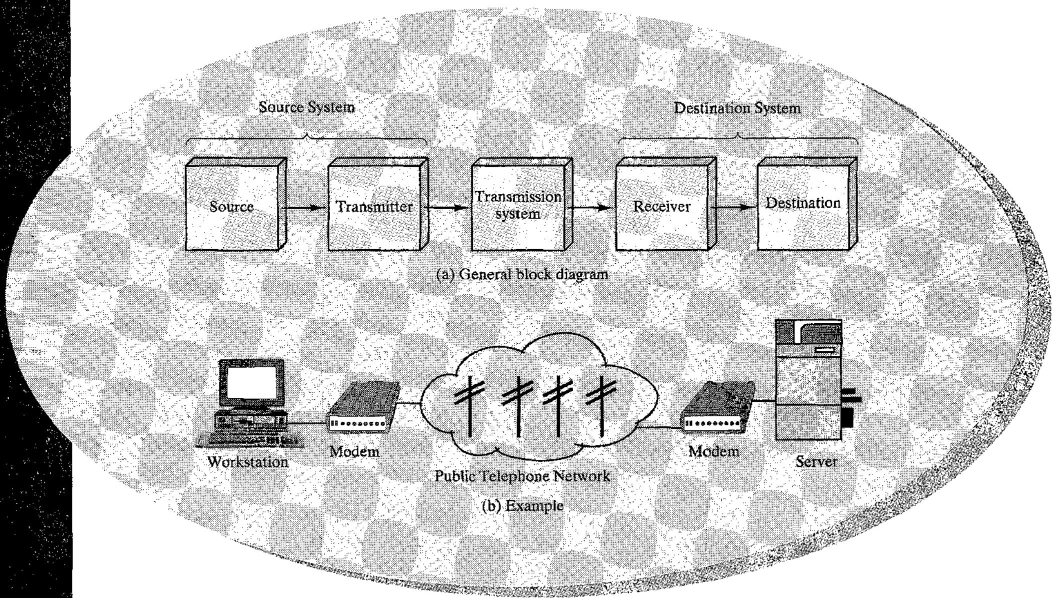
CHAPTER 1

INTRODUCTION



The 1970s and 1980s saw a merger of the fields of computer science and data communications that profoundly changed the technology, products, and companies of the now-combined computer-communications industry. Although the consequences of this revolutionary merger are still being worked out, it is safe to say that the revolution has occurred, and any investigation of the field of data communications must be made within this new context.

The computer-communications revolution has produced several remarkable facts:

- There is no fundamental difference between data processing (computers) and data communications (transmission and switching equipment).
- There are no fundamental differences among data, voice, and video communications.
- The lines between single-processor computer, multi-processor computer, local network, metropolitan network, and long-haul network have blurred.

One effect of these trends has been a growing overlap of the computer and communications industries, from component fabrication to system integration. Another result is the development of integrated systems that transmit and process all types of data and information. Both the technology and the technical-standards organizations are driving toward a single public system that integrates all communications and makes virtually all data and information sources around the world easily and uniformly accessible.

It is the ambitious purpose of this book to provide a unified view of the broad field of data and computer communications. The organization of the book reflects an attempt to break this massive subject into comprehensible parts and to build, piece by piece, a survey of the state of the art. This introductory chapter begins with a general model of communications. Then, a brief discussion introduces each of the four major parts of this book. Next, the all-important role of standards is introduced. Finally, a brief outline of the rest of the book is provided.

1.1 A COMMUNICATIONS MODEL

We begin our study with a simple model of communications, illustrated by the block diagram in Figure 1.1a.

The fundamental purpose of a communications system is the exchange of data between two parties. Figure 1.1b presents one particular example, which is the communication between a workstation and a server over a public telephone network. Another example is the exchange of voice signals between two telephones over the same network. The key elements of the model are

- **Source.** This device generates the data to be transmitted; examples are telephones and personal computers.

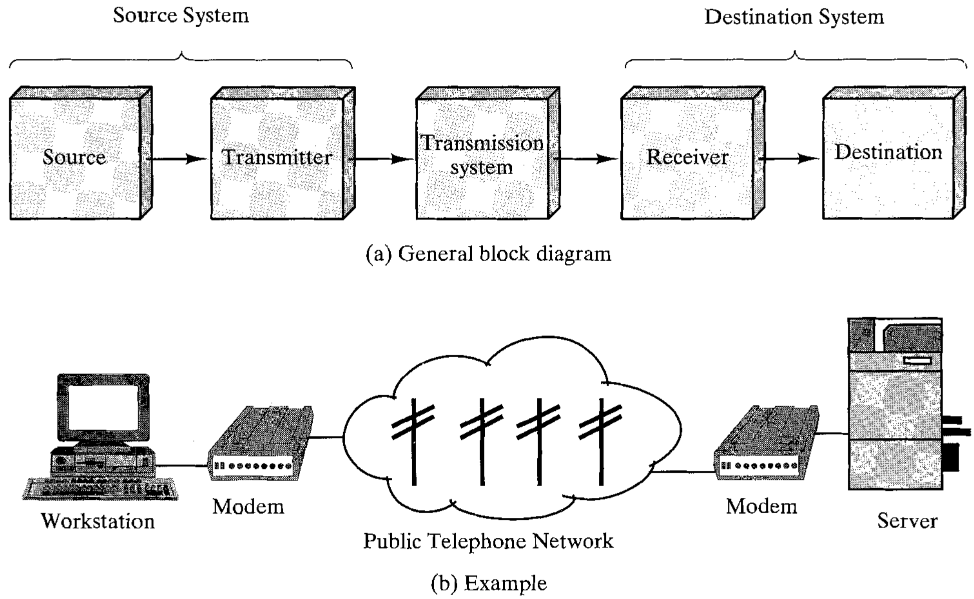


FIGURE 1.1 Simplified communications model.

- **Transmitter.** Usually, the data generated by a source system are not transmitted directly in the form in which they were generated. Rather, a transmitter transforms and encodes the information in such a way as to produce electromagnetic signals that can be transmitted across some sort of transmission system. For example, a modem takes a digital bit stream from an attached device such as a personal computer and transforms that bit stream into an analog signal that can be handled by the telephone network.
- **Transmission System.** This can be a single transmission line or a complex network connecting source and destination.
- **Receiver.** The receiver accepts the signal from the transmission system and converts it into a form that can be handled by the destination device. For example, a modem will accept an analog signal coming from a network or transmission line and convert it into a digital bit stream.
- **Destination.** Takes the incoming data from the receiver.

This simple narrative conceals a wealth of technical complexity. To get some idea of the scope of this complexity, Table 1.1 lists some of the key tasks that must be performed in a data communications system. The list is somewhat arbitrary: Elements could be added; items on the list could be merged; and some items represent several tasks that are performed at different "levels" of the system. However, the list as it stands is suggestive of the scope of this book.

TABLE 1.1 Communications tasks.

Transmission system utilization	Addressing
Interfacing	Routing
Signal generation	Recovery
Synchronization	Message formatting
Exchange management	Security
Error detection and correction	Network management
Flow control	

The first item, **transmission system utilization**, refers to the need to make efficient use of transmission facilities that are typically shared among a number of communicating devices. Various techniques (referred to as multiplexing) are used to allocate the total capacity of a transmission medium among a number of users. Congestion control techniques may be required to assure that the system is not overwhelmed by excessive demand for transmission services.

In order to communicate, a device must **interface** with the transmission system. All the forms of communication discussed in this book depend, at bottom, on the use of electromagnetic signals propagated over a transmission medium. Thus, once an interface is established, **signal generation** is required for communication. The properties of the signal, such as form and intensity, must be such that they are (1) capable of being propagated through the transmission system, and (2) interpretable as data at the receiver.

Not only must the signals be generated to conform to the requirements of the transmission system and receiver, but there must be some form of **synchronization** between transmitter and receiver. The receiver must be able to determine when a signal begins to arrive and when it ends. It must also know the duration of each signal element.

Beyond the basic matter of deciding on the nature and timing of signals, there are a variety of requirements for communication between two parties that might be collected under the term **exchange management**. If data are to be exchanged in both directions over a period of time, the two parties must cooperate. For example, for two parties to engage in a telephone conversation, one party must dial the number of the other, causing signals to be generated that result in the ringing of the called phone. The called party completes a connection by lifting the receiver. For data processing devices, more will be needed than simply establishing a connection; certain conventions must be decided upon. These conventions may include whether both devices may transmit simultaneously or must take turns, the amount of data to be sent at one time, the format of the data, and what to do if certain contingencies, such as an error, arise.

The next two items might have been included under exchange management, but they are important enough to list separately. In all communications systems, there is a potential for error; transmitted signals are distorted to some extent before reaching their destination. **Error detection and correction** are required in circumstances where errors cannot be tolerated; this is usually the case with data processing systems. For example, in transferring a file from one computer to another, it is simply not acceptable for the contents of the file to be accidentally altered. **Flow control** is required to assure that the source does not overwhelm the destination by sending data faster than they can be processed and absorbed.

Next, we mention the related but distinct concepts of **addressing** and **routing**. When a transmission facility is shared by more than two devices, a source system must somehow indicate the identity of the intended destination. The transmission system must assure that the destination system, and only that system, receives the data. Further, the transmission system may itself be a network through which various paths may be taken. A specific route through this network must be chosen.

Recovery is a concept distinct from that of error correction. Recovery techniques are needed in situations in which an information exchange, such as a data base transaction or file transfer, is interrupted due to a fault somewhere in the system. The objective is either to be able to resume activity at the point of interruption or at least to restore the state of the systems involved to the condition prior to the beginning of the exchange.

Message formatting has to do with an agreement between two parties as to the form of the data to be exchanged or transmitted. For example, both sides must use the same binary code for characters.

Frequently, it is important to provide some measure of **security** in a data communications system. The sender of data may wish to be assured that only the intended party actually receives the data; and the receiver of data may wish to be assured that the received data have not been altered in transit and that the data have actually come from the purported sender.

Finally, a data communications facility is a complex system that cannot create or run itself. **Network management** capabilities are needed to configure the system, monitor its status, react to failures and overloads, and plan intelligently for future growth.

Thus we have gone from the simple idea of data communication between source and destination to a rather formidable list of data communications tasks. In this book, we further elaborate this list of tasks to describe and encompass the entire set of activities that can be classified under data and computer communications.

1.2 DATA COMMUNICATIONS

This book is organized into four parts. The first part deals with the most fundamental aspects of the communications function, focusing on the transmission of signals in a reliable and efficient manner. For want of a better name, we have given Part I the title "Data Communications," although that term arguably encompasses some or even all of the topics of Parts II, III, and IV.

To get some flavor for the focus of Part I, Figure 1.2 provides a new perspective on the communications model of Figure 1.1a. Let us trace through the details of this figure using electronic mail as an example.

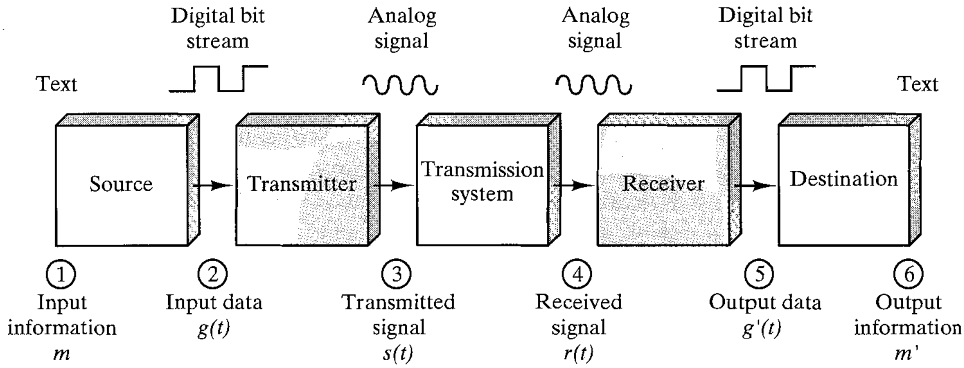


FIGURE 1.2 Simplified data communications model.

Consider that the input device and transmitter are components of a personal computer. The user of the PC wishes to send a message to another user—for example, "The meeting scheduled for March 25 is canceled" (m). The user activates the electronic mail package on the PC and enters the message via the keyboard (input device). The character string is briefly buffered in main memory. We can view it as a sequence of bits (g) in memory. The personal computer is connected to some transmission medium, such as a local network or a telephone line, by an I/O device (transmitter), such as a local network transceiver or a modem. The input data are transferred to the transmitter as a sequence of voltage shifts [$g(t)$] representing bits on some communications bus or cable. The transmitter is connected directly to the medium and converts the incoming stream [$g(t)$] into a signal [$s(t)$] suitable for transmission. Specific alternatives to this procedure will be described in Chapter 4.

The transmitted signal $s(t)$ presented to the medium is subject to a number of impairments, discussed in Chapter 2, before it reaches the receiver. Thus, the received signal $r(t)$ may differ to some degree from $s(t)$. The receiver will attempt to estimate the original $s(t)$, based on $r(t)$ and its knowledge of the medium, producing a sequence of bits $g'(t)$. These bits are sent to the output personal computer, where they are briefly buffered in memory as a block of bits (g). In many cases, the destination system will attempt to determine if an error has occurred and, if so, will cooperate with the source system to eventually obtain a complete, error-free block of data. These data are then presented to the user via an output device, such as a printer or a screen. The message (m'), as viewed by the user, will usually be an exact copy of the original message (m).

Now consider a telephone conversation. In this case, the input to the telephone is a message (m) in the form of sound waves. The sound waves are converted by the telephone into electrical signals of the same frequency. These signals are transmitted without modification over the telephone line. Hence, the input signal $g(t)$ and the transmitted signal $s(t)$ are identical. The signal $s(t)$ will suffer some distortion over the medium, so that $r(t)$ will not be identical to $s(t)$. Nevertheless, the signal $r(t)$ is converted back into a sound wave with no attempt at correction or improvement of signal quality. Thus m' is not an exact replica of m. However, the received sound message is generally comprehensible to the listener.

The discussion so far does not touch on other key aspects of data communications, including data-link control techniques for controlling the flow of data and detecting and correcting errors, and multiplexing techniques for transmission efficiency. All of these topics are explored in Part I.

1.3 DATA COMMUNICATIONS NETWORKING

In its simplest form, data communication takes place between two devices that are directly connected by some form of point-to-point transmission medium. Often, however, it is impractical for two devices to be directly, point-to-point connected. This is so for one (or both) of the following contingencies:

- The devices are very far apart. It would be inordinately expensive, for example, to string a dedicated link between two devices thousands of miles apart.
- There is a set of devices, each of which may require a link to many of the others at various times. Examples are all of the telephones in the world and all of the terminals and computers owned by a single organization. Except for the case of a very few devices, it is impractical to provide a dedicated wire between each pair of devices.

The solution to this problem is to attach each device to a communications network. Figure 1.3 relates this area to the communications model of Figure 1.1a and also suggests the two major categories into which communications networks are traditionally classified: wide-area networks (WANs) and local-area networks (LANs). The distinction between the two, both in terms of technology and application, has become somewhat blurred in recent years, but it remains a useful way of organizing the discussion.

Wide-Area Networks

Wide-area networks have been traditionally been considered to be those that cover a large geographical area, require the crossing of public right-of-ways, and rely at least in part on circuits provided by a common carrier. Typically, a WAN consists of a number of interconnected switching nodes. A transmission from any one device is routed through these internal nodes to the specified destination device. These nodes (including the boundary nodes) are not concerned with the content of the data; rather, their purpose is to provide a switching facility that will move the data from node to node until they reach their destination.

Traditionally, WANs have been implemented using one of two technologies: circuit switching and packet switching. More recently, frame relay and ATM networks have assumed major roles.