WILLIAM STALLINGS, Ph.D.

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221

Macmillan Publishing Company
New York

Collier Macmillan Publishers
London

Macmillan Publishing Company
866 Third Avenue, New York, New York 10022

Collier Macmillan Canada, Inc.

Library of Congress Cataloging in Publication Data

Stallings, William.
Data and computer communications.

Includes bibliographies and index.
1. Data transmission systems. 2. Computer networks.
I. Title.
TK5105.S73 1985 384 84-7914

Printing: 2 3 4 5 6 7 8 Year: 5 6 7 8 9 0 1 2

ISBN 0-02-415440-7

ACRONYMS

ADCCP	Advanced Data Communication Control Procedures
AM	Amplitude Modulation
ANSI	American National Standards Institute
ARQ	Automatic Repeat Request
ASCII	American Standard Code for Information Interchange
ASK	Amplitude-Shift Keying
CATV	Community Antenna Television
CBX	Computerized Branch Exchange
CCITT	International Consultative Committee on Telegraphy and Telephony
CRC	Cyclic Redundancy Check
CSMA	Carrier-Sense Multiple Access
CSMA/CD	Carrier-Sense Multiple Access with Collision Detection
DAMA	Demand-Assignment Multiple Access
DARPA	Defense Advanced Research Projects Agency
DCE	Data Circuit-Terminating Equipment
DM	Delta Modulation
DPA	DOD Protocol Architecture
DTE	Data Terminal Equipment
EIA	Electronic Industries Association
FCS	Frame Check Sequence
FDM	Frequency-Division Multiplexing
FDMA	Frequency-Division Multiple Access
FM	Frequency Modulation
FSK	Frequency-Shift Keying
HDLC	High-Level Data Link Control
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISDN	Integrated Services Digital Network

ISO	International Organization for Standardization
LAP-B	Link Access Protocol—Balanced
LRC	Longitudinal Redundancy Check
NBS	National Bureau of Standards
NRZ	Nonreturn to Zero
OSI	Open Systems Interconnection
PAD	Packet Assembler/Disassembler
PBX	Private Branch Exchange
PCM	Pulse Code Modulation
PDN	Public Data Network
PDU	Protocol Data Unit
PM	Phase Modulation
PSK	Phase-Shift Keying
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
SAP	Service Access Point
SCA	Subsidiary Communications Authorization
SCPC	Single Channel per Carrier
SDLC	Synchronous Data Link Control
SS/TDMA	Satellite-Switched Time-Division Multiple Access
TCP	Transmission Control Protocol
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
TMS	Time Multiplex Switching
TPDU	Transport Protocol Data Unit
TSI	Time Slot Interchange
UDP	User Datagram Protocol
VAN	Value-Added Network
VRC	Vertical Redundancy Check
VTP	Virtual Terminal Protocol

PREFACE

The 1970's and early 1980's 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 occurred, and any investigation of the field of data communications must be made within this new context.

Objectives

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. The book emphasizes basic principles and topics of fundamental importance concerning the technology and architecture of data and computer communications.

The book explores the key topics in the field in the following general categories:

- *Principles:* Although the scope of this book is broad, there are a number of basic principles that appear repeatedly as themes which 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, not to say dominant, role in this field. An understanding of the current status and future direction of the technology is not possible without a comprehensive discussion of the role and nature of the related standards.

The subject, and therefore this book, is highly technical. Nevertheless, an attempt has been made to make the book self-contained. Part I, in particular, draws upon the disciplines of probability and electrical engineering, but the emphasis is on results rather than derivations. In general, a building-block approach is taken. The principles of data communications are carefully and thoroughly explored. These principles are then applied to the complex systems found in communication networks and computer-communications architectures.

Intended Audience

The book is intended for a broad range of readers interested in data and computer communications:

- *Students and professionals in data processing and data communications:* This book is intended as both a textbook for study and a basic reference volume for this exciting and complex field.
- *Designers and implementers:* The book discusses the critical design issues and explores alternative approaches to meeting user requirements.
- *Computer and communication system customers and managers:* The book provides the reader with an understanding of what features and structure are needed in a communications capability, as well as a knowledge of current and evolving standards. This information provides a means of assessing specific implementations and vendor offerings.

Plan of the Text

The book is organized to clarify the unifying and differentiating concepts underlying the field of data and computer communications. It is divided into three parts:

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

II *Data communication networking:* This part examines the internal mechanisms by which communication networks provide a data transfer service for attached devices.

III *Computer communications architecture:* This part explores both the architectural principles and the specific mechanisms required for the exchange of data among computers, terminals and other data processing devices.

The organization of the chapters is as follows:

1. *Introduction:* Provides an overview of the book as well as a discussion of the roles of the various standards-making organizations.
2. *Data transmission:* Explores the behavior of signals propagated through a transmission medium.
3. *Data encoding:* Describes the techniques used for encoding analog and digital data as either analog or digital signals.

4. *Digital data communication techniques:* Examines interfacing and synchronization issues.
5. *Data link control:* Describes the techniques used for converting an unreliable transmission link into a reliable communications link.
6. *Multiplexing:* Examines frequency-division multiplexing and both synchronous and statistical time-division multiplexing.
7. *Communication networking techniques:* Serves as an overview to Part II.
8. *Circuit switching:* Discusses circuit-switching mechanisms and network design.
9. *Packet switching:* Examines the mechanisms of packet switched networking, including routing, traffic control, and error control.
10. *Radio and satellite networks:* Explores design and performance issues for antenna-based communication networks.
11. *Local networks:* Examines alternative approaches in the areas of transmission medium, topology, and medium access control technique.
12. *Protocols and architecture:* Defines communications protocols and motivates the need for a communications architecture.
13. *Network access protocols:* Examines techniques for accessing circuit-switched, packet-switched, and local networks.
14. *Internetworking:* Explores alternative techniques for communicating across multiple networks.
15. *Transport protocols:* Provides a detailed analysis of the most complex and important class of communications protocols.
16. *Process/application protocols:* Provides examples of higher-layer protocols.
17. *Integrated services digital network:* A preview of the network which represents the culmination of the computer-communications revolution.

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

The book is suitable for self-study and can be covered in a two-semester course.

Related Materials

Computer Communications: Architectures, Protocols, and Standards (IEEE Computer Society Press, 1985) is a companion to this text, covering topics in Chapters 4 and 5 and Part III. It contains reprints of many of the key references used herein. The IEEE Computer Society Press is at P. O. Box 80452, Worldway Postal Center, Los Angeles, CA 90080; telephone (714) 821-8380.

A set of videotape courses specifically designed for use with *Data and Computer Communications* is available from the Association for Media-Based Continuing Education for Engineers, Inc., 255 North Avenue NW, Atlanta, Georgia 30332; telephone (404) 894-3362.

Acknowledgments

Many people have helped me during the preparation of this book. I would like to particularly acknowledge and thank the following people. K. C. Houston provided me with the opportunity to pursue this fascinating field. John Burruss, John Carson, Randall Frank, William Franta, Hal Folts, Govind Gupta, Stanislow Kesler, Ralph Martinez, A. A. Nilsson, and Robert Pokress reviewed all or a portion of the

manuscript. Macmillan provided me with not one but three excellent editors: Sally Elliott, Peter Gordon, and Maria Colligan. Alice Wilding-White of A Way With Words, Inc., who typed the manuscript, and John Travis of Macmillan, who managed the book's production, once again did the job in record time. And finally, I thank my wife Tricia, who knew what we were getting into this time.

W.S.

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CHAPTER 1

Introduction

1-1 THE COMPUTER-COMMUNICATIONS REVOLUTION

The 1970s and early 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.

The result has been a growing overlap of the computer and communications industries, from component fabrication to system integration. The forthcoming result is the development of integrated systems that transmit and process all types

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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 three 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.

1-2 A COMMUNICATIONS MODEL

We begin our study with a simple model of communications. A block diagram of this model appears as Figure 1-1.

The fundamental purpose of data communications is to exchange information between two agents. In Figure 1-1, the information to be exchanged is a message labeled m. This information is represented as data g and is generally presented to a transmitter in the form of a time-varying signal, $g(t)$.

The terms data and information are defined in Table 1-1. These definitions seem rather academic, but for our purpose they might be given the following interpretation: data can be identified; data can be described; data do not necessarily represent something physical in terms of the measurable world; but above all data can be and should be used, namely for producing information. They also imply that data to one person may appear as information to another. Information is born when data are interpreted. To exchange information, then, requires access to elements of data and the ability to transmit them.

Returning now to Figure 1-1, the signal $g(t)$ is to be transmitted. Generally, the signal will not be in a form suitable for transmission and must be converted to a signal $s(t)$ that is in some sense matched to the characteristics of the transmission medium. The signal is then transmitted across the medium. On the other end, a signal $r(t)$, which may differ from $s(t)$, is received. This signal is then converted by a receiver into a form suitable for output. The converted signal $\tilde{g}(t)$, or data $\tilde{g}$, is an approximation or estimate of the input. Finally, the output device presents the estimated message, $\tilde{m}$, to the destination agent.

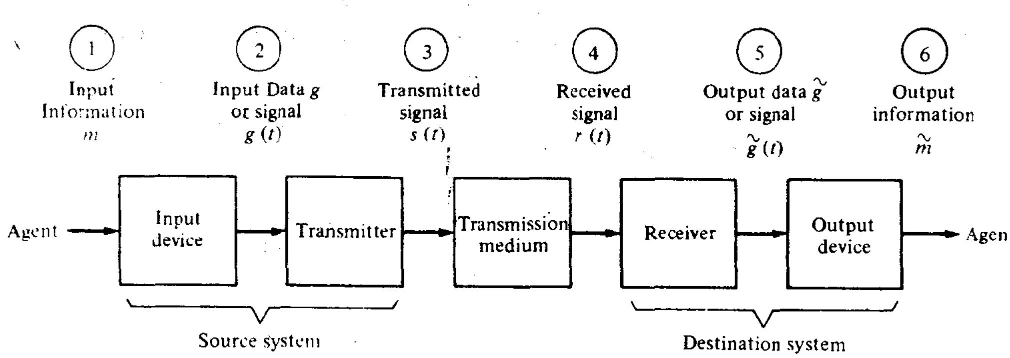

FIGURE 1-1. Simplified communications block diagram.

TABLE 1-1 Data and Information

Data	A representation of facts, concepts, or instructions in a formalized manner suitable for communication, interpretation, or processing by human beings or by automatic means
Information	The meaning that a human being assigns to data by means of the conventions applied to those data

Source: [ANSC82].

This simple narrative conceals a wealth of technical complexity. To attempt to elaborate, we present two examples, one using electronic mail, the other a telephone conversation.

For the case of electronic mail, consider that that input device and transmitter are components of a personal computer. The agent is a user who wishes to send a message to another user, for example, "The meeting scheduled for March 25 is canceled" (m). This string of characters is the information. The user activates the electronic mail package on the personal computer 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 characters (g) or, more literally, 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 bits [$g(t)$] or, more literally, a sequence of voltage shifts [$g(t)$] on some communications bus or cable. The transmitter is connected directly to the medium and converts the incoming bits [$g(t)$] into a signal [$s(t)$] suitable for transmission; specific alternatives will be described in Chapter 3.

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 nature of $s(t)$, based on $r(t)$ and its knowledge of the medium, producing a sequence of bits $\tilde{g}(t)$. These bits are sent to the output personal computer, where they are briefly buffered in memory as a block of bits or characters ($\tilde{g}$). In many cases, the destination system will attempt to determine if an error has occurred and, if so, 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 screen. The message ($\tilde{m}$) as viewed by the user will usually be an exact copy of the original message (m).

A variation is worth mentioning. The agent at either end may be a computer process rather than a human user. For example, messages might be stored on disk or tape to be automatically sent when a certain condition occurs (e.g., in the evening, when phone rates are lower). Or a message might be received when the user is unavailable and stored on disk or tape for later retrieval.

Now consider a telephone conversation. The agent in this case is the speaker, who generates 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 $\tilde{m}$ is not an exact replica of

TABLE 1-2 Communication Tasks

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

m. However, the received sound message is generally comprehensible to the listener.

Again, we mention a variation. In so-called digital telephones, the input signal $g(t)$ is digitized (i.e., converted into a sequence of bits). It is this sequence of bits, in the form of a sequence of voltage shifts, that is transmitted as $s(t)$.

These two examples give some idea of the nature of data communications. Another view is expressed in Table 1-2, which lists 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.

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