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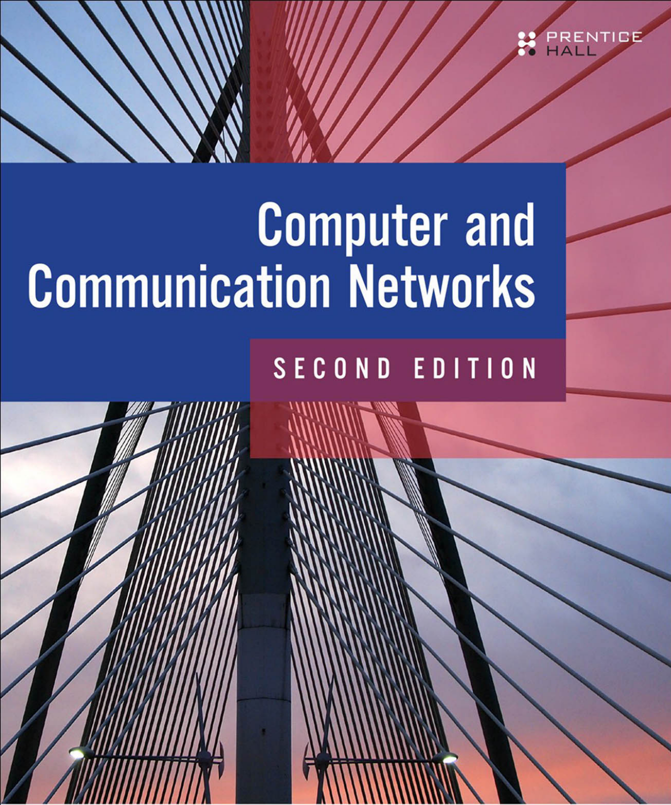

Computer and Communication Networks

SECOND EDITION

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Computer and Communication Networks

Second Edition

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Computer and Communication Networks

Second Edition

Nader F. Mir

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Preface

This textbook represents more than a decade of work. During this time, some material became obsolete and had to be deleted. In my days as a telecommunication engineer and then a university professor, much has changed in the fields of data communications and computer networks. Nonetheless, this text covers both the foundations and the latest advanced topics of computer communications and networking.

The Internet is a revolutionary communication vehicle by which we all conveniently communicate every day and do business with one another. Because of its complexities at both hardware and software levels, the Internet is a challenge to those who want to study this field. The growing number and variety of communication services introduces other challenges to experts of computer networks. Such experts are in need of effective references having in-depth balanced analysis, architecture, and description, and enabling them to better design emerging communication networks. This book fills the gaps in current available texts.

Objectives

This textbook offers a mix of theory, architecture, and applications in computer networking. The lack of computer communications books presenting moderate analysis with detailed figures covering both wireline and wireless communication technologies led me to write this book. The main objective of this book is to help readers learn the fundamentals and certain advanced concepts of computer and communication networks, using a unified set of symbols throughout a single textbook. The preparation of this book responds to the explosive demand for learning computer communication science and engineering.

This book targets two groups of people. For people in academia, at both the undergraduate and graduate levels, the book provides a thorough design and performance evaluation of communication networks. The book can also give researchers the ability to analyze and simulate complex communication networks. For engineers who want to work in the communication and networking industry and need a reference covering various angles of computer networks, this book provides a variety of learning techniques: exercises, case studies, and computer simulation projects. The book makes it easy and fun for an engineer to review and learn from a reliable networking reference covering all the necessary concepts and performance models.

Organization of This Book

The range of topics presented in this text allows instructors to choose the topics best suited for their classes. Besides the explanations provided in each chapter, readers will learn how to model a communication network and how to mathematically analyze it. Readers of this text will benefit from the combination of theory and applications presented in each chapter, with the more theoretical portions of each chapter challenging those readers who are more ambitious.

This book is organized into 22 chapters in two main parts, as follows. The ten chapters of Part I cover the fundamental topics in computer networking, with each chapter serving as a base for the following chapter. Part I of the book begins with an overview of networking, focusing on TCP/IP schemes, describing routing and multicasting in regular networks and wireless networks, and ending with a discussion of network applications, P2P networking, network management, and security. Part I is most appropriate for readers with no experience in computer communications. The 12 chapters in Part II cover detailed analytical aspects and offer a closer perspective of advanced networking protocols: architectures of switches and routers, delay and congestion analysis, label switching, virtual private networks, optical networks, cloud computing, SDN, data compression, voice over IP (VoIP), multimedia networking, ad-hoc networking, and sensor networks. An overview of the 22 chapters is as follows:

- **Chapter 1, Packet-Switched Networks**, introduces computer networks, touching on the need for networks, explaining relevant packet-switched networks, and giving an overview of today's Internet. Fundamental concepts, such as *messages*, *packets*, and *frames* and *packet switching* versus *circuit switching*, are defined. Various types of packet-switched networks are defined, and how a message can be handled by either *connection-oriented networks* or *connectionless networks* is explained. The second part of the chapter presents basics of the five- and seven-layer Internet Protocol reference models, as well as Internet and addressing scheme. Finally, this chapter presents a detailed analysis of packet size and optimization.

- **Chapter 2, Overview of Networking Devices**, introduces the overall architectures of regular and wireless networking devices. The chapter starts with introducing *network interface cards* (NICs), followed by switching and routing devices, such as hubs, bridges, switches, and routers. These devices are used to switch packets from one path to another. The devices include both wireline and wireless devices used as user, server, or network equipment. Networking modems are used for access to the Internet from remote and residential areas. Finally, multiplexers are used in all layers of a network and are utilized to combine data from multiple lines into one line.
- **Chapter 3, Data Links and Link Interfaces**, focuses on the links and transmission interfaces, the two basic components that networking starts with. This chapter presents both wired and wireless links and describes their characteristics, advantages, and channel access methods. This chapter also presents various *error-detection and correction* techniques at the link level and discusses the integrity of transmitted data. The chapter further presents link-layer *stop-and-wait* and *sliding-window* flow controls. We then proceed to presenting methods of link and then channel access by multiple users, both in regular and wireless environments. Finally, at the end of the chapter, the *link aggregation* method is described. The method combines multiple network links to increase throughput beyond what a single link can sustain. Link aggregation also has a second benefit of providing redundancy in case one of the links fails. We then introduce the well-known *Link Aggregation Control Protocol* (LACP).
- **Chapter 4, Local Area Networks and Networks of LANs**, explores the implementation of small networks, using the functional aspects of the fundamental knowledge gained in Chapters 1, 2, and 3 on basic protocols, devices, and links, respectively. The chapter provides some pointers for constructing a network with those devices and making connections, gives several examples of local area networks (LANs), and explains how such LANs are internetworked. Next, the chapter explores address conversion protocols by which addresses at layers 2 and 3 are converted to one another. The chapter at this point proceeds to the very important topic of the Spanning-Tree Protocol (STP). STP prevents frames or

packets from the looping that causes infinite circulation of frames in a network. *Virtual LANs* (VLANs) are the next topic. A VLAN methodology allows a single LAN to be partitioned into several seemingly and virtually separate LANs. At the end of the chapter, a reader can see an overview of wireless local area networks including WiFi, and wireless LANs and associated standards such as IEEE 802.11.

- **Chapter 5, Wide-Area Routing and Internetworking**, focuses on routing in wide area networks (WANs) and introduces related routing algorithms and protocols. We begin the chapter with some IP packet format and basic routing policies such as the *Internet Control Message Protocol* (ICMP), *Dynamic Host Configuration Protocol* (DHCP), and *Network Address Translation* (NAT). We then proceed to explain path selection algorithms such as the *Open Shortest Path First* (OSPF) protocol, and the *Routing Information Protocol* (RIP) followed by the interdomain routing protocols with a focus on the *Border Gateway Protocol* (BGP) covering both internal BGP (iBGP) and external BGP (eBGP). The chapter then presents IPv6 and its packet format. The chapter finally covers congestion-control algorithms at the network layer: *network-congestion control* and *link-flow control*, and especially looks at *random early detection* for congestion control and describes a useful technique to estimate the link-blocking probability.
- **Chapter 6, Multicast Routing and Protocols**, covers the multicast extension of routing protocols in the Internet. First, the chapter defines basic terms and algorithms: multicast group, multicast addresses, and multicast tree algorithms, which form the next set of foundations for understanding packet multicast in the Internet. Two main classes of protocols are discussed: *intradomain* multicast routing protocols, by which packets are multicast within a domain; and *interdomain* routing protocol, by which packet multicast among domains is managed.
- **Chapter 7, Wireless Wide Area Networks and LTE Technology**, presents the basics of wireless wide area networking. The chapter discusses challenges in designing a wireless network: *management of mobility*, *network reliability*, and *frequency reuse*. The chapter then shifts to cellular networks, one of the main backbones of our wireless wide area networking infrastructure. The *mobile IP* in cellular networks is then presented, in which a mobile user can make a data connection while changing its location. The chapter then focuses on *wireless mesh networks* (WMNs). Finally, the chapter proceeds to the presentation of the fourth-generation wireless wide area networks called *Long-Term Evolution* (LTE).

- **Chapter 8, Transport and End-to-End Protocols**, first looks at the basics of the *transport layer* and demonstrates how a simple file is transferred. This layer handles the details of data transmission. Several techniques for Transmission Control Protocol (TCP) congestion control are discussed. Next, *congestion-avoidance* methods, which are methods of using precautionary algorithms to avoid a possible congestion in a TCP session, are presented. The chapter ends with a discussion of methods of congestion control.
- **Chapter 9, Basic Network Applications and Management**, presents the fundamentals of the *application layer*, which determines how a specific user application should use a network. Among the applications are the *Domain Name System* (DNS); *e-mail protocols*, such as SMTP and Webmail, the *World Wide Web* (WWW), remote login, File Transfer Protocol (FTP), and *peer-to-peer* (P2P) networking. Finally, the chapter proceeds to the presentation of network management techniques and protocol.
- **Chapter 10, Network Security**, focuses on security aspects of networks. After introducing network threats, hackers, and attacks, this chapter discusses *cryptography techniques: public- and symmetric-key protocols, encryption standards, key-exchange algorithms, authentication methods, digital signature* and secure connections, firewalls, IPsec, and security methods for virtual private networks. This chapter also covers some security aspects of wireless networks.
- **Chapter 11, Network Queues and Delay Analysis**, begins Part II of the book by discussing how packets are queued in buffers. Basic modeling theorems are presented such as *Little's theorem*, the *Markov chain theorem*, and *birth and death processes*. Queueing-node models are presented with several scenarios: finite versus infinite queueing capacity, one server versus several servers, and Markovian versus non-Markovian systems. Non-Markovian models are essential for many network applications, as multimedia traffic cannot be modeled by Markovian patterns. In addition, delay analysis, based on networks of queues, is discussed. *Burke's theorem* is applied in both serial and parallel queueing nodes. *Jackson's theorem* is presented for situations in which a packet visits a particular queue more than once, resulting in *loops* or *feedback*.
- **Chapter 12, Advanced Router and Switch Architectures**, looks inside structures of advanced Internet devices such as switches and routers. The chapter begins with general characteristics and block diagrams of switches and routers followed by basic features of *input port processors* (IPPs) and *output port processors* (OPPs) as the interfacing processors to central controllers and switch fabrics.

The details of IPPs and OPPs with several regular IP and IPv6 examples for building blocks such as routing tables, packet parsers, and packet partitioners are presented. A number of switch fabric structures are introduced starting with the building block of *crossbar* switch fabric. In particular, a case study at the end of chapter combines a number of buffered crosspoints to form a buffered crossbar. A number of other switch architectures—both blocking and nonblocking, as well as shared-memory, *concentration-based*, and *expansion-based* switching networks—are presented. The chapter also introduces packet multicast techniques and algorithms used within the hardware of switches and routers.

- **Chapter 13, Quality of Service and Scheduling in Routers**, covers quality-of-service issues in networking. The two broad categories of QoS discussed are the *integrated services approach*, for providing service quality to networks that require maintaining certain features in switching nodes; and the *differentiated services approach* (DiffServ), which is based on providing quality-of-service support to a broad class of applications. These two categories include a number of QoS protocols and architectures, such as *traffic shaping*, *admission control*, *packet scheduling*, *reservation methods*, the *Resource Reservation Protocol* (RSVP), and traffic conditioner and bandwidth broker methods. This chapter also explains fundamentals of resource allocation in data networks.
- **Chapter 14, Tunneling, VPNs, and MPLS Networks**, starts by introducing a useful Internet technique called *tunneling*, used in advanced, secured, and high-speed networking. The chapter explains how networks can be *tunneled* to result in *virtual private networks* (VPNs) by which a private-sector entity tunnels over the public networking infrastructure, maintaining private connections. Another related topic in this chapter is *multiprotocol label switching* (MPLS) networks, in which networks use labels and tunnels to expedite routing.
- **Chapter 15, All-Optical Networks, WDM, and GMPLS**, presents principles of fiber-optic communications and all-optical switching and networking. The optical communication technology uses principles of light emission in a glass medium, which can carry more information over longer distances than electrical signals can carry in a copper or coaxial medium. The discussion on optical networks starts with basic optical devices, such as *optical filters*, *wavelength-division multiplexers* (WDMs), *optical switches*, and *optical buffers* and *optical delay lines*. After detailing optical networks using routing devices, the chapter discusses *wavelength reuse and allocation* as a link in all-optical networks.

Generalized multiprotocol label switching (GMPLS) technology, which is similar to MPLS studied in the previous chapter, is applied to optical networks and is also studied in this chapter. The chapter ends with a case study on an optical switching network, presenting a new topology: the *spherical switching network* (SSN).

- **Chapter 16, Cloud Computing and Network Virtualization**, covers basics of cloud computing, large data centers, networking segments of data centers, and virtualization in networking. Data center and cloud computing architectures continue to target support for tens of thousands of servers, massive data storage, terabits per second of traffic, and tens of thousands of tenants. First, the chapter defines basic terms such as *virtualization*, *virtual machines*, and the structure of large data centers constructed from server racks and large data bases. The chapter also presents *data center networks* (DCNs). In a data center, server and storage resources are interconnected with packet switches and routers to construct the DCN.
- **Chapter 17, Software-Defined Networking (SDN) and Beyond,** covers primarily advanced paradigms in control and management of networks. Growth at the infrastructure and applications of the Internet causes profound changes in the technology ecosystems of Internet-related industries. *Software-Defined Networking* (SDN) is a networking paradigm by which a central software program known as “controller” (or SDN controller) determines and controls the overall network behavior resulting in potential improvement in the network performance. This chapter focuses on the fundamentals of SDN and a couple of other alternative innovative networking features, and describes the details of related topics such as OpenFlow switches and flow tables in switches. Protocols such as *network functions virtualization* (NFV) and *Information-Centric Networking* (ICN) are other advanced network control and management topics covered in this chapter. Finally, the chapter concludes with a section that presents network emulators such as the Mininet emulator.
- **Chapter 18, Voice over IP (VoIP) Signaling**, presents the signaling protocols used in voice over IP (VoIP) telephony and multimedia networking. The chapter starts with reviewing the basics of call control and signaling in the traditional Public Switched Telephone Network (PSTN). The chapter then presents two important voice over IP (VoIP) protocols designed to provide real-time service to the Internet, the *Session Initiation Protocol* (SIP) and the *H.323 series*

of protocols. At the end of the chapter, a reader can find presentations on a series of internetworking examples between a set of callers, each supplied through a different Internet service provider and a different protocol.

- **Chapter 19, Media Exchange and Voice/Video Compression**, focuses on data-compression techniques for voice and video to prepare digital voice and video for multimedia networking. The chapter starts with the analysis of information-source fundamentals, source coding, and limits of data compression, and explains all the steps of the conversion from raw voice to compressed binary form, such as sampling, quantization, and encoding. The chapter also summarizes the limits of compression and explains typical processes of still-image and video-compression techniques, such as JPEG, MPEG, and MP3.
- **Chapter 20, Distributed and Cloud-Based Multimedia Networking**, presents the transport of real-time voice, video, and data in multimedia networking. The chapter first presents protocols designed to provide real-time transport, such as the *Real-time Transport Protocol* (RTP). Also discussed are the *HTTP-based streaming* which is a reliable TCP-based streaming, and the *Stream Control Transmission Protocol* (SCTP), which provides a general-purpose transport protocol for transporting stream traffic. The next topic is streaming video using *content distribution (delivery) networks* (CDNs). We then present *Internet Protocol television* (IPTV). IPTV is a system through which television services are delivered using the Internet. *Video on demand* (VoD) as a unique feature of IPTV is also described in this chapter. Next, cloud-based multimedia networking is introduced. This type of networking consists of distributed and networked services of voice, video, and data. For example, voice over IP (VoIP), video streaming, or *interactive voice response* (IVR) for recognizing human voice, can be distributed in various clouds of services. The chapter ends with detailed streaming source modeling using self-similarity analysis.
- **Chapter 21, Mobile Ad-Hoc Networks**, presents a special type of wireless network, known as a *mobile ad-hoc network* (MANET). Ad-hoc networks do not need any fixed infrastructure to operate and they support dynamic topology scenarios where no wired infrastructure exists. The chapter explains how a mobile user can act as a routing node and how a packet is routed from a source to its destination without having any static router in the network. The chapter also discusses *table-driven routing protocols* such as DSDV, CGSR, and WRP, and also *source-initiated routing protocols*, as well as DSR, ABR, TORA, and AODV. At the end of the chapter, we discuss the security of ad-hoc networks.

- **Chapter 22, Wireless Sensor Networks**, presents an overview of such sensor networks and describes intelligent sensor nodes, as well as an overview of a protocol stack for sensor networks. The chapter explains how the "power" factor distinguishes the routing protocols of sensor networks from those of computer networks and describes *clustering protocols* in sensor networks. These protocols specify the topology of the hierarchical network partitioned into nonoverlapping *clusters* of sensor nodes. The chapter also presents a typical routing protocol for sensor networks, leading to a detailed numerical case study on the implementation of a clustering protocol. This chapter ends with *ZigBee technology*, based on IEEE standard 802.15.4. This technology uses low-power nodes and is a well-known low-power standard.

Exercises and Computer Simulation Projects

A number of exercises are given at the end of each chapter. The exercises normally challenge readers to find the directions to solutions in that chapter. The answers to the exercises may be more elusive, but this is typical of real and applied problems in networking. These problems encourage the reader to go back through the text and pick out what the instructor believes is significant.

Besides typical exercises, there are numerous occasions for those who wish to incorporate projects into their courses. The computer simulation projects are normally meant to be a programming project but the reader can use a simulation tool of choice to complete a project. Projects listed at the end of a chapter range from computer simulations to partial incorporation of hardware design in a simulation.

Appendixes

The book's appendixes make it essentially self-sufficient. **Appendix A, Glossary of Acronyms**, defines acronyms. **Appendix B, RFCs**, encourages readers to delve more deeply into each protocol presented in the book by consulting the many requests for comments (RFCs) references. **Appendix C, Probabilities and Stochastic Processes**, reviews probabilities, random variables, and random processes. **Appendix D, Erlang-B Blocking Probability Table,** provides a numerically expanded version of the Erlang-B formula presented in Chapter 11. This table can be used in various chapters to estimate traffic blocking, which is one of the main factors in designing a computer network.

Instructions and Instructor Supplements

This textbook can be used in a variety of ways. An instructor can use Part I of the book for the first graduate or a senior undergraduate course in networking. Part II of the text is aimed at advanced graduate courses in computer networks. An instructor can choose the desired chapters, depending on the need and the content of the course. The following guidelines suggest the adoption of chapters for five different courses:

- *First undergraduate course in Computer Networking:* Chapters 1, 2, 3, 4, and 5 and another chapter such as part of Chapter 6, 7, 8, or 9.
- *First graduate course in Computer Networking:* Chapters 1 through 10 with less emphasis on Chapters 1 and 2.
- *Second graduate course in Advanced Computer Networking:* Chapters 11 through 17.
- *Graduate course in Convergent Data, Voice and Video over IP:* Chapters 7, 9, 16, 18, 19, and 20.
- *Graduate course in Wireless Networking:* Chapters 2, 3, 4, 7, 9, 16, 21, and 22, and other wireless network examples presented in various chapters such the wireless VoIP signaling covered in Chapter 18.

An instructor's solutions manual and other instructional material, such as PowerPoint presentations, will be available to instructors. Instructors should go to Pearson's Instructor Resource Center (http://www.pearsonhighered.com/educator/profile/ircHomeTab.page) for access to ancillary instructional materials.

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Please feel free to send me any feedback at the Department of Electrical Engineering, Charles W. Davidson College of Engineering, San Jose State University, San Jose, California 95192, U.S.A., or via e-mail at nader.mir@sjsu.edu. I would love to hear from you, especially if you have suggestions for improving this book. I will carefully read all review comments. You can find out more about me at www.engr.sjsu.edu/nmir. I hope that you enjoy the text and that you receive from it a little of my enthusiasm for computer communications and networks.

—Nader F. Mir
San Jose, California

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Nader F. Mir received the B.Sc. degree (with honors) in electrical engineering in 1985, and the M.Sc. and Ph.D. degrees, both in electrical engineering, from Washington University in St. Louis, Missouri, in 1990 and 1995, respectively.

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Dr. Mir is internationally known through his research and scholarly work, and has been invited to speak at a number of major international conferences. He has published more than 100 refereed technical journal and conference articles, all in the field of communications and computer networking. This textbook is now a worldwide adopted university textbook and has been translated into several languages, such as Chinese.

He was granted a successful U.S. Patent (Patent 7,012,895 B1), claiming an invention related to hardware/protocol for use in high-speed computer communication networks.

Dr. Mir has received a number of prestigious national and university awards and research grants. He is the recipient of a university teaching award and also a university research excellence award. He is also the recipient of a number of outstanding presentation awards from leading international conferences.

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Prior to his current position, he was an associate professor at his current school, and assistant professor at University of Kentucky in Lexington. From 1994 to 1996, he was a research scientist at the Advanced Telecommunications Institute, Stevens Institute of Technology in New Jersey, working on the design of advanced communication systems and high-speed computer networks. From 1990 to 1994, he was with the Computer and Communications Research Center at Washington University in St. Louis and worked as a research assistant on the design and analysis of a high-speed switching systems project. From 1985 to 1988, he was with Telecommunication Research & Development Center (TRDC), Surrey, and as a telecommunications system research and development engineer, participated in the design of a high-speed digital telephone Private Branch Exchange (PBX), and received the best "design/idea" award.

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CHAPTER 1

Packet-Switched Networks

Computer and communication networks provide a wide range of services, from simple networks of computers to remote-file access to digital libraries, voice over IP (VoIP), Internet gaming, cloud computing, video streaming and conferencing, television over Internet, wireless data communication, and networking billions of users and devices. Before exploring the world of computer and communication networks, we need to study the fundamentals of *packet-switched networks* as the first step. Packet-switched networks are the backbone of the data communication infrastructure. Therefore, our focus in this chapter is on the big picture and the conceptual aspects of this backbone highlighted as:

- *Basic definitions in networks*
- *Types of packet-switched networks*
- *Packet size and optimizations*
- *Foundation of networking protocols*
- *Addressing scheme in the Internet*
- *Equal-sized packet model*

We start with the basic definitions and fundamental concepts, such as *messages*, *packets*, and *frames*, and *packet switching* versus *circuit switching*. We learn what the Internet is and how Internet service providers (ISPs) are formed. We then proceed to types of packet-switched networks and how a message can be handled by either *connection-oriented networks* or *connectionless networks*. Because readers must get a good understanding of *packets* as data units, packet size and optimizations are also discussed.

We next briefly describe specific type of networks used in the Internet. Users and networks are connected together by certain rules called *protocols*. The Internet Protocol (IP), for example, is responsible for using prevailing rules to establish paths for packets. Protocols are represented by either the TCP/IP model or the OSI model. The *five-layer TCP/IP model* is a widely accepted Internet backbone protocol structure. In this chapter, we give an overview of these five layers and leave any further details to be discussed in the remaining chapters. Among these five layers, the basics of IP *packets and network addressing* are designated a separate section in this chapter, entitled IP Packets and Addressing. We make this arrangement because basic definitions related to this layer are required in the following few chapters.

As numerous protocols can be combined to enable the movement of packets, the explanation of all other protocols will be spread over almost all upcoming chapters. In the meantime, the reader is cautiously reminded that getting a good grasp of the fundamental material discussed in this chapter is essential for following the details or extensions described in the remainder of the book. At the end of this chapter, the *equal-sized packet protocol model* is briefly introduced.

1.1 Basic Definitions in Networks

Communication networks have become essential media for homes and businesses. The design of modern computer and communication networks must meet all the requirements for new communication applications. A ubiquitous *broadband network* is the goal of the networking industry. Communication services need to be available anywhere and anytime. The broadband network is required to support the exchange of multiple types of information, such as voice, video, and data, among multiple types of users, while satisfying the performance requirement of each individual application. Consequently, the expanding diversity of high-bandwidth communication applications calls for a unified, flexible, and efficient network. The design goal of modern communication networks is to meet all the networking demands and to integrate capabilities of networks in a broadband network.

Packet-switched networks are the building blocks of computer communication systems in which data units known as *packets* flow across networks. The goal of a broadband packet-switched network is to provide flexible communication in handling all kinds of connections for a wide range of applications, such as telephone calls, data transfer, teleconferencing, video broadcasting, and distributed data processing. One obvious example for the form of traffic is *multi-rate* connections, whereby traffic containing several different bit rates flows to a communication node. The form of information in packet-switched networks is always digital bits. This kind of communication infrastructure is a significant improvement over the traditional telephone networks known as *circuit-switched networks*.

1.1.1 Packet Switching Versus Circuit Switching

Circuit-switched networks, as the basis of conventional telephone systems, were the only existing personal communication infrastructures prior to the invention of packet-switched networks. In the new communication structure, voice and computer data are treated the same, and both are handled in a unified network known as a packet-switched network, or simply an integrated data network. In conventional telephone networks, a circuit between two users must be established for communication to occur. Circuit-switched networks require resources to be reserved for each pair of end users. This implies that no other users can use the already dedicated resources for the duration of network use and thus the reservation of network resources for each user may result in inefficient use of available bandwidth.

Packet-switched networks with a unified, integrated data network infrastructure collectively known as the *Internet* can provide a variety of communication services requiring different bandwidths. The advantage of having a unified, integrated data network is the flexibility to handle existing and future services with remarkably better performance and higher economical resource utilizations. An integrated data network can also derive the benefits of central network management, operation, and maintenance. Numerous requirements for integrated packet-switched networks are explored in later chapters:

- Having robust routing protocols capable of adapting to dynamic changes in network topology
- Maximizing the utilization of network resources for the integration of all types of services

- Providing quality of service to users by means of priority and scheduling
- Enforcing effective congestion-control mechanisms that can minimize dropping packets

Circuit-switched networking is preferred for real-time applications. However, the use of packet-switched networks, especially for the integration and transmission of voice and data, results in the far more efficient utilization of available bandwidth. Network resources can be shared among other eligible users. Packet-switched networks can span a large geographical area and comprise a web of switching *nodes* interconnected through transmission links. A network provides links among multiple users facilitating the transfer of information. To make efficient use of available resources, packet-switched networks dynamically allocate resources only when required.

1.1.2 Data, Packets, and Frames

A packet-switched network is organized as a multilevel hierarchy. In such a network, digital data are fragmented into one or more smaller units of data, each appended with a *header* to specify control information, such as the source and the destination addresses, while the remaining portion carries the actual data, called the *payload*. This new unit of formatted message is called a *packet*, as shown in Figure 1.1. Packets are forwarded to a data network to be delivered to their destinations. In some circumstances, packets may also be required to be attached together or further partitioned, forming a new packet having a new header. One example of such a packet is referred to as *frame*. Sometimes, a frame may be required to have more than one header to carry out additional tasks in multiple layers of a network.

As shown in Figure 1.2, two packets, A and B, are being forwarded from one side of a network to the other side. Packet-switched networks can be viewed from

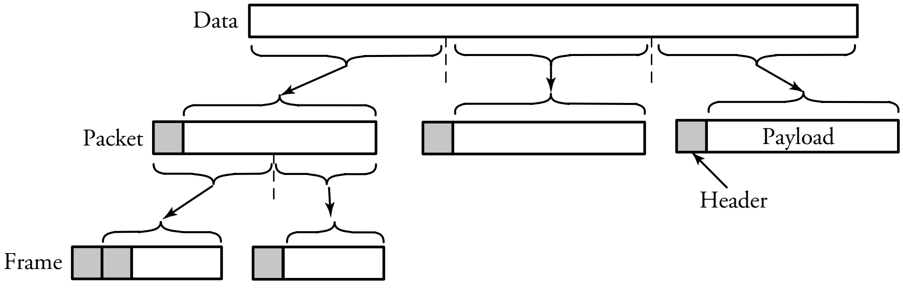


Figure 1.1 Creating packets and frames out of a raw digital data

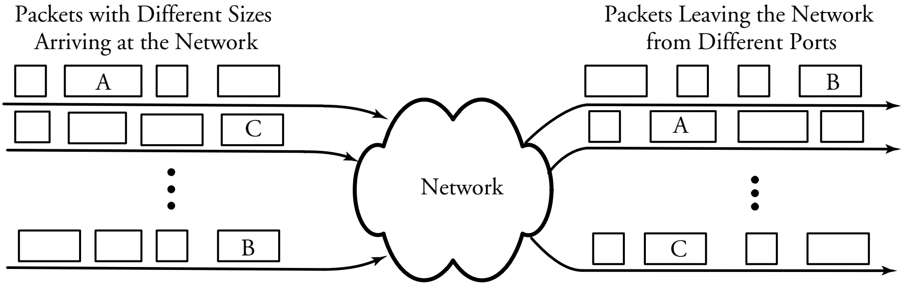


Figure 1.2 A packet-switched network receiving various-sized packets to route out

either an external or an internal perspective. The external perspective focuses on the network services provided to the upper layers; the internal perspective focuses on the fundamentals of *network topology*, the structure of communication protocols, and addressing schemes.

A single packet may even be split into multiple smaller packets before transmission. This well-known technique is called *packet fragmentation*. Apart from measuring the delay and ensuring that a packet is correctly sent to its destination, we also focus on delivering and receiving packets in a correct sequence when the data is fragmented. The primary function of a network is directing the flow of data among the users.

1.1.3 The Internet and ISPs

The *Internet* is the collection of hardware and software components that make up our global communication network. The Internet is indeed a collaboration of interconnected communication vehicles that can network all connected communicating devices and equipment and provide services to all distributed applications. It is almost impossible to plot an exact representation of the Internet, since it is continuously being expanded or altered. One way of imagining the Internet is shown in Figure 1.3, which illustrates a big-picture view of the worldwide computer network.

To connect to the Internet, users need the services of an *Internet service provider* (ISP). ISPs consist of various networking devices. One of the most essential networking devices is a *router*. Routers are network "nodes" that can operate to collectively form a network and to also connect ISPs together. Routers contain information about the network routes, and their tasks are to route packets to requested destinations.

Users, networking devices, and servers are connected together by communication *links*. Routers operate on the basis of one or more common *routing protocols*. In

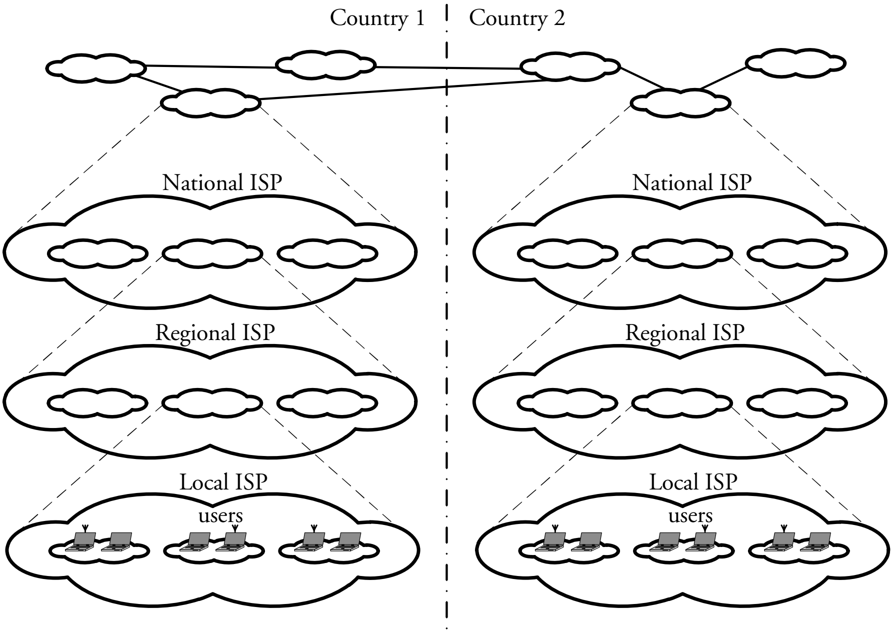


Figure 1.3 The Internet, a global interconnected network

computer networks, the entities must agree on a protocol, a set of rules governing data communications and defining when and how two users can communicate with each other. Each country has three types of ISPs:

- *National* ISPs
- *Regional* ISPs
- *Local* ISPs

At the top of the Internet hierarchy, national ISPs connect nations or provinces together. The traffic between each two national ISPs is very heavy. Two ISPs are connected together through complex switching nodes called *border routers* (or gateway routers). Each border router has its own system administrator. In contrast, *regional* ISPs are smaller ISPs connected to a national ISP in a hierarchical chart. Each regional ISP can give services to part of a province or a city. The lowest networking entity of the Internet is a local ISP. A local ISP is connected to a regional ISP or directly to a national service provider and provides a direct service to end users called *hosts*. An organization that supplies services to its own employees can also be a local ISP.

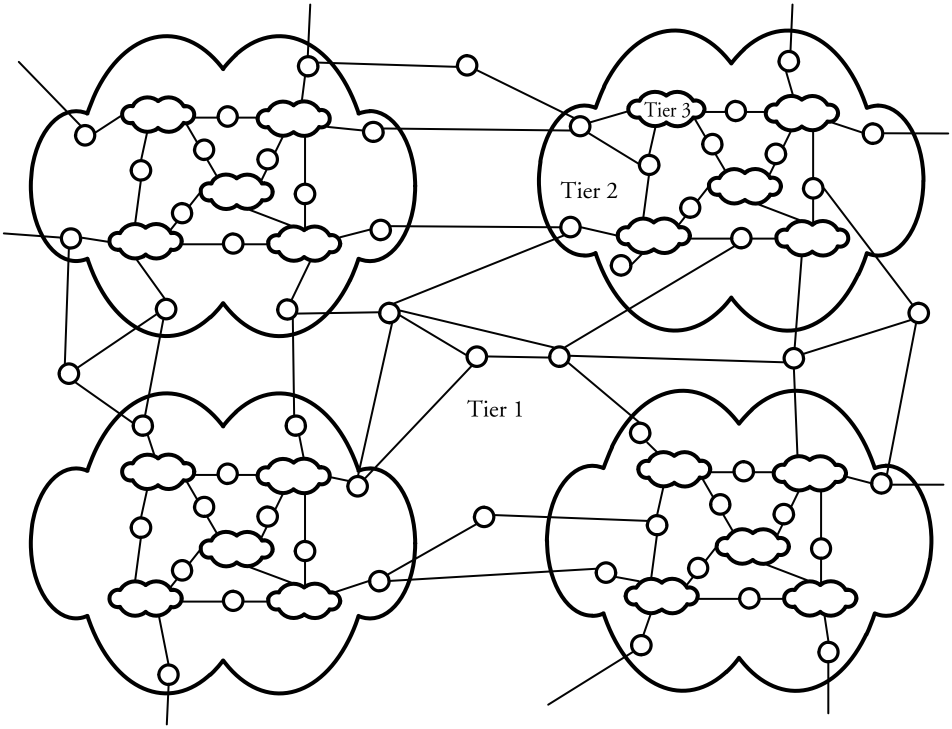


Figure 1.4 Hierarchy of networks from a different angle

Figure 1.4 illustrates a different perspective of the global interconnected network. Imagine the global network in a hierarchical structure. Each ISP of a certain hierarchy or tier manages a number of other network domains at its lower hierarchy. The structure of such networks resembles the hierarchy of nature from the universe to atoms and molecules. Here, Tier 1, Tier 2, and Tier 3 represent, respectively, a national ISP, a regional ISP, and a local ISP.

1.1.4 Classification of ISPs

In most cases, a separate network managed by a network administrator is known as a *domain*, or an *autonomous system*. A domain is shown by a cloud in this book. Figure 1.5 shows several domains. An autonomous system can be administered by an *Internet service provider* (ISP). An ISP provides Internet access to its users. Networks under management of ISPs can be classified into two main categories: *wide area networks* (WANs) and *local area networks* (LANs). A wide area network can be as large as the entire infrastructure of the data network access system known as the Internet.

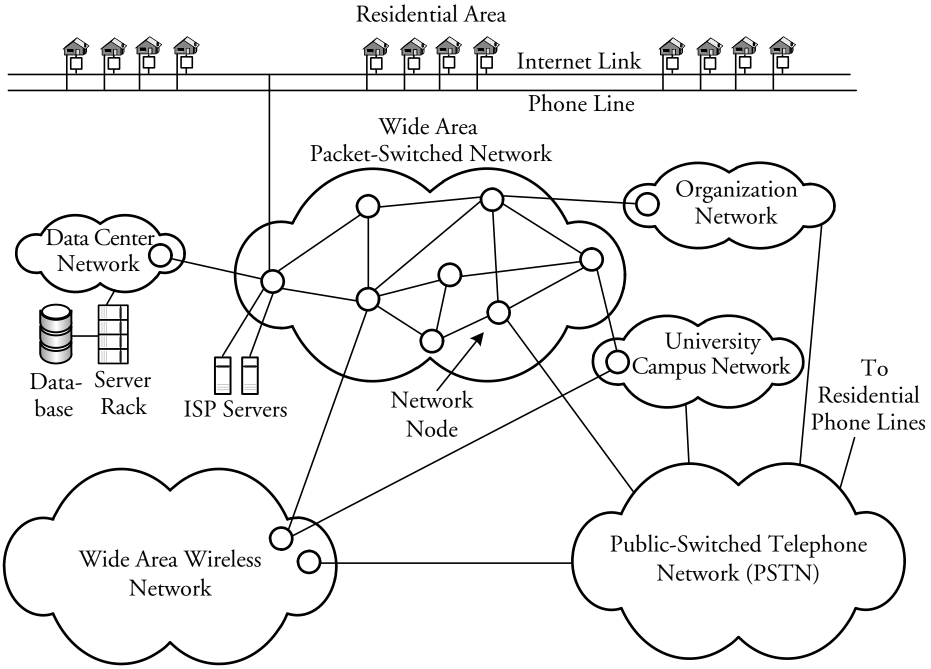


Figure 1.5 Overview of various types of Internet service providers (ISPs)

A communication network can also be of wireless type both at LAN or WAN scales. We refer to such networks as *wireless networks*.

Figure 1.5 shows several major WANs each connected to several smaller networks such as a university campus network. Depending on the size of the network, a smaller network can be classified as a LAN or as a WAN. The major WANs are somehow connected together to provide the best and fastest communication for customers. One of the WANs is a wide area wireless network that connects wireless or mobile users to destination users. We notice that aggregated traffic coming from wireless equipment such as smartphone and a mobile laptop in the wide area wireless network is forwarded to a link directed from a major node. The other WAN is the telephone network known as *public-switched telephone network* (PSTN) that provides telephone services.

As an example of the local area network, a university campus network is connected to the Internet via a router that connects the campus to an Internet service provider. ISP users from a residential area are also connected to an access point router of the wide area ISP, as seen in the figure. Service providers have varying policies to overcome the problem of bandwidth allocations on routers. An ISP's *routing server* is conversant with the policies of all other service providers. Therefore, the "ISP server" can direct the received routing information to an appropriate part of the ISP. Finally, on the left side of Figure 1.5, we see the *data center network* connected to the wide area packet-switched network. Cloud computing data centers contain databases and racks of servers that provide brilliant data processing services; these are discussed in detail in Chapter 16.

Network nodes (devices) such as *routers* are key components that allow the flow of information to be switched over other links. When a link failure occurs in a packet-switched network, the neighboring routers share the fault information with other nodes, resulting in updating of the routing tables. Thus, packets may get routed through alternative paths bypassing the fault. Building the *routing table* in a router is one of the principal challenges of packet-switched networks. Designing the routing table for large networks requires maintaining data pertaining to traffic patterns and network topology information.

1.2 Types of Packet-Switched Networks

Packet-switched networks are classified as *connectionless networks* and *connection-oriented networks*, depending on the technique used for transferring information. The simplest form of a network service is based on the connectionless protocol that does not require a call setup prior to transmission of packets. A related, though more complex, service is the connection-oriented protocol in which packets are transferred through an established virtual circuit between a source and a destination.

1.2.1 Connectionless Networks

Connectionless networks, or datagram networks, achieve high throughput at the cost of additional queuing delay. In this networking approach, a large piece of data is normally fragmented into smaller pieces, and then each piece of data is encapsulated into a certain "formatted" header, resulting in the basic Internet transmission packet, or *datagram*. We interchangeably use packets and datagrams for connectionless networks. Packets from a source are routed independently of one another. In this type of network, a user can transmit a packet anytime, without notifying the network layer. A packet is then sent over the network, with each router receiving the packet forwarding it to the best router it knows, until the packet reaches the destination.

The connectionless networking approach does not require a call setup to transfer packets, but it has error-detection capability. The main advantage of this scheme is its capability to route packets through an alternative path in case a fault is present on the desired transmission link. On the flip side, since packets belonging to the same source may be routed independently over different paths, the packets may arrive out of sequence; in such a case, the misordered packets are resequenced and delivered to the destination.

Figure 1.6 (a) shows the routing of three packets, packets 1, 2, and 3, in a connectionless network from point A to point B. The packets traverse the intermediate nodes in a *store-and-forward* fashion, whereby packets are received and stored at a node on a route; when the desired output port of the node is free for that packet, the output is forwarded to its next node. In other words, on receipt of a packet at a node, the packet must wait in a queue for its turn to be transmitted. Nevertheless, packet loss may still occur if a node's buffer becomes full. The node determines the next hop read from the packet header. In this figure, the first two packets are moving along the path A, D, C, and B, whereas the third packet moves on a separate path, owing to congestion on path A–D.

The delay model of the first three packets discussed earlier is shown in Figure 1.7. The total transmission delay for a message three packets long traversing from the source node A to the destination node B can be approximately determined. Let t_p be the propagation delay between each of the two nodes, t_f be the time it takes to inject a packet onto a link, and t_r be the total processing delay for all packets at each node. A packet is processed once it is received at a node. The total transmission delay, D_p for n_h nodes and n_p packets, in general is

$$D_p = [n_p + (n_h - 2)]t_f + (n_h - 1)t_p + n_h t_r. \tag{1.1}$$

In this equation, t_r includes a certain crucial delay component, primarily known as the *packet-queueing delay* plus some delay due to route finding for it. At this point,

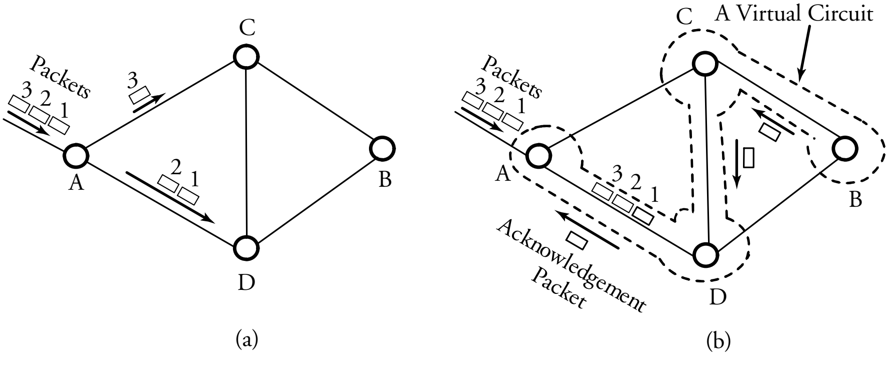


Figure 1.6 Two models of packet-switched networks: (a) a connectionless network and (b) a connection-oriented network

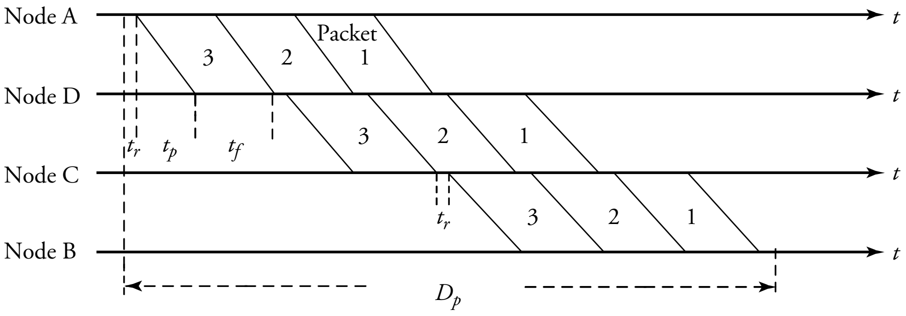


Figure 1.7 Signaling delay in a connectionless network

we focus only on t_p and t_f, assume t_r is known or given, and will discuss the queueing delay and all components of t_r in later chapters, especially in Chapter 11.

Example. Figure 1.7 shows a timing diagram for the transmission of three (instead of two) packets on path A, D, C, B in Figure 1.6(a). Determine the total delay for transferring these three packets from node A to node B.

Solution. Assume that the first packet is transmitted from the source, node A, to the next hop, node D. The total delay for this transfer is $t_p + t_f + t_r$. Next, the packet is similarly transferred from node D to the next node to ultimately reach node B. The delay for each of these jumps is also $t_p + t_f + t_r$. However, when all three packets are released from node A, multiple and simultaneous transmissions of packets become possible. This means, for example, while packet 2 is being processed at node A, packet 3 is processed at node D. Figure 1.7 clearly shows this parallel processing of packets. Thus, the total delay for all three packets to traverse the source and destination via two intermediate nodes is $D_p = 3t_p + 5t_f + 4t_r$.

Connectionless networks demonstrate the efficiency of transmitting a large message as a whole, especially in noisy environments, where the error rate is high. It is obvious that the large message should be split into packets. Doing so also helps reduce the maximum delay imposed by a single packet on other packets. In fact, this realization resulted in the advent of connectionless packet switching.

1.2.2 Connection-Oriented Networks

In *connection-oriented networks*, or *virtual-circuit networks*, a route setup between a source and a destination is required prior to data transfer, as in the case of conventional telephone networks. In this networking scheme, once a connection or a path is initially set up, network resources are reserved for the communication duration, and all packets belonging to the same source are routed over the established connection. After the communication between a source and a destination is finished, the connection is terminated using a connection-termination procedure. During the call setup, the network can offer a selection of options, such as best-effort service, reliable service, guaranteed delay service, and guaranteed bandwidth service, as explained in various sections of upcoming chapters.

Figure 1.6 (b) shows a connection-oriented - network. The connection set-up procedure shown in this figure requires three packets to move along path A, D, C, and B with a prior connection establishment. During the connection set-up process, a virtual path is dedicated, and the forwarding routing tables are updated at each node in the route. Figure 1.6 (b) also shows acknowledgement packets in connection-oriented networks initiated from destination node B to source node A to acknowledge the receipt of previously sent packets to source node. The acknowledgement mechanism is not typically used in connectionless networks. Connection-oriented packet switching typically reserves the network resources, such as the buffer capacity and the link bandwidth, to provide guaranteed quality of service and delay. The main disadvantage in connection-oriented packet-switched networks is that in case of a link or switch failure, the call set-up process has to be repeated for all the affected routes. Also, each switch needs to store information about all the flows routed through the switch.

The total delay in transmitting a packet in connection-oriented packet switching is the sum of the connection set-up time and the data-transfer time. The data-transfer time is the same as the delay obtained in connectionless packet switching. Figure 1.8 shows the overall delay for the three packets presented in the previous example. The transmission of the three packets starts with *connection request packets* and then

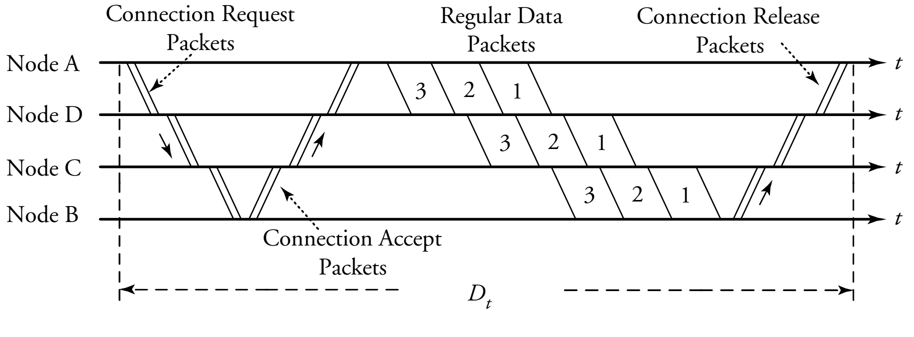

Connection Request Packets
Regular Data Packets
Connection Release Packets
Node A
Node D
Node C
Node B
t
t
t
t
3
2
1
3
2
1
3
2
1
Connection Accept Packets
D_t

Figure 1.8 Signaling delay in a connection-oriented packet-switched network

connection accept packets. At this point, a circuit is established, and a partial path bandwidth is reserved for this connection. Then, the three packets are transmitted. At the end, a *connection release packet* clears and removes the established path.

The estimation of total delay time, D_t, to transmit n_p packets is similar to the one presented for connectionless networks. For connection-oriented networks, the total time consists of two components: D_p, which represents the time to transmit packets, and D_c, which represents the time for the control packets. The control packets' time includes the transmission delay for the connection request packet, the connection accept packet, and the connection release packet:

$$D_t = D_p + D_c. \tag{1.2}$$

Another feature, called *cut-through switching*, can significantly reduce the delay. In this scheme, the packet is forwarded to the next hop as soon as the header is received and the destination is parsed. We see that the delay is reduced to the aggregate of the propagation times for each hop and the transfer time of one hop. This scheme is used in applications in which retransmissions are not necessary. Optical fiber transmission has a very low loss rate and hence uses cut-through switching to reduce the delay in transmitting a packet. We will further explain the concept of cut-through switching and its associated devices in Chapters 2 and 12.

1.3 Packet Size and Optimizations

Packet size has a substantial impact on the performance of data transmission. Consider Figure 1.9, which compares the transmission of a 16-byte message from node A to node B through nodes D and C. Assume that for this transmission we would like to compare the transmission of the message with two different packet

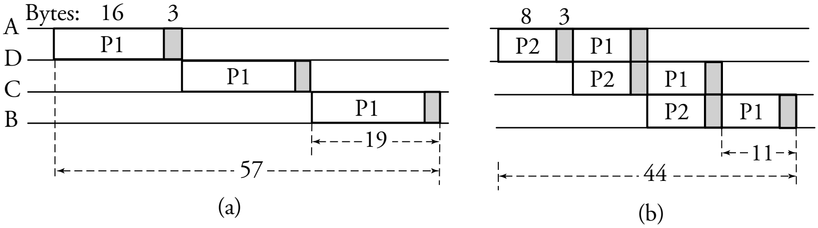


Figure 1.9 Comparison of two cases of transmitting data: (a) using three packets and (b) using six packets

sizes but each requiring the same-size packet header of 3 bytes. In the first scheme shown in part (a) of the figure, the message is converted to a packet, P1, with 16-byte payload and 3-byte header. When the packet is received by node B, a total of 57-byte units have elapsed. If the message is fragmented into two packets, P1 and P2, of 8 bytes each as shown in part (b) of the figure, the total elapsed time becomes 44-byte units of delay.

The reason for the time reduction in the second case is the parallel transmission of two packets at nodes D and C. The parallel transmission of multiple packets can be understood better by referring again to Figure 1.7 or 1.8 in which the times of packets 2 and 1 are coinciding on the times of packets 3 and 2 in nodes D or C. The trend of delay reduction using smaller packets, however, is reversed at a certain point, owing to the dominance of packet overhead when a packet becomes very small.

To analyze packet size optimization, consider a link with a speed of s b/s or a rate of μ packets per second. Assume that packets of size $d + h$ are sent over this link at the rate λ packets per second, where d and h are the sizes of the packet data and the packet header, respectively, in bits. Clearly,

$$\mu = \frac{s}{d + h}. \tag{1.3}$$

We define *link utilization* to be $\rho = \lambda/\mu$. Then the percentage of link utilization used by data, ρ_d, is obtained by

$$\rho_d = \rho \left(\frac{d}{d + h} \right). \tag{1.4}$$

The average delay per packet, D, can be calculated by using $\mu - \lambda$, where this term exhibits how close the offered load is to the link capacity:

$$D = \frac{1}{\mu - \lambda}. \tag{1.5}$$

Using Equations (1.3) and (1.4), we can rewrite the average delay per packet as

$$D = \frac{1}{\mu(1 - \rho)} = \frac{d + h}{s(1 - \rho)} = \frac{d + h}{s\left[1 - \frac{\rho_d}{d}(d + h)\right]}. \tag{1.6}$$

Apparently, the optimum size of a packet depends on several contributing factors. Here, we examine one of the factors by which the delay and the packet size become optimum. For optimality, consider d as one possible variable, where we want

$$\frac{\partial D}{\partial d} = 0. \tag{1.7}$$

This releases the two optimum values (we skip from the detail of derivation):

$$d_{opt} = h\left(\frac{\sqrt{\rho_d}}{1-\sqrt{\rho_d}}\right) \tag{1.8}$$

and

$$D_{opt} = \frac{h}{s}\left(\frac{\sqrt{\rho_d}}{1-\sqrt{\rho_d}}\right)^2. \tag{1.9}$$

Note that here, d_{opt} and D_{opt} are optimized values of d and D, respectively, given only the mentioned variables. The optimality of d and D can also be derived by using a number of other factors that will result in a more accurate approach.

1.4 Foundation of Networking Protocols

As discussed earlier in this chapter, users and networks are connected together by certain rules and regulations called *network communication protocols*. The Internet Protocol (IP), for example, is responsible for using prevailing rules to establish paths for packets. Communication protocols are the intelligence behind the driving force of packets and are tools by which a network designer can easily expand the capability of networks. One growth aspect of computer networking is clearly attributed to the ability to conveniently add new features to networks. New features can be added by connecting more hardware devices, thereby expanding networks. New features can also be added on top of existing hardware, allowing the network features to expand.

Protocols of communication networks are represented by either the TCP/IP model or its older version, the OSI model. The *five-layer TCP/IP model* is a widely accepted Internet backbone protocol structure. In this section, we describe the basics of these five layers and leave further details to be discussed in the remaining chapters.

However, among these five layers, the basics of IP *packets and network addressing* are designated a separate section, 1.5 IP Packets and Addressing. As stated before, we make this arrangement because basic definitions related to this layer are required in the following chapters, mostly in Part I of this book.

1.4.1 Five-Layer TCP/IP Protocol Model

The basic structure of communication networks is represented by the *Transmission Control Protocol/Internet Protocol* (TCP/IP) model. This model is structured in five layers. An end system, an intermediate network node, or each communicating user or program is equipped with devices to run all or some portions of these layers, depending on where the system operates. These five layers, shown in Figure 1.10, are as follows:

1. Physical layer
2. Link layer
3. Network layer
4. Transport layer
5. Application layer

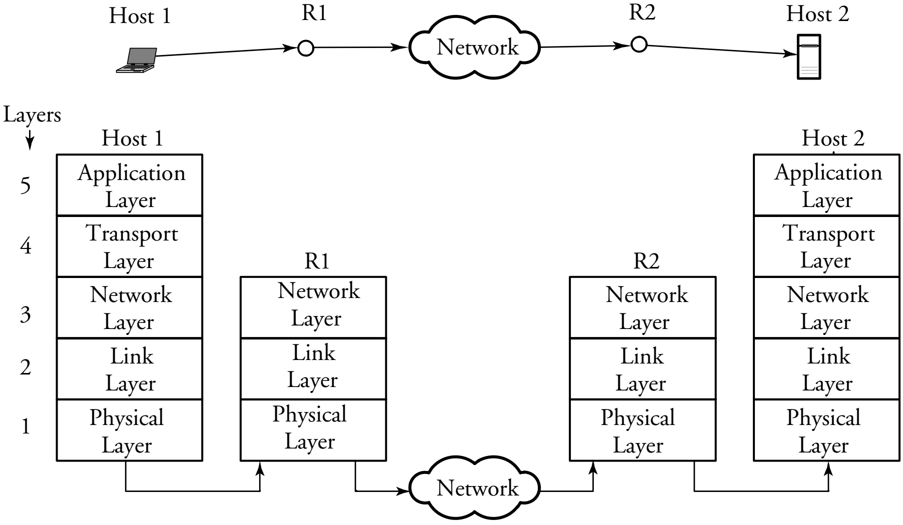


Figure 1.10 Hierarchy of the five-layer communication protocol model

Layer 1, known as the *physical layer*, defines electrical aspects of activating and maintaining physical links in networks. The physical layer represents the basic network hardware. The physical layer also specifies the type of medium used for transmission and the network topology. The details of this layer are explained in later chapters, especially in Chapters 3, 4, 6, 13, 15, 17, and 20.

Layer 2, the *link layer*, provides a reliable synchronization and transfer of information across the physical layer for accessing the transmission medium. Layer 2 specifies how packets access links and are attached to additional headers to form frames when entering a new networking environment, such as a LAN. Layer 2 also provides error detection and flow control. This layer is discussed further in Chapters 3 and 4 and the discussion is extended in almost all other chapters.

Layer 3, the *network layer* (IP) specifies the networking aspects. This layer handles the way that addresses are assigned to packets and the way that packets are supposed to be forwarded from one end point to another. Some related parts of this layer are described in Chapters 5, 6, and 7, and the discussion is extended in other chapters such as Chapters 10, 12, 13, 14, 15, 16, 21, and 22.

Layer 4, the *transport layer*, lies just above the network layer and handles the details of data transmission. Layer 4 is implemented in the end points but not in network routers and acts as an interface protocol between a communicating device and a network. Consequently, this layer provides logical communication between processes running on different hosts. The concept of the transport layer is discussed in Chapter 8, and the discussion is extended in other chapters such as Chapters 9, 14, 17, 18, 20, 21, and 22.

Layer 5, the *application layer*, determines how a specific user application should use a network. Among such applications are the *Simple Mail Transfer Protocol* (SMTP), *File Transfer Protocol* (FTP), and the *World Wide Web* (WWW). The details of layer 5 are described in Chapter 9, and descriptions of other advanced applications such as voice over IP (VoIP) are extended in other chapters such as Chapters 18, 19, and 20.

The transmission of a given message between two users is carried out by (1) flowing the data down through each and all layers of the transmitting end, (2) sending it to certain layers of protocols in the devices between two end points, and (3) when the message arrives at the other end, letting the data flow up through the layers of the receiving end until it reaches its destination.

Hosts

A network *host* is a computing device connected to a computer network and is assigned a network layer address. A host can offer information resources, services, and applications to users or other nodes on the network. Figure 1.10 illustrates a scenario in which different layers of protocols are used to establish a connection between two hosts. A message is transmitted from host 1 to host 2, and, as shown, all five layers of the protocol model participate in making this connection. The data being transmitted from host 1 is passed down through all five layers to reach router R1. Router R1 is located as a gateway to the operating regions of host 1 and therefore does not involve any tasks in layers 4 and 5. The same scenario is applied at the other end: router R2. Similarly, router R2, acting as a gateway to the operating regions of host 2, does not involve any tasks in layers 4 and 5. Finally at host 2, the data is transmitted upward from the physical layer to the application layer.

The main idea of the communication protocol stack is that the process of communication between two end points in a network can be partitioned into layers, with each layer adding its own set of special related functions. Figure 1.11 shows a different way of realizing protocol layers used for two hosts communicating through two routers. This figure illustrates a structural perspective of a communication setup and identifies the order of fundamental protocol layers involved.

1.4.2 Seven-Layer OSI Model

The *open systems interconnection* (OSI) model was the original standard description for how messages should be transmitted between any two points. To the five TCP/IP layers, OSI adds the following two layers below the application layer:

1. *Layer 5*, the *session layer*, which sets up and coordinates the applications at each end
2. *Layer 6* the *presentation layer*, which is the operating system part that converts incoming and outgoing data from one presentation format to another

The tasks of these two additional layers are dissolved into the application and transport layers in the newer five-layer TCP/IP model. The OSI model is becoming less popular. TCP/IP is gaining more attention, owing to its stability and its ability to offer better communication performance. Therefore, this book focuses on the five-layer model.

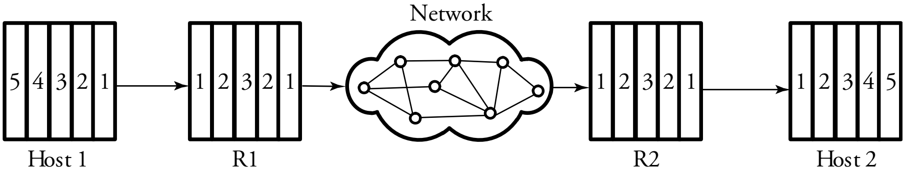


Figure 1.11 Structural view of protocol layers for two hosts communicating through two routers

1.5 Addressing Scheme in the Internet

An addressing scheme is clearly a requirement for communications in a computer network. With an addressing scheme, packets are forwarded from one location to another. Each of the three layers, 2, 3, and 4, of the TCP/IP protocol stack model produces a header, as indicated in Figure 1.12. In this figure, host 1 communicates with host 2 through a network of seven nodes, R1 through R7, and a payload of data encapsulated in a frame by the link layer header, the network layer header, and the transport layer header is carried over a link. Within any of these three headers, each source or destination is assigned an address as identification for the corresponding protocol layer. The three types of addresses are summarized as follows.

- *Link layer (layer 2) address.* A 6-byte (48-bit) field called Media Access Control (MAC) address that is represented by a 6-field hexadecimal number, such as 89-A1-33-2B-C3-84, in which each field is two bytes long. Every input or output of a networking device has an interface to its connected link, and every interface has a unique MAC address. A MAC address is known only locally at the link level. Normally, it is safe to assume that no two interfaces share the same MAC address. A link layer header contains both MAC addresses of a source interface and a destination interface, as seen in the figure.
- *Network layer (layer 3) address.* A 4-byte (32-bit) field called Internet Protocol (IP) address that is represented by a 4-field dot-separated number, such as 192.2.32.83, in which each field is one byte long. Every entity in a network must have an IP address in order to be identified in a communication. An IP address can be known globally at the network level. A network layer header contains both IP addresses of a source node and a destination node, as seen in the figure.
- *Transport layer (layer 4) address.* A 2-byte (16-bit) field called port number that is represented by a 16-bit number, such as 4,892. The port numbers identify the two end hosts' ports in a communication. Any host can be running several network applications at a time and thus each application needs to be identified by another host communicating to a targeted application. For example, source host 1 in Figure 1.12 requires a port number for communication to uniquely identify an application process running on the destination host 2. A transport layer header contains the port numbers of a source host and a destination host, as seen in the figure. Note that a transport-layer "port" is a logical port and not an actual or a physical one, and it serves as the end-point application identification in a host.

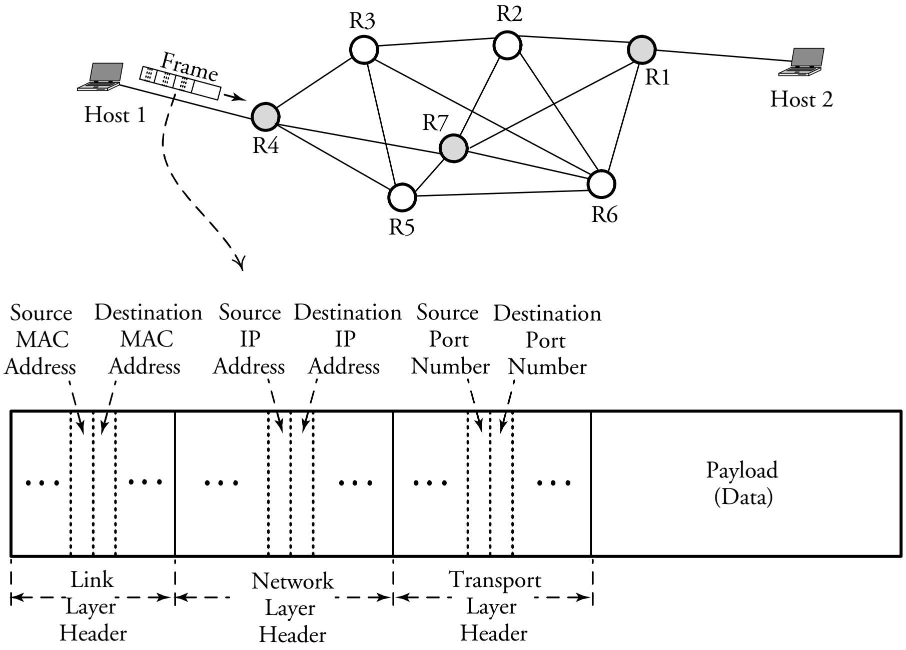


Figure 1.12 A typical frame structure that is forwarded over a link

The details of the link layer header, including the MAC addresses and all other of the header's fields are described in Chapter 4. The details of the network layer header fields, including the IP addresses and all other of the header's fields are presented in Chapter 5. Finally, the details of the transport layer header, including the port numbers and all other of the header's fields are explained in Chapter 8. In the meanwhile, some of the basic IP addressing schemes are presented in the next section, as understanding IP addressing will help us better understand the upcoming networking concepts.

1.5.1 IP Addressing Scheme

The IP header has 32 bits assigned for addressing a desired device on the network. An IP address is a unique identifier used to locate a device on the IP network. To make the system scalable, the address structure is subdivided into the *network* ID and the *host* ID. The network ID identifies the network the device belongs to; the host ID identifies the device. This implies that all devices belonging to the same network have a single network ID. Based on the bit positioning assigned to the network ID and the host ID, the IP address is further subdivided into classes A, B, C, D (multicast), and E (reserved), as shown in Figure 1.13.

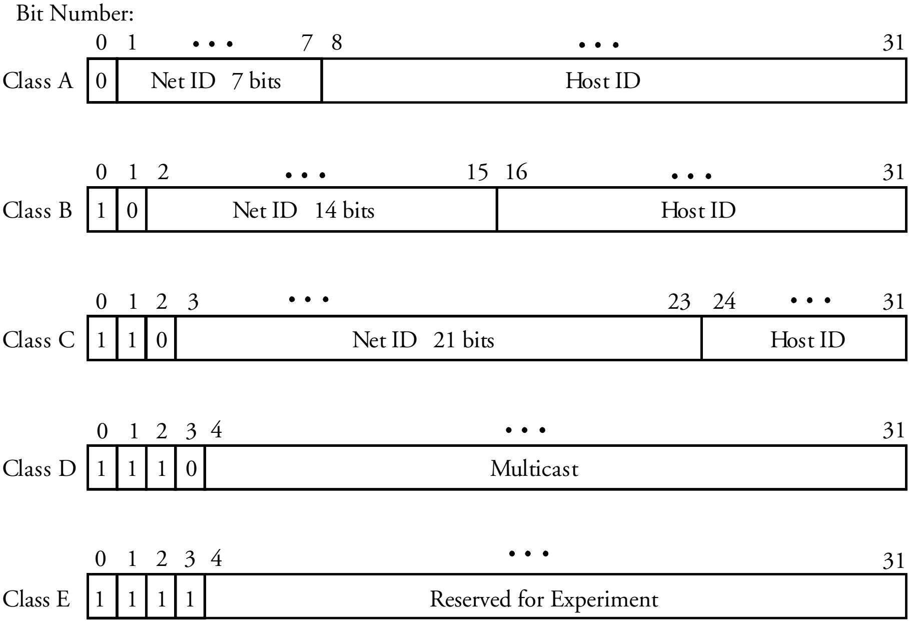


Figure 1.13 Classes of IP addresses

Consider the lengths of corresponding fields for each class shown in this figure:

- Class A starts with 0 followed by 7 bits of network ID and 24 bits of host ID.
- Class B starts with 10 followed by 14 bits of network ID and 16 bits of host ID.
- Class C starts with 110 followed by 21 bits of network ID and 8 bits of host ID.
- Class D starts with 1110 followed by 28 bits. Class D is used only for multicast addressing by which a group of hosts form a multicast group and each group requires a multicast address. Chapter 6 is entirely dedicated to multicast techniques and routing.
- Class E starts with 1111 followed by 28 bits. Class E is reserved for network experiments only.

For ease of use, the IP address is represented in *dot-decimal* notation. The address is grouped into four dot-separated bytes. For example, an IP address with 32 bits of all 0s can be shown by a dot-decimal form of 0.0.0.0 where each 0 is the representation of 00000000 in a logic bit format.

A detailed comparison of IP addressing is shown in the Table 1.1. Note that in this table, each of the "number of available network addresses" and the "number of available

Table 1.1 Comparison of IP addressing schemes

Class	Bits to Start	Size of Network ID Field	Size of Host ID Field	Number of Available Network Addresses	Number of Available Host Addresses per Network	Start Address	End Address
A	0	7	24	126	16,777,214	0.0.0.0	127.255.255.255
B	10	14	16	16,382	65,534	128.0.0.0	191.255.255.255
C	110	21	8	2,097,150	254	192.0.0.0	223.255.255.255
D	1110	N/A	N/A	N/A	N/A	224.0.0.0	239.255.255.255
E	1111	N/A	N/A	N/A	N/A	240.0.0.0	255.255.255.255

host addresses per network" has already been decreased by 2. For example, in class A, the size of the network ID field is indicated in the table to be $N = 7$; however, the number of available network addresses is presented as $2^N - 2 = 128 - 2 = 126$. The subtraction of 2 adjusts for the use of the all-bits-zero network ID (0 in decimal) and the all-bits-one network ID (127 in decimal). These two network IDs, 0 and 127, are reserved for management and cannot be available for any other use. The same argument is true for the number of available host addresses, where with the size of the host ID field indicated as $N = 24$, we can have $2^N - 2 = 16,777,216 - 2 = 16,777,214$ host addresses per network available for use. The last two columns of the table show the start address and the end address of each class, including the reserved addresses explained earlier.

Example. A host has an IP address of 10001000 11100101 11001001 00010000. Find the class and decimal equivalence of the IP address.

Solution. The host's IP address belongs to class B, since it starts with 10. Its decimal equivalent is 136.229.201.16.

1.5.2 Subnet Addressing and Masking

The concept of subnetting was introduced to overcome the shortcomings of IP addressing. Managing a large number of hosts is an enormous task. For example, a company that uses a class B addressing scheme can support up to 65,535 hosts on one network. If the company has more than one network, a multiple-network address scheme, or *subnet scheme*, is used. In this scheme, the host ID of the original IP address is subdivided into *subnet ID* and *host ID*, as shown in Figure 1.14.

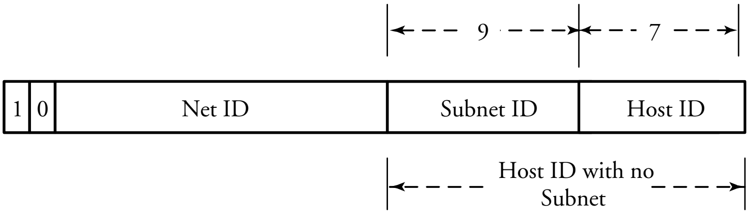


Figure 1.14 A subnet ID and host ID in class B addressing

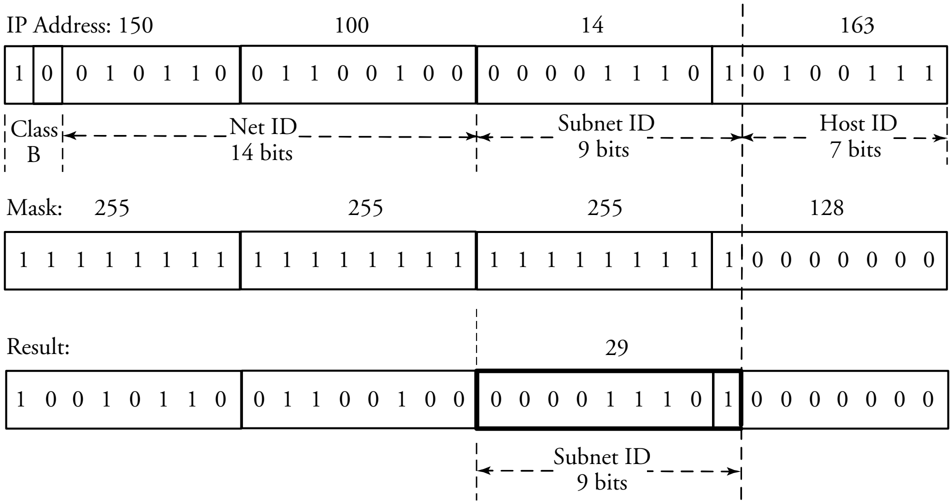


Figure 1.15 An example of subnet and masking

Depending on the network size, different values of subnet ID and host ID can be chosen. Doing so would prevent the outside world from being burdened by a shortage of new network addresses. To determine the subnetting number, a subnet *mask*—logic AND function—is used. The subnet mask has a field of all 0s for the host ID and a field of all 1s for the remaining field.

Example. Given an IP address of 150.100.14.163 and a subnet mask of 255.255.255.128, determine the maximum number of hosts per subnet.

Solution. Figure 1.15 shows the details of the solution. Masking 255.255.255.128 on the IP address results in 150.100.14.128. Clearly, the IP address 150.100.14.163 is a class B address. In a class B address, the lower 16 bits are assigned to the subnet and host fields. Applying the mask, we see that the maximum number of hosts is $2^7 = 128$.

Example. A router attached to a network receives a packet with the destination IP address 190.155.16.16. The network is assigned an address of 190.155.0.0. Assume that the network has two subnets with addresses 190.155.16.0 and 190.155.15.0 and that both subnet ID fields have 8 bits. Demonstrate the details of routing the packet.

Solution. When it receives the packet, the router determines to which subnet the packet needs to be routed, as follows: The destination IP address is 190.155.16.16, the subnet mask used in the router is 255.255.255.0, and the result is 190.155.16.0. The router looks up its routing table for the next subnet corresponding to the subnet 190.155.16.0, which is subnet 2. When the packet arrives at subnet 2, the router determines that the destination is on its own subnet and routes the packet to its destination.

1.5.3 Classless Interdomain Routing (CIDR)

The preceding section described an addressing scheme requiring that the address space be subdivided into five classes. However, giving a certain class C address space to a certain university campus does not guarantee that all addresses within the space can be used and therefore might waste some addresses. This kind of situation is inflexible and would exhaust the IP address space. Thus, the classful addressing scheme consisting of classes A, B, C, D, and E results in an inefficient use of the address space.

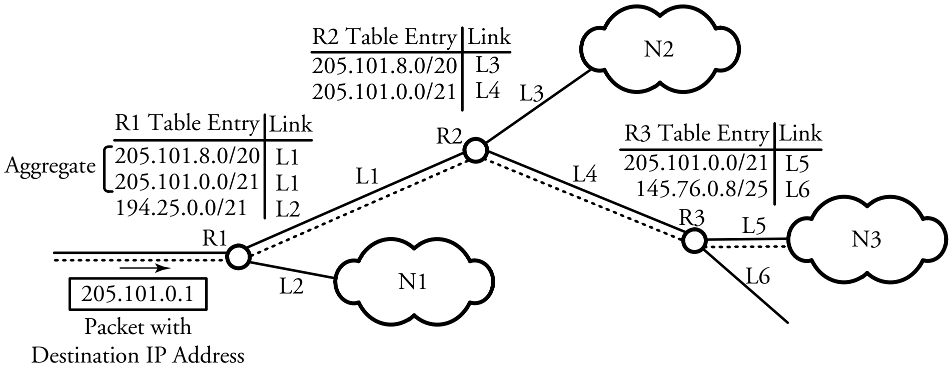
A new scheme, with no restriction on the classes, emerged. *Classless interdomain routing* (CIDR) is extremely flexible, allowing a variable-length *prefix* to represent the network ID and the remaining bits of the 32-field address to represent the hosts within the network. For example, one organization may choose a 20-bit network ID, whereas another organization may choose a 21-bit network ID, with the first 20 bits of these two network IDs being identical. This means that the address space of one organization contains that of another one.

CIDR results in a significant increase in the speed of routers and has greatly reduced the size of routing tables. A routing table of a router using the CIDR address space has entries that include a pair of network IP addresses and the mask. *Supernetting* is a CIDR technique whereby a single routing entry is sufficient to represent a group of adjacent addresses. Because of the use of a variable-length prefix, the routing table may have two entries with the same prefix. To route a packet that matches both of these entries, the router chooses between the two entries, using the longest-prefix-match technique.

Example. Assume that a packet with destination IP address 205.101.0.1 is received by router R1, as shown in Figure 1.16. Find the final destination of the packet.

Solution. In the table entries of router R1, two routes, L1 and L2, belonging to 205.101.8.0/20 and 205.101.0.0/21, respectively, are initially matched with the packet's IP address. CIDR protocol then dictates that the longer prefix must be the eligible match. As indicated at the bottom of this figure, link L1, with its 21-bit prefix, is selected, owing to a longer match. This link eventually routes the packet to the destination network, N3.

CIDR allows us to reduce the number of entries in a router's table by using an *aggregate technique*, whereby all entries that have some common partial prefix can be combined into one entry. For example, in Figure 1.16, the two entries 205.101.8.0/20 and 205.101.0.0/21 can be combined into 205.101.0.0/20, saving one entry in the table. Combining entries in routing tables not only saves space but also enhances the speed of the routers, as each time, routers need to search among fewer addresses.



Packet Dest:	205.101.0.1	1100 1101 . 0110 0101 . 0000 0000 . 0000 0001
L1:	205.101.8.0/20	1100 1101 . 0110 0101 . 0000 1000 . 0000 0000
L1:	205.101.0.0/21	1100 1101 . 0110 0101 . 0000 0000 . 0000 0000

Figure 1.16 CIDR routing

1.6 Equal-Sized Packets Model

A networking model in which packets are of equal size can also be constructed. Equal-sized packets, or *cells*, bring a tremendous amount of simplicity to the networking hardware, since buffering, multiplexing, and switching of cells become extremely simple. However, a disadvantage of this kind of networking is the typically high overall ratio of header to data. This issue normally arises when the message size is large and the standard size of packets is small. As discussed in Section 1.3, the dominance of headers in a network can cause delay and congestion.

One of the networking technologies established using the equal-sized packets model is *asynchronous transfer mode* (ATM). The objective of ATM technology is to provide a homogeneous backbone network in which all types of traffic are transported with the same small fixed-sized *cells*. One of the key advantages of ATM systems is flexible processing of packets (cells) at each node. Regardless of traffic types and the speed of sources, the traffic is converted into 53-byte ATM cells. Each cell has a 48-byte data payload and a 5-byte header. The header identifies the virtual channel to which the cell belongs. However, because the high overall ratio of header to data in packets results in huge delays in wide area networks, ATM is rarely deployed in networking infrastructure and therefore we do not expand our discussion on ATM beyond this section.

1.7 Summary

This chapter established a conceptual foundation for realizing all upcoming chapters. First, we clearly identified and defined all basic key terms in networking. We showed a big-picture view of computer networks in which from one side, mainframe servers can be connected to a network backbone, and from the other side, home communication devices are connected to a backbone network over long-distance telephone lines. We illustrated how an Internet service provider (ISP) controls the functionality of networks. ISPs have become increasingly involved in supporting packet-switched networking services for carrying all sorts of data, not just voice, and the cable TV industry.

The transfer of data in packet-switched networks is organized as a multilevel hierarchy, with digital messages fragmented into units of formatted messages, or packets. In some circumstances, such as local area networks, packets must be modified further, forming a smaller or larger packet known as a frame. Two types of packet-switched networks are networks using connectionless protocol, in which no particular advanced connection is required, and networks using connection-oriented protocol, in which an advance dedication of a path is required.

A packet's size can be optimized. Using the percentage of link utilization by data, ρ_d, as a main variable, we showed that the optimized packet size and the optimized packet delay depend on ρ_d. The total delay of packet transfer in a connectionless network may be significantly smaller than the one for a connection-oriented network since if you have a huge file to transfer, the set-up and tear-down times may be small compared to the file transfer time.

This chapter also covered a tremendous amount of fundamental networking protocol material. We presented the basic structure of the Internet network protocols and an overview of the TCP/IP layered architecture. This architectural model provides a communication service for peers running on different machines and exchanging messages.

We also covered the basics of protocol layers: the *network layer* and the structure of IPv4 and IPv6. IP addressing is further subdivided as either *classful* or *classless*. Classless addressing is more practical for managing routing tables. Finally, we compared the equal-sized packet networking environment to IP networks. Although packet multiplexing is easy, the traffic management is quite challenging.

The next chapter focuses on the fundamental operations of networking devices and presents an overview of the hardware foundations of our networking infrastructure. Networking devices are used to construct a computer network.

1.8 Exercises

1. We transmit data directly between two servers 6,000 km apart through a geostationary satellite situated 10,000 km from Earth exactly between the two servers. The data enters this network at 100Mb/s.
   (a) Find the propagation delay if data travels at the speed of light (2.3×10^8 m/s).
   (b) Find the number of bits in transit during the propagation delay.
   (c) Determine how long it takes to send 10 bytes of data and to receive 2.5 bytes of acknowledgment back.

2. We would like to analyze a variation of Exercise 1 where servers are placed in substantially closer proximity to each other still using satellite for communication. We transmit data directly between two servers 60 m apart through a geostationary satellite situated 10,000 km from Earth exactly between the two servers. The data enters this network at 100Mb/s.
   (a) Find the propagation delay if data travels at the speed of light (2.3×10^8 m/s).
   (b) Find the number of bits in transit during the propagation delay.
   (c) Determine how long it takes to send 10 bytes of data and to receive 2.5 bytes of acknowledgment back.

3. Stored on a flash memory device is a 200 megabyte (MB) message to be transmitted by an e-mail from one server to another, passing three nodes of a *connectionless network*. This network forces packets to be of size 10KB, excluding a packet header of 40 bytes. Nodes are 400 miles apart, and servers are 50 miles away from their corresponding nodes. All transmission links are of type 100Mb/s. The processing time at each node is 0.2 seconds.
   (a) Find the propagation delays per packet between a server and a node and between nodes.
   (b) Find the total time required to send this message.

4. Equation (1.2) gives the total delay time for connection-oriented networks. Let t_p be the packet propagation delay between each two nodes, t_{f1} be the data packet transfer time to the next node, and t_{r1} be the data packet processing time. Also, let t_{f2} be the control-packet transfer time to the next node, and t_{r2} be the control-packet processing time. Give an expression for D in terms of all these variables.

5. Suppose that a 200MB message stored on a flash memory device attached to a server is to be uploaded to a destination server through a connection-oriented packet-switched network with three serially connected nodes. This network forces packets to be of size 10KB, including a packet header of 40 bytes. Nodes are 400 miles apart from each other and each server is 50 miles away from its corresponding node. All transmission links are of type 100Mb/s. The processing time at each node is 0.2 seconds. For this purpose, the signaling packet is 500 bits long.
   (a) Find the total connection request/accept process time.
   (b) Find the total connection release process time.
   (c) Find the total time required to send this message.

6. We want to deliver a 12KB message by uploading it to the destination's Web site through a 10-node path of a *virtual-circuit packet-switched network*. For this purpose, the signaling packet is 500 bits long. The network forces packets to be of size 10KB including a packet header of 40 bytes. Nodes are 500 miles apart. All transmission links are of type 1Gb/s. The processing time at each node is 100 ms per packet and the propagation speed is 2.3×10^8 m/s.
   (a) Find the total connection request/accept process time.
   (b) Find the total connection release process time.
   (c) Find the total time required to send this message.

7. Consider five serial connected nodes A, B, C, D, E and that 100 bytes of data are supposed to be transmitted from node A to E using a protocol that requires packet headers to be 20 bytes long.
   (a) Ignore t_p, t_r, and all control signals; and sketch and calculate total t_f in terms of byte-time to transmit the data for cases in which the data is converted into 1 packet, 2 packets, 5 packets, and 10 packets.
   (b) Put all the results obtained from part (a) together in one plot and estimate where the plot approximately shows the minimum delay (no mathematical work is needed, just indicate the location of the lowest delay transmission on the plot).

8. To analyze the transmission of a 10,000-bit-long packet, we want the percentage of link utilization used by the data portion of a packet to be 72 percent. We also want the ratio of the packet header, h, to packet data, d, to be 0.04. The transmission link speed is $s = 100$ Mb/s.
   (a) Find the link utilization, ρ.
   (b) Find the link capacity rate, μ, in terms of packets per second.
   (c) Find the average delay per packet.
   (d) Find the optimum average delay per packet.

9. Consider a digital link with a maximum capacity of $s = 100$ Mb/s facing a situation resulting in 80 percent utilization. Equal-sized packets arrive at 8,000 packets per second. The link utilization dedicated to headers of packets is 0.8 percent.
   (a) Find the total size of each packet.
   (b) Find the header and data sizes for each packet.
   (c) If the header size is not negotiable, what would the optimum size of packets be?
   (d) Find the delay for each optimally sized packet.

10. Develop a signaling delay chart, similar to Figures 1.7 and 1.8, for circuit-switched networks. From the mentioned steps, get an idea that would result in the establishment of a telephone call over circuit-switched networks.

11. In practice, the optimum size of a packet estimated in Equation (1.7) depends on several other contributing factors.
    (a) Derive the optimization analysis, this time also including the header size, h. In this case, you have two variables: d and h.
    (b) What other factors might also contribute to the optimization of the packet size?

12. Specify the class of address and the subnet ID for the following cases:
    (a) A packet with IP address 127.156.28.31 using mask pattern 255.255.255.0
    (b) A packet with IP address 150.156.23.14 using mask pattern 255.255.255.128
    (c) A packet with IP address 150.18.23.101 using mask pattern 255.255.255.128

13. Specify the class of address and the subnet ID for the following cases:

(a) A packet with IP address 173.168.28.45 using mask pattern 255.255.255.0

(b) A packet with IP address 188.145.23.1 using mask pattern 255.255.255.128

(c) A packet with IP address 139.189.91.190 using mask pattern 255.255.255.128

14. Apply CIDR aggregation on the following IP addresses: 150.97.28.0/24, 150.97.29.0/24, and 150.97.30.0/24.

15. Apply CIDR aggregation on the following IP addresses: 141.33.11.0/22, 141.33.12.0/22, and 141.33.13.0/22.

16. Use the subnet mask 255.255.254.0 on the following IP addresses, and then convert them to CIDR forms:

(a) 191.168.6.0

(b) 173.168.28.45

(c) 139.189.91.190

17. A certain organization owns a subnet with prefix 143.117.30.128/26.

(a) Give an example of one of the organization's IP addresses.

(b) Assume the organization needs to be downsized, and it wants to partition its block of addresses and create three new subnets, with each new block having the same number of IP addresses. Give the CIDR form of addresses for each of the three new subnets.

18. A packet with the destination IP address 180.19.18.3 arrives at a router. The router uses CIDR protocols, and its table contains three entries referring to the following connected networks: 180.19.0.0/18, 180.19.3.0/22, and 180.19.16.0/20, respectively.

(a) From the information in the table, identify the exact network ID of each network in binary form.

(b) Find the right entry that is a match with the packet.

19. Part of a networking infrastructure consists of three routers R1, R2, and R3 and six networks N1 through N6, as shown in Figure 1.17. All address entries of each router are also given as seen in the figure. A packet with the destination IP address 195.25.17.3 arrives at router R1.

(a) Find the exact network ID field of each network in binary form.

(b) Find the destination network for the packet (proof needed).

(c) Specify how many hosts can be addressed in network N1.

R1 Table Entry	Link
195.25.0.0/21	L11
195.25.16.0/20	L12
195.25.8.0/22	L13
135.11.2.0/22	L14

R2 Table Entry	Link
195.25.24.0/19	L21
195.25.16.0/20	L22
195.25.8.0/22	L23

R3 Table Entry	Link
111.5.0.0/21	L31
Else	L32
195.25.16.0/20	L33

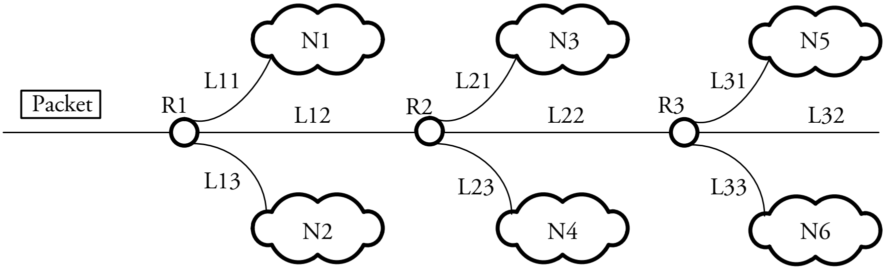


Figure 1.17 Exercise 19 network example

20. Consider an estimated population of 620 million people.

(a) What is the maximum number of IP addresses that can be assigned per person using IPv4?

(b) Design an appropriate CIDR to deliver the addressing in part (a).

21. A router with four output links L1, L2, L3, and L4 is set up based on the following routing table:

Mask Result	Link
192.5.150.16	L3
192.5.150.18	L2
129.95.38.0	L1
129.95.38.15	L3
129.95.39.0	L2
Unidentified	L4

The router has a masking pattern of 255.255.255.240 and examines each packet using the mask in order to find the right output link. For a packet addressed to each of the following destinations, specify which output link is found:

(a) 192.5.150.18

(b) 129.95.39.10

(c) 129.95.38.15

(d) 129.95.38.149

22. A router with four output links L1, L2, L3, and L4 is set up based on the following routing table:

Mask Result	Link
192.5.150.0	L1
129.95.39.0	L2
129.95.38.128	L3
Unidentified	L4

The router has two masking patterns of 255.255.255.128 and 255.255.255.1 and examines each packet using these masks in the preceding order to find a right output link among L1, L2, and L3. If a mask finds one of the three outputs, the second mask is not used. Link L4 is used for those packets for which none of the masks can determine an output link. For a packet addressed to a destination having each of the following IP addresses, specify which mask pattern finds a link for the packet and then which output port (link) is found:

(a) 129.95.39.10
(b) 129.95.38.16
(c) 129.95.38.149

1.9 Computer Simulation Project

1. ***Simulation of Networking Packets.*** Write a computer program in C or C++ to simulate a "packet." Each packet must have two distinct parts: header and data. The data is fixed on 10 bytes consisting of all logic 1s. The header is 9 bytes long and consists of three fields only: priority (1 byte), source address (4 bytes), and destination address (4 bytes).

(a) For a Packet A, initialize the priority field to be 0, and source and destination addresses to be 10.0.0.1 and 192.0.1.0, respectively.
(b) For a Packet B, initialize the priority field to be 1, and source and destination addresses to be 11.1.0.1 and 192.0.1.0, respectively.
(c) For a Packet C, initialize the priority field to be 0, and source and destination addresses to be 11.1.0.1 and 192.0.1.0, respectively.
(d) Demonstrate that your program can create the packets defined in parts (a), (b), and (c).

(e) Extend your program such that a comparator looks at the priority fields and destination addresses of any combination of two packets. If the destination addresses are the same, it chooses the packet with the highest priority and leaves the packet with lower priority in a register with incremented priority. Otherwise, it chooses randomly one of the packets and leaves the other one in the register with incremented priority. Show that your program is capable of choosing Packet B.

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