

usually cover a city. An example is the cable television system, which is now used by many people to access the Internet. WANs may cover a country or a continent. Some of the technologies used to build these networks are point-to-point (e.g., a cable) while others are broadcast (e.g., wireless). Networks can be interconnected with routers to form internetworks, of which the Internet is the largest and best known example. Wireless networks, for example 802.11 LANs and 3G mobile telephony, are also becoming extremely popular.

Network software is built around protocols, which are rules by which processes communicate. Most networks support protocol hierarchies, with each layer providing services to the layer above it and insulating them from the details of the protocols used in the lower layers. Protocol stacks are typically based either on the OSI model or on the TCP/IP model. Both have link, network, transport, and application layers, but they differ on the other layers. Design issues include reliability, resource allocation, growth, security, and more. Much of this book deals with protocols and their design.

Networks provide various services to their users. These services can range from connectionless best-efforts packet delivery to connection-oriented guaranteed delivery. In some networks, connectionless service is provided in one layer and connection-oriented service is provided in the layer above it.

Well-known networks include the Internet, the 3G mobile telephone network, and 802.11 LANs. The Internet evolved from the ARPANET, to which other networks were added to form an internetwork. The present-day Internet is actually a collection of many thousands of networks that use the TCP/IP protocol stack. The 3G mobile telephone network provides wireless and mobile access to the Internet at speeds of multiple Mbps, and, of course, carries voice calls as well. Wireless LANs based on the IEEE 802.11 standard are deployed in many homes and cafes and can provide connectivity at rates in excess of 100 Mbps. New kinds of networks are emerging too, such as embedded sensor networks and networks based on RFID technology.

Enabling multiple computers to talk to each other requires a large amount of standardization, both in the hardware and software. Organizations such as ITU-T, ISO, IEEE, and IAB manage different parts of the standardization process.

PROBLEMS

1. Imagine that you have trained your St. Bernard, Bernie, to carry a box of three 8-mm tapes instead of a flask of brandy. (When your disk fills up, you consider that an emergency.) These tapes each contain 7 gigabytes. The dog can travel to your side, wherever you may be, at 18 km/hour. For what range of distances does Bernie have a higher data rate than a transmission line whose data rate (excluding overhead) is 150 Mbps? How does your answer change if (i) Bernie's speed is doubled; (ii) each tape capacity is doubled; (iii) the data rate of the transmission line is doubled.

2. An alternative to a LAN is simply a big timesharing system with terminals for all users. Give two advantages of a client-server system using a LAN.
3. The performance of a client-server system is strongly influenced by two major network characteristics: the bandwidth of the network (that is, how many bits/sec it can transport) and the latency (that is, how many seconds it takes for the first bit to get from the client to the server). Give an example of a network that exhibits high bandwidth but also high latency. Then give an example of one that has both low bandwidth and low latency.
4. Besides bandwidth and latency, what other parameter is needed to give a good characterization of the quality of service offered by a network used for (i) digitized voice traffic? (ii) video traffic? (iii) financial transaction traffic?
5. A factor in the delay of a store-and-forward packet-switching system is how long it takes to store and forward a packet through a switch. If switching time is 10 μ sec, is this likely to be a major factor in the response of a client-server system where the client is in New York and the server is in California? Assume the propagation speed in copper and fiber to be $2/3$ the speed of light in vacuum.
6. A client-server system uses a satellite network, with the satellite at a height of 40,000 km. What is the best-case delay in response to a request?
7. In the future, when everyone has a home terminal connected to a computer network, instant public referendums on important pending legislation will become possible. Ultimately, existing legislatures could be eliminated, to let the will of the people be expressed directly. The positive aspects of such a direct democracy are fairly obvious; discuss some of the negative aspects.
8. Five routers are to be connected in a point-to-point subnet. Between each pair of routers, the designers may put a high-speed line, a medium-speed line, a low-speed line, or no line. If it takes 100 ms of computer time to generate and inspect each topology, how long will it take to inspect all of them?
9. A disadvantage of a broadcast subnet is the capacity wasted when multiple hosts attempt to access the channel at the same time. As a simplistic example, suppose that time is divided into discrete slots, with each of the n hosts attempting to use the channel with probability p during each slot. What fraction of the slots will be wasted due to collisions?
10. What are two reasons for using layered protocols? What is one possible disadvantage of using layered protocols?
11. The president of the Specialty Paint Corp. gets the idea to work with a local beer brewer to produce an invisible beer can (as an anti-litter measure). The president tells her legal department to look into it, and they in turn ask engineering for help. As a result, the chief engineer calls his counterpart at the brewery to discuss the technical aspects of the project. The engineers then report back to their respective legal departments, which then confer by telephone to arrange the legal aspects. Finally, the two corporate presidents discuss the financial side of the deal. What principle of a multilayer protocol in the sense of the OSI model does this communication mechanism violate?

12. Two networks each provide reliable connection-oriented service. One of them offers a reliable byte stream and the other offers a reliable message stream. Are these identical? If so, why is the distinction made? If not, give an example of how they differ.
13. What does “negotiation” mean when discussing network protocols? Give an example.
14. In Fig. 1-19, a service is shown. Are any other services implicit in this figure? If so, where? If not, why not?
15. In some networks, the data link layer handles transmission errors by requesting that damaged frames be retransmitted. If the probability of a frame’s being damaged is p , what is the mean number of transmissions required to send a frame? Assume that acknowledgements are never lost.
16. A system has an n -layer protocol hierarchy. Applications generate messages of length M bytes. At each of the layers, an h -byte header is added. What fraction of the network bandwidth is filled with headers?
17. What is the main difference between TCP and UDP?
18. The subnet of Fig. 1-25(b) was designed to withstand a nuclear war. How many bombs would it take to partition the nodes into two disconnected sets? Assume that any bomb wipes out a node and all of the links connected to it.
19. The Internet is roughly doubling in size every 18 months. Although no one really knows for sure, one estimate put the number of hosts on it at 600 million in 2009. Use these data to compute the expected number of Internet hosts in the year 2018. Do you believe this? Explain why or why not.
20. When a file is transferred between two computers, two acknowledgement strategies are possible. In the first one, the file is chopped up into packets, which are individually acknowledged by the receiver, but the file transfer as a whole is not acknowledged. In the second one, the packets are not acknowledged individually, but the entire file is acknowledged when it arrives. Discuss these two approaches.
21. Mobile phone network operators need to know where their subscribers’ mobile phones (hence their users) are located. Explain why this is bad for users. Now give reasons why this is good for users.
22. How long was a bit in the original 802.3 standard in meters? Use a transmission speed of 10 Mbps and assume the propagation speed in coax is $2/3$ the speed of light in vacuum.
23. An image is 1600×1200 pixels with 3 bytes/pixel. Assume the image is uncompressed. How long does it take to transmit it over a 56-kbps modem channel? Over a 1-Mbps cable modem? Over a 10-Mbps Ethernet? Over 100-Mbps Ethernet? Over gigabit Ethernet?
24. Ethernet and wireless networks have some similarities and some differences. One property of Ethernet is that only one frame at a time can be transmitted on an Ethernet. Does 802.11 share this property with Ethernet? Discuss your answer.
25. List two advantages and two disadvantages of having international standards for network protocols.

26. When a system has a permanent part and a removable part (such as a CD-ROM drive and the CD-ROM), it is important that the system be standardized, so that different companies can make both the permanent and removable parts and everything still works together. Give three examples outside the computer industry where such international standards exist. Now give three areas outside the computer industry where they do not exist.
27. Suppose the algorithms used to implement the operations at layer k is changed. How does this impact operations at layers $k - 1$ and $k + 1$?
28. Suppose there is a change in the service (set of operations) provided by layer k . How does this impact services at layers $k-1$ and $k+1$?
29. Provide a list of reasons for why the response time of a client may be larger than the best-case delay.
30. What are the disadvantages of using small, fixed-length cells in ATM?
31. Make a list of activities that you do every day in which computer networks are used. How would your life be altered if these networks were suddenly switched off?
32. Find out what networks are used at your school or place of work. Describe the network types, topologies, and switching methods used there.
33. The *ping* program allows you to send a test packet to a given location and see how long it takes to get there and back. Try using *ping* to see how long it takes to get from your location to several known locations. From these data, plot the one-way transit time over the Internet as a function of distance. It is best to use universities since the location of their servers is known very accurately. For example, *berkeley.edu* is in Berkeley, California; *mit.edu* is in Cambridge, Massachusetts; *vu.nl* is in Amsterdam; The Netherlands; *www.usyd.edu.au* is in Sydney, Australia; and *www.uct.ac.za* is in Cape Town, South Africa.
34. Go to IETF's Web site, *www.ietf.org*, to see what they are doing. Pick a project you like and write a half-page report on the problem and the proposed solution.
35. The Internet is made up of a large number of networks. Their arrangement determines the topology of the Internet. A considerable amount of information about the Internet topology is available on line. Use a search engine to find out more about the Internet topology and write a short report summarizing your findings.
36. Search the Internet to find out some of the important peering points used for routing packets in the Internet at present.
37. Write a program that implements message flow from the top layer to the bottom layer of the 7-layer protocol model. Your program should include a separate protocol function for each layer. Protocol headers are sequence up to 64 characters. Each protocol function has two parameters: a message passed from the higher layer protocol (a char buffer) and the size of the message. This function attaches its header in front of the message, prints the new message on the standard output, and then invokes the protocol function of the lower-layer protocol. Program input is an application message (a sequence of 80 characters or less).

Transmission media can be guided or unguided. The principal guided media are twisted pair, coaxial cable, and fiber optics. Unguided media include terrestrial radio, microwaves, infrared, lasers through the air, and satellites.

Digital modulation methods send bits over guided and unguided media as analog signals. Line codes operate at baseband, and signals can be placed in a passband by modulating the amplitude, frequency, and phase of a carrier. Channels can be shared between users with time, frequency and code division multiplexing.

A key element in most wide area networks is the telephone system. Its main components are the local loops, trunks, and switches. ADSL offers speeds up to 40 Mbps over the local loop by dividing it into many subcarriers that run in parallel. This far exceeds the rates of telephone modems. PONs bring fiber to the home for even greater access rates than ADSL.

Trunks carry digital information. They are multiplexed with WDM to provision many high capacity links over individual fibers, as well as with TDM to share each high rate link between users. Both circuit switching and packet switching are important.

For mobile applications, the fixed telephone system is not suitable. Mobile phones are currently in widespread use for voice, and increasingly for data. They have gone through three generations. The first generation, 1G, was analog and dominated by AMPS. 2G was digital, with GSM presently the most widely deployed mobile phone system in the world. 3G is digital and based on broadband CDMA, with WCDMA and also CDMA2000 now being deployed.

An alternative system for network access is the cable television system. It has gradually evolved from coaxial cable to hybrid fiber coax, and from television to television and Internet. Potentially, it offers very high bandwidth, but the bandwidth in practice depends heavily on the other users because it is shared.

PROBLEMS

1. Compute the Fourier coefficients for the function $f(t) = t$ ($0 \leq t \leq 1$).
2. A noiseless 4-kHz channel is sampled every 1 msec. What is the maximum data rate? How does the maximum data rate change if the channel is noisy, with a signal-to-noise ratio of 30 dB?
3. Television channels are 6 MHz wide. How many bits/sec can be sent if four-level digital signals are used? Assume a noiseless channel.
4. If a binary signal is sent over a 3-kHz channel whose signal-to-noise ratio is 20 dB, what is the maximum achievable data rate?
5. What signal-to-noise ratio is needed to put a T1 carrier on a 50-kHz line?
6. What are the advantages of fiber optics over copper as a transmission medium? Is there any downside of using fiber optics over copper?

7. How much bandwidth is there in 0.1 microns of spectrum at a wavelength of 1 micron?
8. It is desired to send a sequence of computer screen images over an optical fiber. The screen is 2560×1600 pixels, each pixel being 24 bits. There are 60 screen images per second. How much bandwidth is needed, and how many microns of wavelength are needed for this band at 1.30 microns?
9. Is the Nyquist theorem true for high-quality single-mode optical fiber or only for copper wire?
10. Radio antennas often work best when the diameter of the antenna is equal to the wavelength of the radio wave. Reasonable antennas range from 1 cm to 5 meters in diameter. What frequency range does this cover?
11. A laser beam 1 mm wide is aimed at a detector 1 mm wide 100 m away on the roof of a building. How much of an angular diversion (in degrees) does the laser have to have before it misses the detector?
12. The 66 low-orbit satellites in the Iridium project are divided into six necklaces around the earth. At the altitude they are using, the period is 90 minutes. What is the average interval for handoffs for a stationary transmitter?
13. Calculate the end-to-end transit time for a packet for both GEO (altitude: 35,800 km), MEO (altitude: 18,000 km) and LEO (altitude: 750 km) satellites.
14. What is the latency of a call originating at the North Pole to reach the South Pole if the call is routed via Iridium satellites? Assume that the switching time at the satellites is 10 microseconds and earth's radius is 6371 km.
15. What is the minimum bandwidth needed to achieve a data rate of B bits/sec if the signal is transmitted using NRZ, MLT-3, and Manchester encoding? Explain your answer.
16. Prove that in 4B/5B encoding, a signal transition will occur at least every four bit times.
17. How many end office codes were there pre-1984, when each end office was named by its three-digit area code and the first three digits of the local number? Area codes started with a digit in the range 2–9, had a 0 or 1 as the second digit, and ended with any digit. The first two digits of a local number were always in the range 2–9. The third digit could be any digit.
18. A simple telephone system consists of two end offices and a single toll office to which each end office is connected by a 1-MHz full-duplex trunk. The average telephone is used to make four calls per 8-hour workday. The mean call duration is 6 min. Ten percent of the calls are long distance (i.e., pass through the toll office). What is the maximum number of telephones an end office can support? (Assume 4 kHz per circuit.) Explain why a telephone company may decide to support a lesser number of telephones than this maximum number at the end office.
19. A regional telephone company has 10 million subscribers. Each of their telephones is connected to a central office by a copper twisted pair. The average length of these twisted pairs is 10 km. How much is the copper in the local loops worth? Assume

that the cross section of each strand is a circle 1 mm in diameter, the density of copper is 9.0 grams/cm³, and that copper sells for \$6 per kilogram.

20. Is an oil pipeline a simplex system, a half-duplex system, a full-duplex system, or none of the above? What about a river or a walkie-talkie-style communication?
21. The cost of a fast microprocessor has dropped to the point where it is now possible to put one in each modem. How does that affect the handling of telephone line errors? Does it negate the need for error checking/correction in layer 2?
22. A modem constellation diagram similar to Fig. 2-23 has data points at the following coordinates: (1, 1), (1, -1), (-1, 1), and (-1, -1). How many bps can a modem with these parameters achieve at 1200 symbols/second?
23. What is the maximum bit rate achievable in a V.32 standard modem if the baud rate is 1200 and no error correction is used?
24. How many frequencies does a full-duplex QAM-64 modem use?
25. Ten signals, each requiring 4000 Hz, are multiplexed onto a single channel using FDM. What is the minimum bandwidth required for the multiplexed channel? Assume that the guard bands are 400 Hz wide.
26. Why has the PCM sampling time been set at 125 μ sec?
27. What is the percent overhead on a T1 carrier? That is, what percent of the 1.544 Mbps are not delivered to the end user? How does it relate to the percent overhead in OC-1 or OC-768 lines?
28. Compare the maximum data rate of a noiseless 4-kHz channel using
 - (a) Analog encoding (e.g., QPSK) with 2 bits per sample.
 - (b) The T1 PCM system.
29. If a T1 carrier system slips and loses track of where it is, it tries to resynchronize using the first bit in each frame. How many frames will have to be inspected on average to resynchronize with a probability of 0.001 of being wrong?
30. What is the difference, if any, between the demodulator part of a modem and the coder part of a codec? (After all, both convert analog signals to digital ones.)
31. SONET clocks have a drift rate of about 1 part in 10⁹. How long does it take for the drift to equal the width of 1 bit? Do you see any practical implications of this calculation? If so, what?
32. How long will it take to transmit a 1-GB file from one VSAT to another using a hub as shown in Figure 2-17? Assume that the uplink is 1 Mbps, the downlink is 7 Mbps, and circuit switching is used with 1.2 sec circuit setup time.
33. Calculate the transmit time in the previous problem if packet switching is used instead. Assume that the packet size is 64 KB, the switching delay in the satellite and hub is 10 microseconds, and the packet header size is 32 bytes.
34. In Fig. 2-40, the user data rate for OC-3 is stated to be 148.608 Mbps. Show how this number can be derived from the SONET OC-3 parameters. What will be the gross, SPE, and user data rates of an OC-3072 line?

35. To accommodate lower data rates than STS-1, SONET has a system of virtual tributaries (VTs). A VT is a partial payload that can be inserted into an STS-1 frame and combined with other partial payloads to fill the data frame. VT1.5 uses 3 columns, VT2 uses 4 columns, VT3 uses 6 columns, and VT6 uses 12 columns of an STS-1 frame. Which VT can accommodate
- (a) A DS-1 service (1.544 Mbps)?
 - (b) European CEPT-1 service (2.048 Mbps)?
 - (c) A DS-2 service (6.312 Mbps)?
36. What is the available user bandwidth in an OC-12c connection?
37. Three packet-switching networks each contain n nodes. The first network has a star topology with a central switch, the second is a (bidirectional) ring, and the third is fully interconnected, with a wire from every node to every other node. What are the best-, average-, and worst-case transmission paths in hops?
38. Compare the delay in sending an x -bit message over a k -hop path in a circuit-switched network and in a (lightly loaded) packet-switched network. The circuit setup time is s sec, the propagation delay is d sec per hop, the packet size is p bits, and the data rate is b bps. Under what conditions does the packet network have a lower delay? Also, explain the conditions under which a packet-switched network is preferable to a circuit-switched network.
39. Suppose that x bits of user data are to be transmitted over a k -hop path in a packet-switched network as a series of packets, each containing p data bits and h header bits, with $x \gg p + h$. The bit rate of the lines is b bps and the propagation delay is negligible. What value of p minimizes the total delay?
40. In a typical mobile phone system with hexagonal cells, it is forbidden to reuse a frequency band in an adjacent cell. If 840 frequencies are available, how many can be used in a given cell?
41. The actual layout of cells is seldom as regular that as shown in Fig. 2-45. Even the shapes of individual cells are typically irregular. Give a possible reason why this might be. How do these irregular shapes affect frequency assignment to each cell?
42. Make a rough estimate of the number of PCS microcells 100 m in diameter it would take to cover San Francisco (120 square km).
43. Sometimes when a mobile user crosses the boundary from one cell to another, the current call is abruptly terminated, even though all transmitters and receivers are functioning perfectly. Why?
44. Suppose that A , B , and C are simultaneously transmitting 0 bits, using a CDMA system with the chip sequences of Fig. 2-28(a). What is the resulting chip sequence?
45. Consider a different way of looking at the orthogonality property of CDMA chip sequences. Each bit in a pair of sequences can match or not match. Express the orthogonality property in terms of matches and mismatches.
46. A CDMA receiver gets the following chips: $(-1 +1 -3 +1 -1 -3 +1 +1)$. Assuming the chip sequences defined in Fig. 2-28(a), which stations transmitted, and which bits did each one send?

47. In Figure 2-28, there are four stations that can transmit. Suppose four more stations are added. Provide the chip sequences of these stations.
48. At the low end, the telephone system is star shaped, with all the local loops in a neighborhood converging on an end office. In contrast, cable television consists of a single long cable snaking its way past all the houses in the same neighborhood. Suppose that a future TV cable were 10-Gbps fiber instead of copper. Could it be used to simulate the telephone model of everybody having their own private line to the end office? If so, how many one-telephone houses could be hooked up to a single fiber?
49. A cable company decides to provide Internet access over cable in a neighborhood consisting of 5000 houses. The company uses a coaxial cable and spectrum allocation allowing 100 Mbps downstream bandwidth per cable. To attract customers, the company decides to guarantee at least 2 Mbps downstream bandwidth to each house at any time. Describe what the cable company needs to do to provide this guarantee.
50. Using the spectral allocation shown in Fig. 2-52 and the information given in the text, how many Mbps does a cable system allocate to upstream and how many to downstream?
51. How fast can a cable user receive data if the network is otherwise idle? Assume that the user interface is
 - (a) 10-Mbps Ethernet
 - (b) 100-Mbps Ethernet
 - (c) 54-Mbps Wireless.
52. Multiplexing STS-1 multiple data streams, called tributaries, plays an important role in SONET. A 3:1 multiplexer multiplexes three input STS-1 tributaries onto one output STS-3 stream. This multiplexing is done byte for byte. That is, the first three output bytes are the first bytes of tributaries 1, 2, and 3, respectively. the next three output bytes are the second bytes of tributaries 1, 2, and 3, respectively, and so on. Write a program that simulates this 3:1 multiplexer. Your program should consist of five processes. The main process creates four processes, one each for the three STS-1 tributaries and one for the multiplexer. Each tributary process reads in an STS-1 frame from an input file as a sequence of 810 bytes. They send their frames (byte by byte) to the multiplexer process. The multiplexer process receives these bytes and outputs an STS-3 frame (byte by byte) by writing it to standard output. Use pipes for communication among processes.
53. Write a program to implement CDMA. Assume that the length of a chip sequence is eight and the number of stations transmitting is four. Your program consists of three sets of processes: four transmitter processes (t_0 , t_1 , t_2 , and t_3), one joiner process, and four receiver processes (r_0 , r_1 , r_2 , and r_3). The main program, which also acts as the joiner process first reads four chip sequences (bipolar notation) from the standard input and a sequence of 4 bits (1 bit per transmitter process to be transmitted), and forks off four pairs of transmitter and receiver processes. Each pair of transmitter/receiver processes (t_0, r_0 ; t_1, r_1 ; t_2, r_2 ; t_3, r_3) is assigned one chip sequence and each transmitter process is assigned 1 bit (first bit to t_0 , second bit to t_1 , and so on). Next, each transmitter process computes the signal to be transmitted (a sequence of 8 bits) and sends it to the joiner process. After receiving signals from all four transmitter processes, the joiner process combines the signals and sends the combined signal to

the four receiver processes. Each receiver process then computes the bit it has received and prints it to standard output. Use pipes for communication between processes.