Link Layer

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Link Layer

- Moves datagrams node-to-node
- Link layer protocols: Ethernet, IEEE 802.11 (Wirelss LAN/ Wifi), Token-ring, PPP
- Services
    - Framing
    - Link-access
    - Reliable-delivery
    - Flow Control
    - Error detection
    - Error correction
    - Half-duplex and Full-duplex

Link Layer

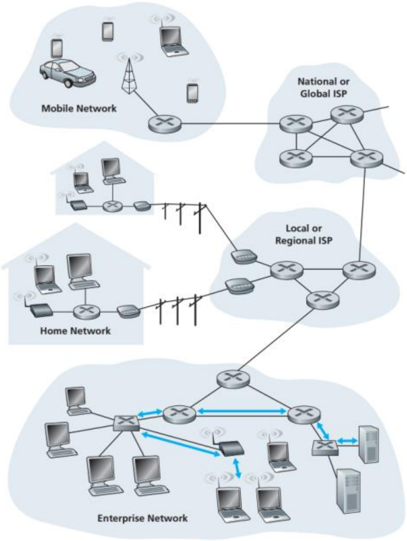
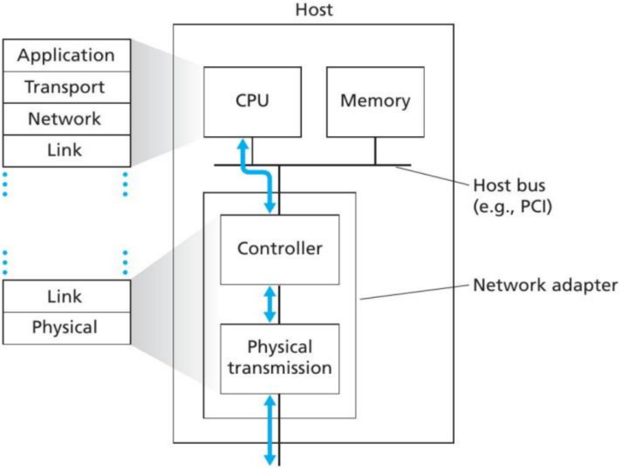


Figure 5.1 ♦ Six link-layer hops between wireless host and server

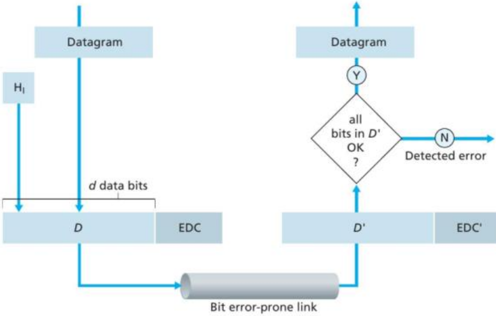
Where is the Link layer implemented



Link Layer Implementation

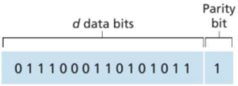
- Software components
  - receiving datagram from network layer
  - assembling link-layer addressing information
  - activating the controller hardware
- Hardware components
  - transfer frame from one adapter to another adapter
  - error detection and correction

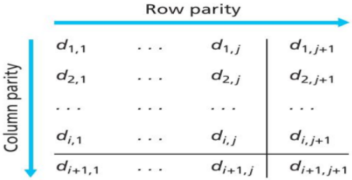
Error Detection and Correction

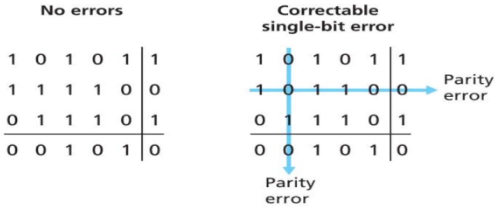


- EDC: error detection and correction bits
- Parity checks
- Checksumming methods
- Cyclic redundancy checks (CRC)

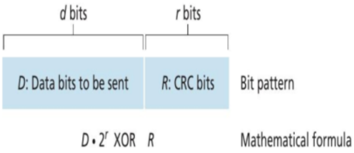
Parity Checks







Cyclic Redundancy Check (CRC)



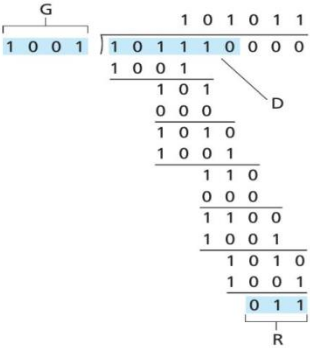
- Bit string can be viewed as a polynomial
- Sender and receiver agree on $r + 1$ bit pattern known as generator G
- Most significant bit of G should be 1
- Given data D, sender will choose additional r bits, R and append them to D
- The resulting $d + r$ bit pattern should be divisible by G.
- CRC calculations are done in modulo-2 arithmetic without carries and borrows (XOR operations)

CRC

- Find R such that there exists n that satisfies

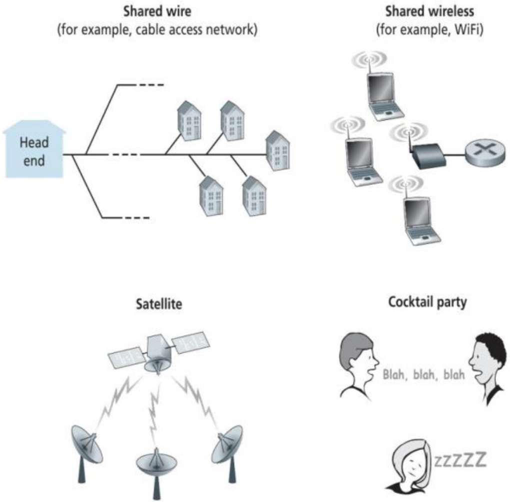
$$D.2^r \text{XOR } R = nG$$

- $R = \text{remainder } \frac{D.2^r}{G}$
- Example:



- International standards define 8-, 16-, 24-, 32-bit generators.

Multiple Access Channels



Multiple Access Protocols

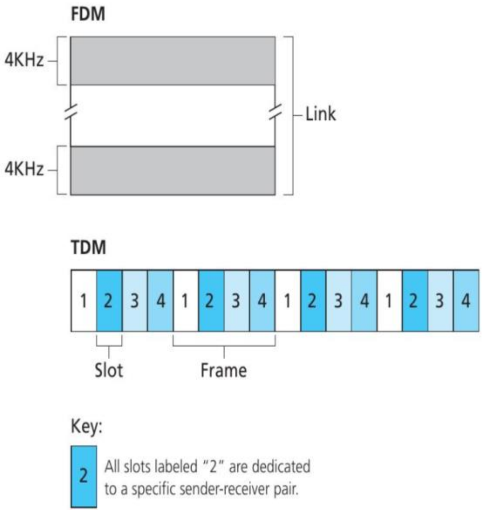
- If multiple nodes transmit frames at same time, packets collide!
- Channel partitioning protocols
  - TDM
  - FDM
- Random access protocols
  - Pure ALOHA
  - Slotted ALOHA
  - Carrier sense multiple access (CSMA), CSMA/CD
- Taking-turns Protocols
  - Polling protocol
  - Token-passing Protocol

Multiple Access Protocols

Desirable characteristics of MAC protocols on a broadcast channel of rate R bps:

- When only one node is has frames to send, that node should have throughput of R bps
- When M nodes have frames to send, each node should have throughput of R/M bps
- Protocol is decentralized
- Protocol is simple and inexpensive to implement.

Channel Partitioning Protocol



Drawbacks of TDM and FDM

- When only one node is active, it gets throughput of R/N bps.
- Node has to wait for its turn!
- Code division multiple access (CDMA)

Slotted ALOHA

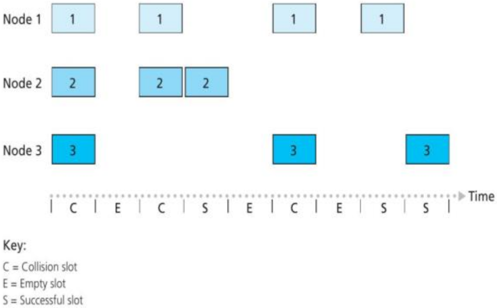
Model and assumptions

- All frame consists of exactly L bits
- Time is divided into slots of size L/R seconds
- Nodes start to transmit frames only at the beginning of slots
- Nodes are synchronized
- If two or more frames collide in a slot, then all nodes can detect the collision before the slot ends

Slotted ALOHA

- When a node has fresh frame to send, it waits for beginning of the next slot and transmits the frame in the slot
- If there is no collision, the node has successfully transmitted the packet and no need to retransmit
- If there is a collision, the node detects it before end of the slot. The node retransmits the frame in each subsequent slot with probability p until the frame is transmitted without a collision

Slotted ALOHA: Drawbacks



- Collisions
- Empty spaces
- Efficiency: fraction of successful slots

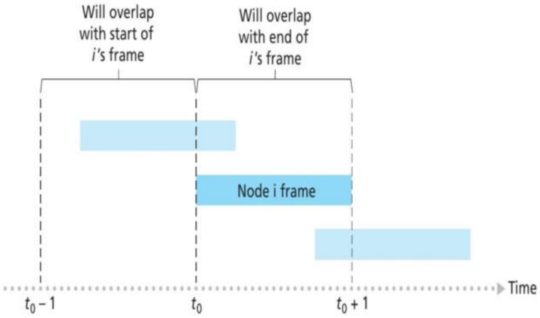
Efficiency of Slotted ALOHA

- Assume that each node always has a frame to send
- Probability that only one node (out of N) transmits
- $Np(1-p)^{N-1}$
- Efficiency $= Np(1-p)^{N-1}$
- Find p that maximizes efficiency, let it be p^*
- As $N \to \infty$, Efficiency $\to \frac{1}{e}$
- Only 37% of slots are used for successful transmission! a similar analysis show that 37% slots are empty and remaining slots have collisions.

Pure ALOHA

- Unslotted time axis
- Transmit a frame as soon as it arrives
- If there is a collision, node retransmits the frame immediately with probability p. Otherwise, wait for frame transmission time.
- After this wait, it then retransmits the frame with probability p or waits for another frame time with probability $1 - p$.

Pure ALOHA

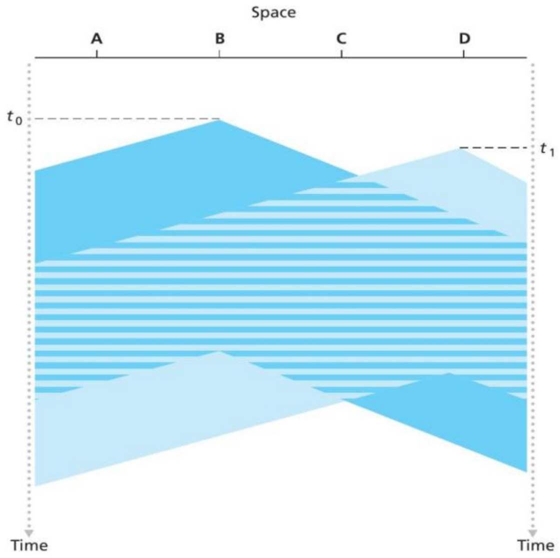


- Efficiency : $\frac{1}{2e}$

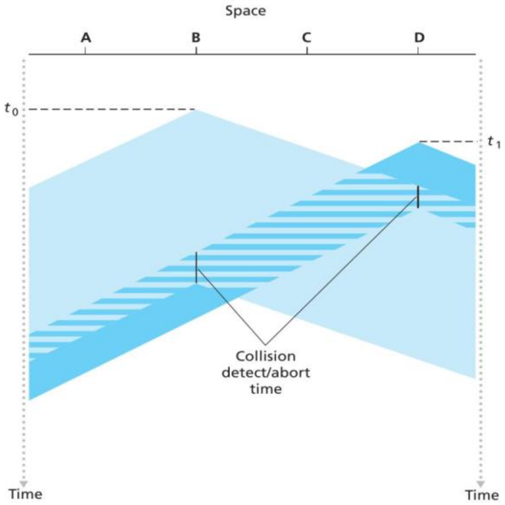
Carrier Sense Multiple Access

- Listen before speaking: carrier sensing
- If channel is busy, nodes 'backs off' a random amount of time and then senses again.
- If the channel is idle, node transmits the frame
- collision detection: If someone else begins talking at the same time, stop talking

CSMA



CSMA/CD

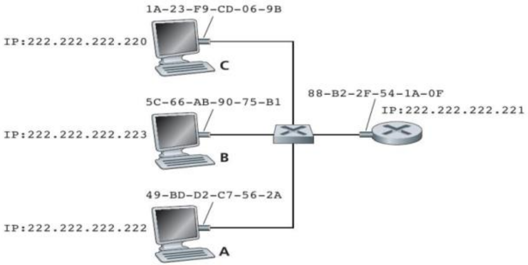


Taking-Turns Protocol

- Polling Protocol
  - Master node polls each of the nodes in a round-robin fashion
  - Polling delay
  - Master node may fail!
- Token-passing Protocol
  - A special-purpose frame known as a token is exchanged among the nodes
  - A node with token can transmit a maximum number of frames and send the token to next node
  - A node holds token only if it has frames to transmit
  - Very efficient.

Link-Layer Addressing

- Are IP addresses really unique?
- Node's adapter has a link-layer address
- Also known as LAN address or Physical address or MAC address
- MAC address
  - Managed by IEEE
  - Flat structure
  - Broadcast address : FF-FF-FF-FF-FF-FF



Address Resolution Protocol

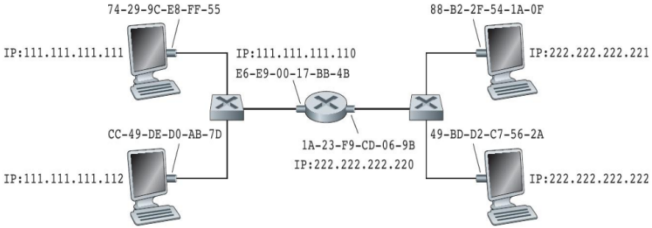
- Sending node has to provide it's link layer not only IP address of destination but also destination's MAC address
- How does the source node determines the MAC address of it's destination?
- Address Resolution Protocol (ARP)
- Analogous to DNS

IP Address	MAC Address	TTL
222.222.222.221	88-B2-2F-54-1A-0F	13:45:00
222.222.222.223	5C-66-AB-90-75-B1	13:52:00

ARP

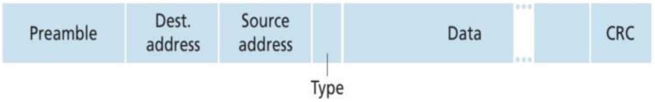
- Suppose node 222.222.222.220 wants to send a datagram to 222.222.222.222
- If ARP does not have an entry about the destination, it first constructs an ARP query packet.
- Query:
  - IP addresses of sender and receiver
  - sender's MAC address
  - Broadcast MAC address
- Encapsulated in a link-layer frame and sent in to the subnet
- Each node checks to see if its IP address matches with the destination address
- The one node with a match sends a ARP response packet with desired mapping

Sending a Datagram Off the Subnet



- Destination MAC address should be that of router's MAC on subnet 1
- The router determines the correct interface based on destination IP address
- After processing, router encapsulates the datagram in a frame with destination MAC address.

Ethernet



- Popular wired LAN technology
- Data field: minimum length is 46 bytes and maximum length is 1500 bytes
- Type field: specifies the protocol at network layer
- Preamble:
  - 8-bytes
  - first byte has value 10101010
  - last byte has value 10101011
  - to synchronize the clocks

Ethernet's MAC Protocol: CSMA/CD

- The adapter takes datagram from network layer and prepares Ethernet frame and keeps in adapter's buffer
- If the channel is idle for 96 bit times, it starts to transmit the frame
- If the channel is busy, it waits until it senses no signal energy plus 96 bit times and then starts to transmit the frame
- If the adapter transmits the entire frame without detecting collision, the adapter is finished with the frame
- If the adapter detects a collision, it stops transmitting its frame and instead transmits a 48-bit jam signal

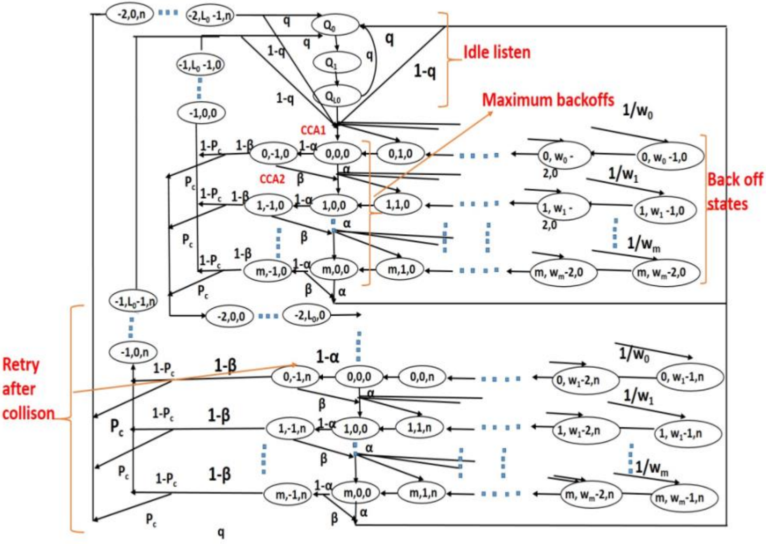
Ethernet's MAC Protocol: CSMA/CD

- After transmitting the jam signal, the adapter enters an exponential backoff phase.
- Exponential Backoff: After experiencing nth collision in a row for a frame, the adapter chooses a value for K at random from $\{0, 1, 2, \ldots, 2^m - 1\}$ for $m = \min(n, 10)$. The adapter then waits $K.512$ bit times and then returns to step 2.
- d_{prop} is maximum time it takes signal energy to propagate between any two adapters
- d_{trans} is the time to transmit a maximum size Ethernet frame.
- Efficiency $= \frac{1}{1+5d_{prop}/d_{trans}}$

IEEE 802.11 MAC

- IEEE 802.11 MAC - Carrier Sense Multiple Access - Collision Avoidance (CSMA/CA)
- Exponential Backoff delay
- *Minimum backoff exponent (m_0), backoff stages (m), Collision retries(n))*
- minimum delay and worst case delay

IEEE 802.11 MAC



IEEE 802.11 MAC

backoff stage-0: $2^{m_0} = 8$ slots
backoff stage-1: $2{*}2^{m_0} = 16$ slots
backoff stage-2: $4{*}2^{m_0} = 32$ slots
backoff stage-3: $8{*}2^{m_0} = 64$ slots
backoff stage-4: $16{*}2^{m_0} = 128$ slots
worst case backoff delay for 1 collision retry n = 0 is $8+16+32+64+128 = 248$ worst case backoff delay for 3 collision retries till n = 3 is $(248+2){*}4 = 1000$ backoff slots Worst case delay in seconds $= 1000{*}T_b = 1000$ milliseconds $= 1$ second

Link-layer Switch

- Forwarding: Switch function that determines an interface to which a frame should be directed
- Filtering: Switch function that determines whether a frame should be forwarded or dropped
- Self-Learning
- Elimination of collisions

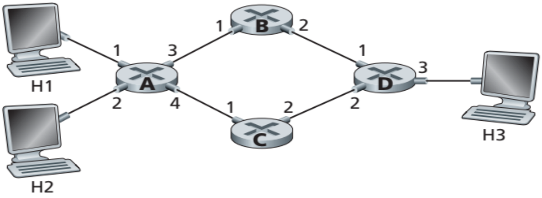
Tutorial_Network_Layer

a. Suppose that this network is a datagram network. Show the forwarding table in router A, such that all traffic destined to host H3 is forwarded through interface 3.

b. Suppose that this network is a datagram network. Can you write down a forwarding table in router A, such that all traffic from H1 destined to host H3 is forwarded through interface 3, while all traffic from H2 destined to host H3 is forwarded through interface 4? (Hint: this is a trick question.)

c. Now suppose that this network is a virtual circuit network and that there is one ongoing call between H1 and H3, and another ongoing call between H2 and H3. Write down a forwarding table in router A, such that all traffic from H1 destined to host H3 is forwarded through interface 3, while all traffic from H2 destined to host H3 is forwarded through interface 4.

d. Assuming the same scenario as (c), write down the forwarding tables in nodes B, C, and D.



Tutorial_Network_Layer

P8. In Section 4.3, we noted that the maximum queuing delay is $(n-1)D$ if the switching fabric is n times faster than the input line rates. Suppose that all packets are of the same length, n packets arrive at the same time to the n input ports, and all n packets want to be forwarded to *different* output ports. What is the maximum delay for a packet for the (a) memory, (b) bus, and (c) crossbar switching fabrics?

Tutorial_Network_Layer

Chapter - 4

P4 :-

a) Data to host H_3 → interface 3.

Destination Address (H3) | Link Interface 3.

b) Forwarding rule :- destination address.

~~$H_1 \to H_3$ → interface~~

Dest Address | Link interface.

$H_1 \to$ { (H3) is fixed } { Cannot be different }

$H_2 \to$ (H3)

c) For VC diagram

Incoming interface	Incoming VC	Outgoing Interface	Outgoing VC
1	12	3	22
2	63	4	18

P8

* Single datagram in both Memory and Shared bus.

(a) & (b) → delay. (n-1)D.

(c) * Cross-bar

Parallel flows for different i/p → o/p pairs

No Queing delay.

Tutorial_Network_Layer

P9 :

- Slot - 1 : i/p - ~~port~~ - 1 → X; i/p - 2 → Y Port
- Slot - 2 : i/p - 3 → Y Port (o/p)
- Slot - 3 : i/p - 2 → X; i/p - 3 → Z

Total - 3 slots

Even worst case scheduling is 3 slots.

P10

a)

Prefix	Interface
11100000 00	0
11100000 01000000	1
1110000	2
11100001 1	3
otherwise	3

b)

(First address) → 5th → Interface - 3
(Second address) → 3rd → Interface - 2
(third address) → 4th → " - 3

P11

8-bit	Interface	Address
00000000 – 111111	0	(6bit) 2^6 = 64
01000000 – 01011111	1	(5bit) 2^5 = 32
01100000 – 01111111	2	(5bit) 2^5 + (6bit) 2^6 = 32+64 = 96
10000000 – 10111111	2	
11000000 – 11111111	3	2^6 = 64/256

P13

given Prefix : 223.1.17/24

Subnet-1 to support = 60
Subnet-2 " " = 90
Subnet-3 " " = 12

Sub Net-1 ⟹ 60 ⟶ $2^6 = 64$ 32 bits − 6 = 26

223.1.17.0 /26

Sub Net-2 ⟹ 90 ⟶ $2^7 = 128$ 32 − 7 = 25

223.1.17.128/25

Subnet-3 ⟹ 12 ⟶ $2^4 = 16$ 32 − 4 = 28

223.1.17.192/28

P19

Assume header = 20

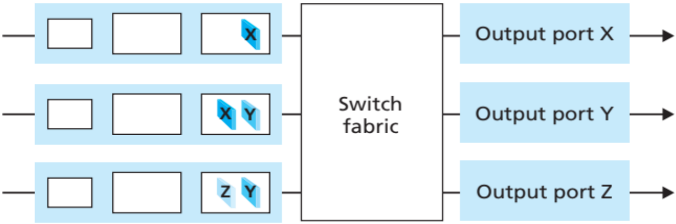
700 − 20 = 680

$= \frac{2400 - 20}{680} = 4$

data gram 1, 2 & 3 ⟶ 700
" − 4 ⟶ 360

	offset	flag	bytes	seq NO
D-1 :	0	1	700	422
D2 :	85	1	700	422
D-3 :	170	1	700	422
D-4 :	255	0	360	422

P9. Consider the switch shown below. Suppose that all datagrams have the same fixed length, that the switch operates in a slotted, synchronous manner, and that in one time slot a datagram can be transferred from an input port to an output port. The switch fabric is a crossbar so that at most one datagram can be transferred to a given output port in a time slot, but different output ports can receive datagrams from different input ports in a single time slot. What is the minimal number of time slots needed to transfer the packets shown from input ports to their output ports, assuming any input queue scheduling order you want (i.e., it need not have HOL blocking)? What is the largest number of slots needed, assuming the worst-case scheduling order you can devise, assuming that a non-empty input queue is never idle?



Tutorial_Network_Layer

P10. Consider a datagram network using 32-bit host addresses. Suppose a router has four links, numbered 0 through 3, and packets are to be forwarded to the link interfaces as follows:

Destination Address Range	Link Interface
11100000 00000000 00000000 00000000 through 11100000 00111111 11111111 11111111	0
11100000 01000000 00000000 00000000 through 11100000 01000000 11111111 11111111	1
11100000 01000001 00000000 00000000 through 11100001 01111111 11111111 11111111	2
otherwise	3

a. Provide a forwarding table that has five entries, uses longest prefix matching, and forwards packets to the correct link interfaces.

b. Describe how your forwarding table determines the appropriate link interface for datagrams with destination addresses:

11001000 10010001 01010001 01010101
11100001 01000000 11000011 00111100
11100001 10000000 00010001 01110111

P11. Consider a datagram network using 8-bit host addresses. Suppose a router uses longest prefix matching and has the following forwarding table:

Prefix Match	Interface
00	0
010	1
011	2
10	2
11	3

For each of the four interfaces, give the associated range of destination host addresses and the number of addresses in the range.

P13. Consider a router that interconnects three subnets: Subnet 1, Subnet 2, and Subnet 3. Suppose all of the interfaces in each of these three subnets are required to have the prefix 223.1.17/24. Also suppose that Subnet 1 is required to support at least 60 interfaces, Subnet 2 is to support at least 90 interfaces, and Subnet 3 is to support at least 12 interfaces. Provide three network addresses (of the form a.b.c.d/x) that satisfy these constraints.

Tutorial_Network_Layer

P19. Consider sending a 2400-byte datagram into a link that has an MTU of 700 bytes. Suppose the original datagram is stamped with the identification number 422. How many fragments are generated? What are the values in the various fields in the IP datagram(s) generated related to fragmentation?

P19. Consider sending a 2400-byte datagram into a link that has an MTU of 700 bytes. Suppose the original datagram is stamped with the identification number 422. How many fragments are generated? What are the values in the various fields in the IP datagram(s) generated related to fragmentation?

Tutorial_Link_Layer

P1. Suppose the information content of a packet is the bit pattern 1110 0110 1001 1101 and an even parity scheme is being used. What would the value of the field containing the parity bits be for the case of a two-dimensional parity scheme? Your answer should be such that a minimum-length checksum field is used.

Tutorial_Link_Layer

P3. Suppose the information portion of a packet (*D* in Figure 5.3) contains 10 bytes consisting of the 8-bit unsigned binary ASCII representation of string "Networking." Compute the Internet checksum for this data.

P5. Consider the 7-bit generator, G=10011, and suppose that D has the value 1010101010. What is the value of R?

P8. In Section 5.3, we provided an outline of the derivation of the efficiency of slotted ALOHA. In this problem we'll complete the derivation.

a. Recall that when there are N active nodes, the efficiency of slotted ALOHA is $Np(1-p)^{N-1}$. Find the value of p that maximizes this expression.

b. Using the value of p found in (a), find the efficiency of slotted ALOHA by letting N approach infinity. *Hint*: $(1 - 1/N)^N$ approaches $1/e$ as N approaches infinity.

Tutorial_Link_Layer

P10. Consider two nodes, A and B, that use the slotted ALOHA protocol to contend for a channel. Suppose node A has more data to transmit than node B, and node A's retransmission probability p_A is greater than node B's retransmission probability, p_B.

a. Provide a formula for node A's average throughput. What is the total efficiency of the protocol with these two nodes?

b. If $p_A = 2p_B$, is node A's average throughput twice as large as that of node B? Why or why not? If not, how can you choose p_A and p_B to make that happen?

c. In general, suppose there are N nodes, among which node A has retransmission probability $2p$ and all other nodes have retransmission probability p. Provide expressions to compute the average throughputs of node A and of any other node.

P17. Recall that with the CSMA/CD protocol, the adapter waits $K \cdot 512$ bit times after a collision, where K is drawn randomly. For $K = 100$, how long does the adapter wait until returning to Step 2 for a 10 Mbps broadcast channel? For a 100 Mbps broadcast channel?

P17. Recall that with the CSMA/CD protocol, the adapter waits $K \cdot 512$ bit times after a collision, where K is drawn randomly. For $K = 100$, how long does the adapter wait until returning to Step 2 for a 10 Mbps broadcast channel? For a 100 Mbps broadcast channel?

P19. Suppose nodes A and B are on the same 10 Mbps broadcast channel, and the propagation delay between the two nodes is 245 bit times. Suppose A and B send Ethernet frames at the same time, the frames collide, and then A and B choose different values of K in the CSMA/CD algorithm. Assuming no other nodes are active, can the retransmissions from A and B collide? For our purposes, it suffices to work out the following example. Suppose A and B begin transmission at $t = 0$ bit times. They both detect collisions at $t = 245$ bit times. Suppose $K_A = 0$ and $K_B = 1$. At what time does B schedule its retransmission? At what time does A begin transmission? (*Note*: The nodes must wait for an idle channel after returning to Step 2—see protocol.) At what time does A's signal reach B? Does B refrain from transmitting at its scheduled time?

Chapter- 5

P1 :-

```
1110 | 1
0110 | 0
1001 | 0
1101 | 1
-----+
1100 |
```

P2 :

```
1 1 1 0
0 1 0 0
1 0 0 1
1 1 0 1
```

Row-2

Can detect and Correct 1-bit

P3 :

Check-sum

Networking.
1 2 3 4 5 6 7 8 9 10

ASCII 2 bytes addition.

```
  01001100 01101001
  01101110 01101011
  -----------------
  10111010 11010100
+ 00100000 01001100
  -----------------
  11011011 00100000
+ 01100001 01111001
  -----------------
  00111100 10011010
+ 01100101 01110010
  -----------------
  10100010 00001100
```

1's Complement → 01011101 11110011

Tutorial_Link_Layer

P5 G = 10011 D = 1010101010 R = 4?

```
              20110
G = 10011 | 10101010100000
            10011
            ------
            001100l
              10011
            ------
              010100
               10011
            ------
               0011110
                 10011
            ------
                 011010
                  10011
            ------
                  010010
                   10011
            ------
                  0000100
```

R = 0100

P7 G = 1001 | 101110000

R = 011

P8 (8)

$$= NP(1-P)^{N-1}$$

$$N(1-P)^{N-1} + NP(1-P)^{N-2} \times (N-1) = 0$$

$$N\cancel{(1-P)^{N-1}}\left(1 - \frac{P(N-1)}{1-P}\right) \qquad N(1-P)^{N-2}\left(1-P-P(N-1)\right)$$

$$\frac{1-\cancel{P}-PN+\cancel{P}}{\cancel{1-P}} \qquad \frac{1-PN}{1-P} = 0 \qquad 1-\cancel{P}-PN+\cancel{P}$$

$$1 = NP \qquad P = \frac{1}{N}$$

$$= \frac{\cancel{N}}{N}\left(1-\frac{1}{N}\right)^{N-1}$$

$$= \lim_{N\to\infty} \frac{\left(1-\frac{1}{N}\right)^{N}}{1-\frac{1}{N} = 1} = \frac{N\cancel{\left(1-\frac{1}{N}\right)^{N-1} \times \frac{-1}{N^2}}}{\cancel{\frac{1}{N^2}}}$$

$$\left(1-\frac{1}{x}\right)^{x} = \lim_{N\to\infty}\left(1-\frac{1}{N}\right)^{N} = \frac{1}{e}$$

P9

$$= NP(1-P)^{N-1}(1-P)^{N-1}$$

$$= NP(1-P)^{2(N-1)}$$

P10

a) $\text{Ans thr} = P_A(1-P_B)$

$\text{Total} = P_A(1-P_B) + P_B(1-P_A)$

b) If $P_A = 2P_B$

$\text{Thr}_A = P_A(1-P_B) = 2P_B(1-P_B)$

$\text{Thr}_B = P_B(1-P_A) = P_B(1-2P_B) = P_B - 2P_B^2$

$\text{Th}_A \neq 2\,\text{Th}_B$

$P_A(1-P_B) = 2P_B(1-P_A) \implies P_A = 2-(P_A/P_B)$

Tutorial_Link_Layer

4

P_{11}

$\cancel{(1-p)^2}\ \cancel{(1-p)}$

$$(1-p)p^3 + (1-p)^2p^3 + (1-p)^3p^3 + (1-p)^4p^3$$

$$(1-p)(1-(1-p)^3) + (1-p)^2(1-(1-p)^3)$$

$$\left[1-(1-p)^3\right]\left[(1-p)+(1-p)^2+(1-p)^3+(1-p)^4\right]$$

$$(1-p)\left[1-(1-p)^3\right]\frac{1-(1-p)^5}{p}$$

P_{17}

$K = 100$

$= 512 \times K = \underline{512 \times 100}$

$= 100\ Mb/sec.$

Time for $512 \times 100 = \dfrac{512 \times 100}{10 \times 10^6} = \underline{51.2\ \mu sec}$

P_{19}

Time	Event
0	A & B → transmit
245	A & B → detect collision
245+48 = 293	A & B → transmit jam signal.
293+245 = 538	B's last bit at A
538+96 = 634	A starts transmitting
293+512 = 805 (k=1)	B starts to sense mode. +96 sense slots
634+245 = ~~854~~ 879	A reaches B

B → starts at 805+96 = 901, where A's bit reaches B at 879

NO – Collision.