1. (KR) Consider two hosts, A and B, connected by a single link of rate R bps. Suppose that the two hosts are separated by m meters, and suppose the propagation speed along the link is s meters/sec. Host A is to send a packet of size L bits to Host B.

   (a) Express the propagation delay, d_{prop} in terms of m and s.
   $d_{\text{prop}} = m/s$ seconds.

   (b) Determine the transmission time of the packet, d_{trans}, in terms of L and R.
   $d_{\text{trans}} = L/R$ seconds.

   (c) Ignoring processing and queueing delays, obtain an expression for the end-to-end delay.
   $d_{\text{end-to-end}} = m/s + L/R$ seconds.

   (d) Suppose Host A begins to transmit the packet at time $t = 0$. At time $t = d_{\text{trans}}$, where is the last bit of the packet?
   The bit is just leaving host A.

   (e) Suppose d_{prop} is greater than d_{trans}. At the time $t = d_{\text{trans}}$, where is the first bit of the packet?
   The first bit is in the link and has not yet reached Host B

   (f) Suppose d_{prop} is less than d_{trans}. At the time $t = d_{\text{trans}}$, where is the first bit of the packet?
   The first bit has already reached Host B.

   (g) Suppose $s = 2.4 \cdot 10^8$, $L = 1500$ bits, and $R = 512$ kbps. Find the distance m so that $d_{\text{prop}} = d_{\text{trans}}$.

$$m = Ls/R = \frac{1500 \times 2.4 \times 10^8}{512 \times 10^3} = 7.03125 \times 10^5 \text{ meters}$$

2. (KR) Suppose two hosts, A and B, are separated by 15,000 kilometers and are connected by a direct link of $R = 2.5$ Mbps. Suppose the propagation speed over the link is $2.2 \cdot 10^8$ meters/s.

   (a) Calculate the bandwidth delay product, $R \cdot d_{\text{prop}}$.

$$2.5 \times 10^6 \times \frac{15,000}{2.2 \times 10^5} = 170,454.545 \text{ bits}$$

   (b) Consider sending a file of 1,500,000 bits from Host A to Host B. Suppose the file is sent continuously as one large message. What is the maximum number of bits that will be in the link at any given time?
   170,454.545

   (c) Provide an interpretation of the bandwidth delay product.
   The bandwidth-delay product of a link is the maximum number of bits that can be in the link.

   (d) What is the width (in meters) of a bit in the link?
   The width of a bit = length of link / bandwidth-delay product, so 1 bit is $\frac{15000 \times 10^3}{170,454.545} =$ 87.99999998 meters long, which is almost the length football field.

   (e) Derive a general expression for the width of a bit in terms of the propagation speed s, the transmission rate R, and the length of the link m.
   s/R

   (f) If we can modify R, for what value of R is the width of a bit as long as the length of the link?

$$R = s/15000, \text{km} = 2.2 * 10^5/(15 * 10^3) = 14.66667 \,\text{bps}$$

3. (KR) Consider queueing delay in a router buffer (preceding an outbound link). Suppose all packets are L bits, the transmission rate is R bps, and that N packets simultaneously arrive at the buffer every LN/R seconds.

(a) Find the average queueing delay of a packet. (Hint: The queueing delay for the first packet is zero; for the second packet, L/R; for the third packet $2L/R$. The Nth packet has already been transmitted when the second batch of packets arrives.)

$$\frac{(N-1)L}{2R}$$

4. (KR) Suppose users share a 4 Mbps link. Also suppose each user requires 100 kbps when transmitting, but each user transmits only 10 percent of the time.

   (a) When circuit switching is used, how many users can be supported?
   40 users.

   (b) For the remainder of this problem, suppose packet switching is used. Find the probability that a given user is transmitting.
   $p = 0.1$

   (c) Suppose there are 40 users. Find the probability that at any given time, exactly n users are transmitting simultaneously. (Hint: Use the binomial distribution.)

   $$\binom{40}{n} p^n (1-p)^{40-n}$$

   (d) Find the probability that there are 15 or more users transmitting simultaneously.

   $$\binom{40}{n} p^n (1-p)^{40-n}$$

5. (KR) Consider a case of statistical multiplexing where users are generating data at a rate of 100 kbps when busy, but are busy generating data only with probability $p = 0.2$. Suppose the link is a 2 Gbps link.

   (a) What is N, the maximum number of users that can be supported simultaneously under circuit switching?

   $$N = \frac{2 \times 10^9}{100 \times 10^3} = 20,000$$

   (b) Now consider packet switching and a user population of M users. Give a formula (in terms of p, M, N) for the probability that more than N users are sending data.

   $$1 - \sum_{k=0}^{N} \binom{M}{k} p^k (1-p)^{M-k}$$

   or

   $$\sum_{k=N+1}^{M} \binom{M}{k} p^k (1-p)^{M-k}$$

6. (KR) Consider a packet of length L which begins at end system A, travels over one link to a packet switch (store and forward), and travels from the packet switch over a second link to a second packet switch and finally over a third link to the destination end system. Let D_i, s_i, and R_i denote the length, propagation speed, and the transmission rate of link i, for $i = 1, 2, 3$. The packet switches delay each packet by L/R_i.

   (a) Assuming no queueing delays, in terms of D_i, s_i, and R_i ($i = 1, 2, 3$), and L, what is the total end-to-end delay of the packet?

$$d_{end-to-end} = L/R_1 + L/R_2 + L/R_3 + D_1/s_1 + D_2/s_2 + D_3/s_3 + L/R_1 + L/R_2$$

   (b) Suppose the length of a message is 4 packets. Each packet is 1,500 bytes, the propagation speed on all links is $2.5 \cdot 10^8$ m/s, the transmission rates of all links is 1Mbps, the packet switch processing delay is 1 msec, the length of the first link is 5,000 km, and the length of the last two links is 1,000 km. For these values what is the end-to-end delay?

$$6 * \frac{1500 \times 8}{1 \times 10^6} + \frac{7 \times 10^3}{2.5 \times 10^8} + 0.002 = 102 \text{ ms}$$

   If switch processing delay is not considered 100ms. If processing delay is per packet 108ms

   (c) Suppose the data rate of the last link is 2 Mbps, what is the end-to-end delay?

$$5 * \frac{1500 \times 8}{1 \times 10^6} + \frac{1500 \times 8}{2 \times 10^6} + \frac{7 \times 10^3}{2.5 \times 10^8} + 0.002 = 96 \text{ ms}$$

   If switch processing delay is not considered 94ms. If processing delay is per packet 102ms

   (d) Suppose the data rate of the first link is 2 Mbps and on the other links it is 1 Mbps, what is the end-to-end delay?

$$5 * \frac{1500 \times 8}{1 \times 10^6} + \frac{1500 \times 8}{2 \times 10^6} + \frac{7 \times 10^3}{2.5 \times 10^8} + 0.002 = 96 \text{ ms}$$

   If switch processing delay is not considered 94ms. If processing delay is per packet 102ms

7. (PD) Suppose a 1-Gbps point-to-point link is being set up between the Earth and a new lunar colony. The distance from the moon to the Earth is approximately 385,000 km, and data travels over the link at the speed of light -3×10^8m/s.

   (a) Calculate the minimum RTT for the link.

$$2 \times 385,000,000m/3 \times 10^8 m/s = 2.57s$$

   Using the RTT as the delay, calculate the delay $\times$ bandwidth product for the link. 2.57Gb

   (b) A camera on the lunar base takes pictures of the Earth and saves them in digital format to a disk. Suppose Mission Control on Earth wishes to download the most current image, which is 25MB. What is the minimum amount of time that will elapse between when the request for data goes out and the transfer is finished? $0.2 + 2.57 = 2.77$sec

8. (PD) Calculate the effective bandwidth for the following cases. For (a) and (b) assume there is a steady supply for data to send; for (c) calculate the average over 12 hours.

   (a) 12,000 byte packets over 100Mbps Ethernet through three store-and-forward switches. Switches can send on one link while receiving on the other.
   Effective bandwidth is 100Mbps.

   (b) Same as (a) but with the sender having to wait for a 50-byte acknowledgement packet after sending each 12,000-bit data packet.
   Data packet takes 520μs, ACKs take total 56μs, total RTT is 576μs. 1200 bits in 576μs is about 20.8 Mbps.

(c) Overnight (12-hour) shipment of 100 DVDs that hold 4.7 GB each. $100 \times 4.7 \times 10^11 bytes/(12 \times 3600s) = 87Mbps$.

9. (PD) Calculate the delay × bandwidth product for the following links. Use one-way delay, measured from first bit sent to first bit received.
   (a) 100-Mbps Ethernet with a delay of 10 μs. 125 bytes
   (b) 100-Mbps Ethernet with a single store-and-forward switch, packet size of 12,000 bits and 10μs per link propagation delay. 650bytes
   (c) 1.5-Mbps T1 link, with a transcontinental one-way delay of 50ms.9375 bytes
   (d) 1.5-Mbps T1 link between two ground stations communicating via satellite in geosynchronous orbit 35900 km high. The only delay is speed of light propagation delay from Earth to the satellite and back. 360,000 bits

10. (PD) Suppose that a certain communications protocol involves a per-packet overhead of 50 bytes for headers and framing. We send 1 million bytes of data using this protocol; however, one data byte is corrupted and the entire packet containing it is thus lost. Give the total number of overhead + loss bytes for packet data sizes of 1000, 10,000, and 20,000 bytes. Which size is optimal?
    1000 = 51000, 10000=15000, 20000=22500

11. (PD) For the following, assume that no data compression is done, although in practice this would almost never be the case. For (a) to (c), calculate the bandwidth necessary for transmitting in real time.
    (a) Video at a resolution of 640 × 480, 3 bytes/pixel, 30 frames a second.
    26.4MB/sec
    (b) Video at a resolution of 160 × 120, 1 byte/pixel, 5 frames a second.
    94KB/sec
    (c) CD-ROM music, assuming one CD holds 75 minutes' worth and takes 650 MB.
    148KB/sec
    (d) Assume a fax transmits an 8×10-inch black-and-white image at a resolution of 72 pixels per inch. How long would his take over a 14.4-kbps modem?
    28.8 sec

12. (PD) Discuss the relative performance needs of the following applications in terms of average bandwidth, peak bandwidth, latency, jitter, and loss tolerance:
    (a) File server.
    Needs lots of peak bandwidth. Latency is a problem if it dominated bandwidth. No lost data is tolerated, but can be retransmitted.
    (b) Print server.
    Requires less bandwidth and more latency tolerant.
    (c) Digital library.
    Similar to file server
    (d) Routine monitoring of remote weather instruments.
    Latency and jitter is not much of a problem.
    (e) Voice.
    need guarantees on average bandwidth, latency and jitter.
    (f) Video monitoring of a waiting room.
    guaranteed average bandwidth
    (g) Television broadcasting.
    lots of bandwidth, some loss acceptable. Jitter is OK of there is sufficient room in the buffer.