Homework 1

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Problem 1 (20 points). Consider figure 1, where the sender transmits one packet of size L = 1 KB (kilobytes). The link speed are $R_1 = R_2 = R_3$ = 1 Mbps (megabits per second). The length of each link is 100 Km. Compute the end-to-end delay for the following situations. We assume that the propagation speed of the packet is 20,000 Km/s, and that the processing time of the packet at each router is 5 µs.

Given:

- Sender transmit one packet of size ⇒ $L = 1KB$
- Link speed $R_1 = R_2 = R_3 = 1$ Mbps
- Length of each link = 100Km
- propagation speed of the packet = 20 000 km/s
- processing time of the packet at each router = 5 µs = 0.000005 s
- Number of routers = 3
- Number of links = Number of routers − 1 = 3 − 1 ⇒ $N = 2$

(a) Both routers are store-and-forward routers.

- packet transmission delay: $L/R = 1000B / 1Ms = 1ms$
- Propagation Delay: Length of each Link / Propagation speed of packet

$$= 100/20000 = 0.005s$$

- End to end delay: $N \cdot (\text{transmission delay} + \text{propagation delay}) + 2(\text{processing time})$

$$= 3(0.001 + 0.005) + 2(0.000005s)$$

$$= 18.01 \text{ ms}$$

(b) Both routers are cut-through routers. Note that a cut-through router does not wait for the entire packet to arrive before it starts the transmission of the packet. (Remark: In reality, there are cut-through switches instead of cut-through routers. But, for this problem, we assume there are cut-through routers.)

- Transmission Delay: $L/R = 0$
- Propagation Delay: $100/20000 = 0.005$ s
- processing Delay: 0

End to end delay = N(transmission delay + propagation delay + processing Delay)

$= 2(0.005)$

$= 0.15$ s

(c) Suppose $R_1 = R_2 = R_3 = 1$ Gbps (gigabits per second). Repeat part (a) and (b).

We are only changing the packet transmission delay since it is $\left(\frac{L}{R}\right)$

c.1

End to end Delay

$= 3(\text{propagation delay} + 0.005) + 2(0.000005)$

Transmission delay $= \left(\frac{L}{R}\right)$

$= \frac{1000\text{ B}}{1\text{ Gbps}} = 1\ \mu s$

End to End delay = 0.015013 seconds

c.2

End to End Delay

$= 3(\text{propagation delay}) + 2(0.000005)$

$= 0.01501$ s

(d) Again repeat part (a) and (b). However, now, $R_1 = R_2 = 2$ Mbps, and $R_3 = 1$ Mbps. Three packets of the same length, each with $L = 1$KB, are transmitted at the sender. What is the end-to-end delay of each packet? For simplicity, you may neglect the processing time, which is small compare with other delays. Also, you need not count packets' waiting time at the sender.

d.1 Store-and-forward

Transmission Delay R_1 & R_2 = $\left(\frac{L}{R}\right)$

$= \left(\frac{1000B}{2}\right) = 5\times10^{-4}$

Transmission Delay R3 = 1 Ms

End to End Delay =

$2(5\times10^{-4} + 0.005)$

$+ (1 Ms + 0.005)$

$= 0.106$ sec

d.2

Transmission Delay R1 & R2 = $\frac{L}{R}$

$= 1000B/2 = 5\times10^{-4}$

Transmission delay R3 = $\frac{L}{R}$

= 1 Ms

End to End delay =

$= 2(5\times10^{-4})$

$+ (1 Ms)$

$= 1.0001\times10^{-3}$ sec

(e) For the situation in (d), draw a timing diagram by completing figure 2 and identify the queueing delay of each packet. Again, you may neglect the processing time.

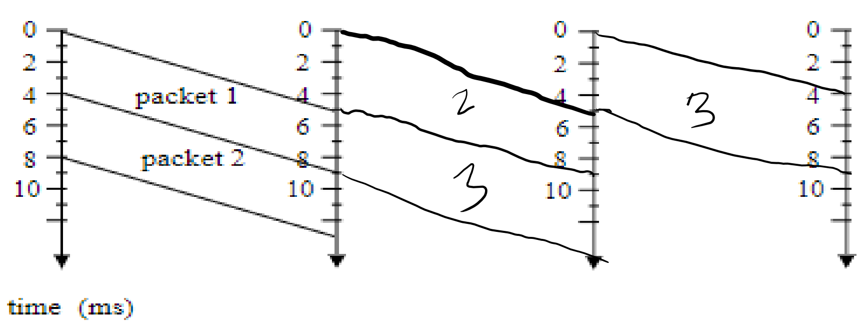


Figure 2. Timing diagram

Problem 2 (20 points). Instead of specifying the starting and ending times of packet transmission (e.g., Problem 1 (e)), an alternative way of describing the traffic generating process is to think the traffic as a bit stream. This continuous approximation of the packet generating process is called the fluid model or the fluid approximation.

One can also make a simple model to understand each output link of a router. This is illustrated in Figure 3. The buffer in the figure accepts and queues data (either packets or bit stream) from a number of connections (i.e., sender-receiver pairs). The queue is serviced when the output link transmits the data. This abstract model is called a multiplexer.

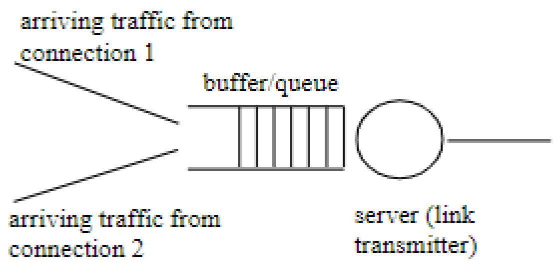


Figure 3. A multiplexer that models one output link of a router

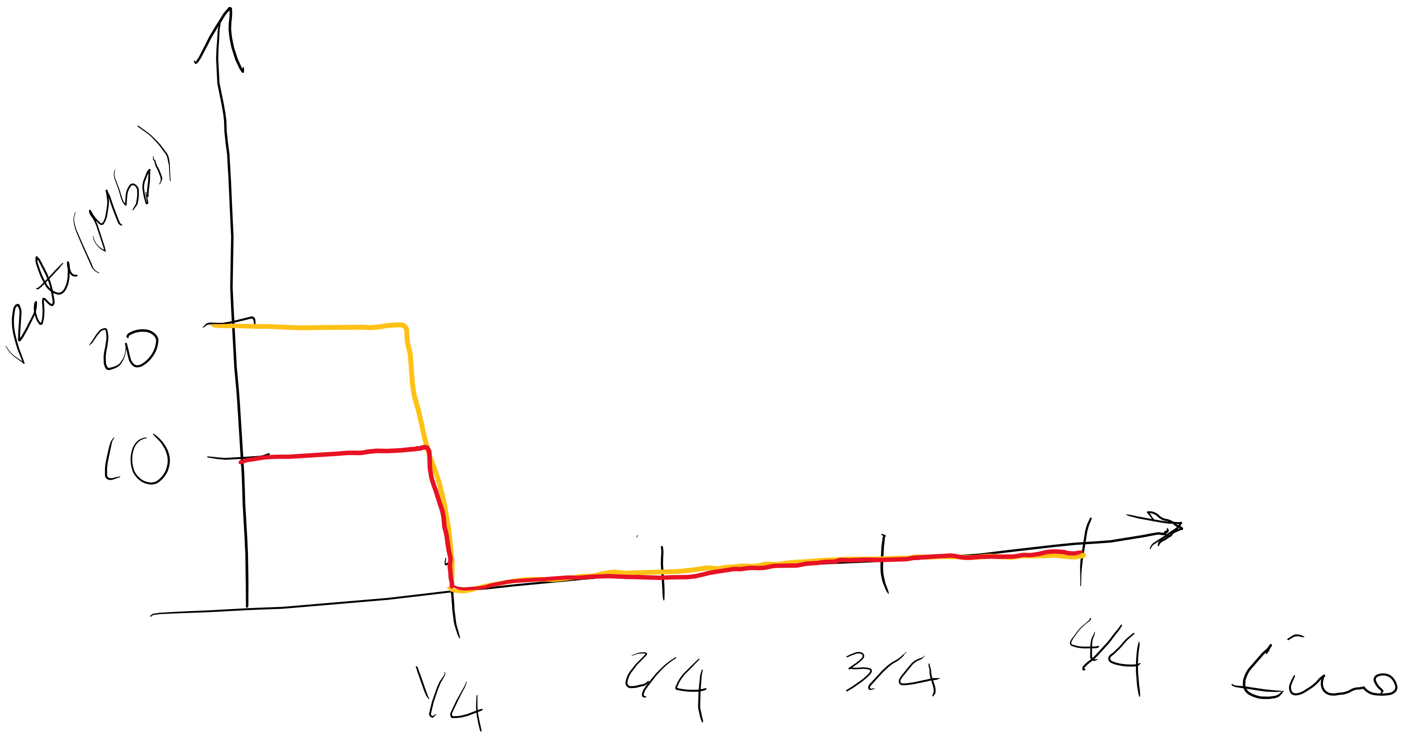
Here is the question. Suppose one bit stream arrives at a buffer. The rate of the bit stream is a periodic function of time with period $T = 1$ second. During $[0, T/4]$, the rate is equal to 10 Mbps and during $(T/4, T)$, it is equal to zero. A transmitter with rate R bps serves the buffer by sending the bits whenever available.

(a) Draw a diagram that shows the occupancy of the buffer as a function of time, for different ranges of values for R.
(b) What is the minimum value R_0 of R so that this occupancy does not keep growing?
(c) For $10 \geq R \geq R_0$, express the average delay $D(R)$ per bit as a function of R.
(d) For $10 \geq R \geq R_0$, express the average buffer occupancy (over time) $L(R)$ as a function of R.
(e) Show that $L(R) = \lambda\, D(R)$, where $\lambda = 2.5$ Mbps is the average arrival rate of the bits. This is an example of the *Little's Formula*.

Hint: When we say average delay, we almost always mean the average delay *experienced by incoming customers*; here, it means the average delay *expeirenced by incoming bits*. On the other hand, when we say the average number in a system such as the average buffer occupancy, the *averaging is over time* unless specified otherwise.

Recall that, for a function of time over a time interval, the time average is the integral of the function over that interval, divided by the length of the interval. The integral of the function on the interval is equal to the area underneath the function on that interval. To compute the aveage buffer occupancy, you integrate the function of buffer occupancy over the interval *[0, T]* and divide it by *T*. For the avearge delay, you **don't** integrate the delay function over the interval *[0, T]*; you do so on the interval *[0, T/4]* and then divide the result by *T/4*. The reason is that we are computing the average delay experienced by the incoming traffic (i.e., bits) and there are no bits arriving on the remaining interval *[T/4, T]*.

a)



b) $\int_0^{3/4} 10x\,dx = 2.8125$ ms

c) $\dfrac{\int_0^1 10x\,dx}{1} = D(x) \Rightarrow 0.5\mu s$

d) $I(x) = \dfrac{\int_0^{1/4} 20x\,dx}{0.25} \Rightarrow 1.25$

e) $1.25 = 2.5(0.5)$

P3. Consider an application that transmits data at a steady rate (for example, the sender generates an N-bit unit of data every k time units, where k is small and fixed). Also, when such an application starts, it will continue running for a relatively long period of time. Answer the following questions, briefly justifying your answer:

a. Would a packet-switched network or a circuit-switched network be more appropriate for this application? Why?

b. Suppose that a packet-switched network is used and the only traffic in this network comes from such applications as described above. Furthermore, assume that the sum of the application data rates is less than the capacities of each and every link. Is some form of congestion control needed? Why?

a) A circuit switched network is the best option for this can kind of application, since we know it will run for long periods of time, we know we will have smooth bandwidth requirements. Thus, it is at a steady state, and will have dedicated resources.

b) In this situation we will not need any congestion control mechanism, since the links have sufficient bandwidth to handle the sum of all the application data rates, we have dedicated resources.

P8. Suppose users share a 3 Mbps link. Also suppose each user requires 150 kbps when transmitting, but each user transmits only 10 percent of the time. (See the discussion of packet switching versus circuit switching in Section 1.3.)

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

b. For the remainder of this problem, suppose packet switching is used. Find the probability that a given user is transmitting.

c. Suppose there are 120 users. Find the probability that at any given time, exactly n users are transmitting simultaneously. (*Hint*: Use the binomial distribution.)

d. Find the probability that there are 21 or more users transmitting simultaneously.

a) Bandwidth = 3 Mbps Each User = 150 Kbps

Max number of users: $\frac{3 \times 10^6}{150 \times 10^3} = \frac{3 \times 10^3}{150} = \frac{300\cancel{0}}{15\cancel{0}} = 20$ users

b) Each users transmits only 10%, thus $\frac{10}{100}$ ⇒ the probability is 0.1

c) Succes = 0.1 Failure = 0.9 Users = 120

$P(n) = 120_{C_n} (0.1)^n (0.9)^{120-n} \Rightarrow P(1) = 0.043$

d) $\underline{120C_{21}(0.1)^{21}(0.9)^{120-21} + \cdots} \Rightarrow 1 - \sum_{n=0}^{20} 120C_n (0.1)^n (0.9)^{120-n}$

total probability 0 to 20

P14. Consider the queuing delay in a router buffer. Let I denote traffic intensity; that is, $I = La/R$. Suppose that the queuing delay takes the form $IL/R\,(1 - I)$ for $I < 1$.

a. Provide a formula for the total delay, that is, the queuing delay plus the transmission delay.

b. Plot the total delay as a function of L/R.

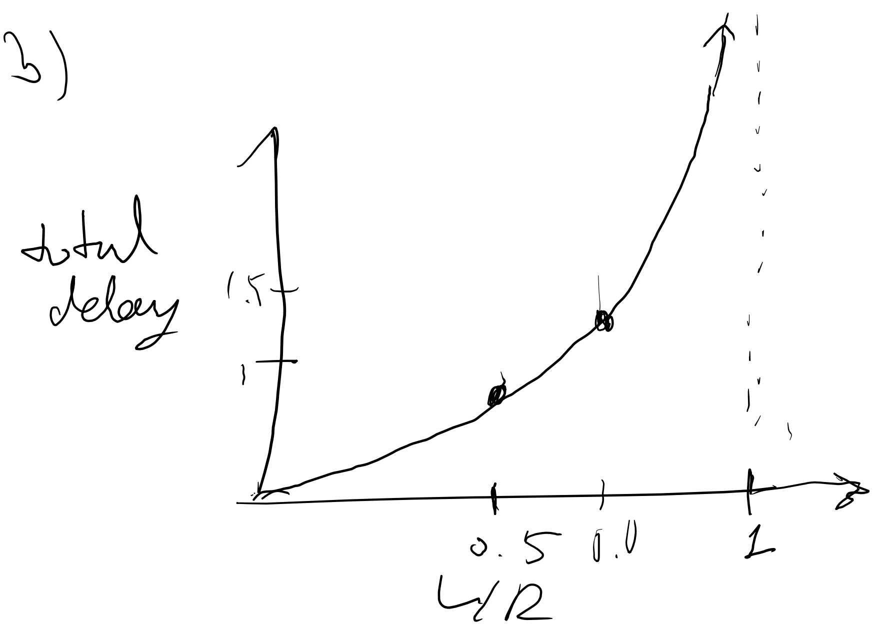
a) Total Delay = Queing Delay + Transmission delay =

$$= \frac{IL}{R(1-I)} + \frac{L}{R} = \frac{L}{R}\left[\frac{I}{1-I} + 1\right]$$

$$= \frac{L}{R}\left[\frac{1}{1-a(L/R)}\right] = \frac{L/R}{1-a(L/R)}$$

$a = 1 \quad x = L/R \Rightarrow f(x)\ \frac{x}{1-a(x)}$

b)



Problem 6 (5 points). Chapter 1, P16. This problem has a mistake. First, try to work out the solutions in the most obvious way. You will need to apply Little's formula twice. Then, find the mistake. You should read a bit about Little's Law, say, on Wikipedia.

Hint: The average number of packets in the system N can be split into two parts: the average number in the buffer and the aveage number in transmission. In general, the average (averaged over time) number in transmission, call it M, is **not** equal to 1 because it is possible that sometimes the system is idle and there is nothing to transmit. We actually don't know what M is. But, the problem tells us $N=10+M$. We can use Little's formla and get

$$a \cdot d = 10 + M \qquad (1)$$

Here, d is the average (total) queueing delay, which is 20 ms. It includes two components: the aveage waiting time in the queue and the average transmission time for a packet. The latter is always equal to 10 ms. Recall that when we say average delay, we almost always mean the average delay *experienced by a packet*. The average transmission delay experienced by a packet is always 10 ms, regardless the system load. On the other hand, when we say the average number in a system, we mean the *average number over time* unless specified otherwise.

In (1), there are two unknows, a and M. Fortunately, we can use Little's formula again. This time focus on the transmission part of the system.

$$a \times 0.01 = M \qquad (2)$$

That is, the average arrival rate multiplied by the average transmission delay is equal to the average number of packets in transmission. From (1) and (2), you will be able to compute a and M.

After your computation, you will find the mistake of the problem. The arrival rate a is greater than the transmission rate! The queue is unstable (it goes to infinity). Little formula is valid only for a stable system, i.e., when the queue is stable. The scenario described by the problem cannot happen.

P16. Consider a router buffer preceding an outbound link. In this problem, you will use Little's formula, a famous formula from queuing theory. Let N denote the average number of packets in the buffer plus the packet being transmitted. Let a denote the rate of packets arriving at the link. Let d denote the average total delay (i.e., the queuing delay plus the transmission delay) experienced by a packet. Little's formula is $N = a \cdot d$. Suppose that on average, the buffer contains 10 packets, and the average packet queuing delay is 10 msec. The link's transmission rate is 100 packets/sec. Using Little's formula, what is the average packet arrival rate, assuming there is no packet loss?

$N + M = a \cdot d$, $N = 10$, Link transmission rate $= 100/s$

$= 1$ packet$/0.01$ sec

queuing delay $= 10$ msec

$q = 0.01$ sec $\quad l = 0.01$

Averge total delay $\Rightarrow d = l + q = 0.02$ sec

1) $a \cdot d = 10 + M \Rightarrow a(0.02) = 10 + M \qquad d = 0.02$

2) $a \times 0.01 = M \qquad a(0.02) = 10 + (a \times 0.01)$

$a(0.01) = 10 \Rightarrow a = 10/0.01 = 1000$

$1000 > 0.01 \Rightarrow$ goes to infinity, buffer always fill

P18. Perform a Traceroute between source and destination on the same continent at three different hours of the day.

a. Find the average and standard deviation of the round-trip delays at each of the three hours.

b. Find the number of routers in the path at each of the three hours. Did the paths change during any of the hours?

c. Try to identify the number of ISP networks that the Traceroute packets pass through from source to destination. Routers with similar names and/or similar IP addresses should be considered as part of the same ISP. In your experiments, do the largest delays occur at the peering interfaces between adjacent ISPs?

d. Repeat the above for a source and destination on different continents. Compare the intra-continent and inter-continent results.

a)

Windows PowerShell

```
Trace complete.
PS C:\Users\thoma> tracert ufl.edu

Tracing route to ufl.edu [128.227.36.35]
over a maximum of 30 hops:

  1     3 ms     3 ms     3 ms  dsldevice.attlocal.net [192.168.1.254]
  2     4 ms     4 ms     4 ms  23-123-104-1.lightspeed.dybhfl.sbcglobal.net [23.123.104.1]
  3     7 ms     7 ms     7 ms  99.168.25.112
  4    10 ms    10 ms    10 ms  99.134.205.130
  5    13 ms    12 ms    13 ms  12.83.114.33
  6    26 ms    25 ms    25 ms  ggr2.attga.ip.att.net [12.122.140.93]
  7    23 ms    22 ms    23 ms  192.205.33.42
  8    28 ms    28 ms    28 ms  mai-b2-link.ip.twelve99.net [62.115.113.49]
  9    28 ms    28 ms    28 ms  mai-b1-link.ip.twelve99.net [62.115.125.7]
 10    28 ms    29 ms    29 ms  gatech-ic309959-mai-b1.ip.twelve99-cust.net [62.115.44.26]
 11    42 ms    42 ms    42 ms  orl-flrcore-asr9010-1-hu0600-1.net.flrnet.org [108.59.31.152]
 12    43 ms    45 ms    43 ms  jax-flrcore-asr9010-1-hu0701-1.net.flrnet.org [108.59.31.150]
 13    45 ms    45 ms    46 ms  con-ufl-gnv-internet-v1804.net.flrnet.org [108.59.29.243]
 14    46 ms    45 ms    46 ms  ssrb230a-pel-asr9001-1-v16-1.ns.ufl.edu [128.227.236.204]
 15     *        *        *     Request timed out.
 16    47 ms    45 ms    45 ms  ssrb230a-nexus-msfc-1-v15-1.ns.ufl.edu [128.227.236.202]
 17    42 ms    44 ms    42 ms  ssrb230a-dcpop13-7009-1-vdc2-v601-1.ns.ufl.edu [128.227.236.155]
 18    45 ms    46 ms    45 ms  presidentsearch.ufl.edu [128.227.36.35]

Trace complete.
PS C:\Users\thoma> tracert ufl.edu

Tracing route to ufl.edu [128.227.36.35]
over a maximum of 30 hops:

  1     3 ms     3 ms     3 ms  dsldevice.attlocal.net [192.168.1.254]
  2     5 ms     4 ms     4 ms  23-123-104-1.lightspeed.dybhfl.sbcglobal.net [23.123.104.1]
  3     7 ms     7 ms     7 ms  99.168.25.112
  4    11 ms    10 ms    10 ms  99.134.205.130
  5    14 ms    41 ms    13 ms  12.83.114.33
  6    28 ms    26 ms    26 ms  ggr2.attga.ip.att.net [12.122.140.93]
  7    23 ms    23 ms    23 ms  192.205.33.42
  8    29 ms    28 ms    28 ms  mai-b2-link.ip.twelve99.net [62.115.113.49]
  9    29 ms    29 ms    28 ms  mai-b1-link.ip.twelve99.net [62.115.125.7]
 10    29 ms    28 ms    28 ms  gatech-ic309959-mai-b1.ip.twelve99-cust.net [62.115.44.26]
 11    43 ms    42 ms    42 ms  orl-flrcore-asr9010-1-hu0600-1.net.flrnet.org [108.59.31.152]
 12    44 ms    44 ms    51 ms  jax-flrcore-asr9010-1-hu0701-1.net.flrnet.org [108.59.31.150]
 13    45 ms    45 ms    44 ms  con-ufl-gnv-internet-v1804.net.flrnet.org [108.59.29.243]
 14    45 ms    45 ms    45 ms  ssrb230a-pel-asr9001-1-v16-1.ns.ufl.edu [128.227.236.204]
 15     *        *        *     Request timed out.
 16    87 ms    44 ms    45 ms  ssrb230a-nexus-msfc-1-v15-1.ns.ufl.edu [128.227.236.202]
 17    42 ms    44 ms    42 ms  ssrb230a-dcpop13-7009-1-vdc2-v601-1.ns.ufl.edu [128.227.236.155]
 18    46 ms    45 ms    45 ms  presidentsearch.ufl.edu [128.227.36.35]

Trace complete.
PS C:\Users\thoma> tracert ufl.edu

Tracing route to ufl.edu [128.227.36.35]
over a maximum of 30 hops:

  1     3 ms     3 ms     3 ms  dsldevice.attlocal.net [192.168.1.254]
  2     5 ms     4 ms     4 ms  23-123-104-1.lightspeed.dybhfl.sbcglobal.net [23.123.104.1]
  3     8 ms     7 ms     7 ms  99.168.25.112
  4    11 ms    11 ms    11 ms  99.134.205.130
  5    12 ms    13 ms    10 ms  12.83.114.33
  6    27 ms    29 ms    25 ms  ggr2.attga.ip.att.net [12.122.140.93]
  7    23 ms    22 ms    23 ms  192.205.33.42
  8    29 ms    28 ms    28 ms  mai-b2-link.ip.twelve99.net [62.115.113.49]
  9    29 ms    28 ms    28 ms  mai-b1-link.ip.twelve99.net [62.115.125.7]
 10    28 ms    28 ms    28 ms  gatech-ic309959-mai-b1.ip.twelve99-cust.net [62.115.44.26]
 11    65 ms    76 ms    69 ms  orl-flrcore-asr9010-1-hu0600-1.net.flrnet.org [108.59.31.152]
 12    50 ms    44 ms    43 ms  jax-flrcore-asr9010-1-hu0701-1.net.flrnet.org [108.59.31.150]
 13    47 ms    47 ms    46 ms  con-ufl-gnv-internet-v1804.net.flrnet.org [108.59.29.243]
 14    48 ms    46 ms    45 ms  ssrb230a-pel-asr9001-1-v16-1.ns.ufl.edu [128.227.236.204]
 15     *        *        *     Request timed out.
 16    45 ms    45 ms    45 ms  ssrb230a-nexus-msfc-1-v15-1.ns.ufl.edu [128.227.236.202]
 17    43 ms    49 ms    42 ms  ssrb230a-dcpop13-7009-1-vdc2-v601-1.ns.ufl.edu [128.227.236.155]
 18    44 ms    45 ms    45 ms  virtual-12www-prod-ac-publicssl.server.ufl.edu [128.227.36.35]

Trace complete.
```

	Average	Standard deviation
1	28.21	17.69
2	26.89	16.71
3	27.89	18.81

b) There were 18 routes in the path for each of the times. There were no changes

c) 14 ISPs. Yes, in this experiment the largest delays occurred at peering interfaces between adjacent ISPs

d)

```
PS C:\Users\thoma> tracert google.com.nz

Tracing route to google.com.nz [23.202.231.169]
over a maximum of 30 hops:

  1     3 ms     3 ms     3 ms  dsldevice.attlocal.net [192.168.1.254]
  2     5 ms     4 ms     4 ms  23-123-104-1.lightspeed.dybhfl.sbcglobal.net [23.123.104.1]
  3     7 ms     8 ms     7 ms  99.168.25.112
  4    12 ms    10 ms    13 ms  99.134.205.130
  5    11 ms    12 ms    10 ms  12.83.114.29
  6    21 ms    20 ms    19 ms  12.123.43.197
  7    22 ms    22 ms    22 ms  12.247.68.178
  8    20 ms    20 ms    20 ms  ae8.r02.atl01.icn.netarch.akamai.com [23.207.235.40]
  9    37 ms    37 ms    37 ms  ae14.r01.iad01.icn.netarch.akamai.com [23.32.63.41]
 10    47 ms    36 ms    35 ms  ae1.r01.iad01.atn.netarch.akamai.com [23.209.164.29]
 11    49 ms    39 ms    47 ms  ae0.r03.iad01.atn.netarch.akamai.com [23.209.164.39]
 12    46 ms    43 ms    38 ms  ae26.ech-iad-a.netarch.akamai.com [23.209.164.65]
 13    37 ms    37 ms    37 ms  a23-202-231-169.deploy.static.akamaitechnologies.com [23.202.231.169]

Trace complete.
PS C:\Users\thoma> tracert google.com.nz

Tracing route to google.com.nz [23.202.231.169]
over a maximum of 30 hops:

  1     3 ms     3 ms     2 ms  dsldevice.attlocal.net [192.168.1.254]
  2     4 ms     4 ms     4 ms  23-123-104-1.lightspeed.dybhfl.sbcglobal.net [23.123.104.1]
  3    21 ms     8 ms     7 ms  99.168.25.112
  4    11 ms    10 ms    10 ms  99.134.205.130
  5    10 ms    14 ms    12 ms  12.83.114.29
  6    21 ms    20 ms    20 ms  12.123.43.197
  7    22 ms    22 ms    22 ms  12.247.68.178
  8    20 ms    20 ms    20 ms  ae8.r02.atl01.icn.netarch.akamai.com [23.207.235.40]
  9    37 ms    37 ms    37 ms  ae14.r01.iad01.icn.netarch.akamai.com [23.32.63.41]
 10    35 ms    35 ms    35 ms  ae1.r01.iad01.atn.netarch.akamai.com [23.209.164.29]
 11    36 ms    36 ms    42 ms  ae0.r03.iad01.atn.netarch.akamai.com [23.209.164.39]
 12    44 ms    38 ms    40 ms  ae26.ech-iad-a.netarch.akamai.com [23.209.164.65]
 13    37 ms    37 ms    37 ms  a23-202-231-169.deploy.static.akamaitechnologies.com [23.202.231.169]

Trace complete.
PS C:\Users\thoma> tracert google.com.nz

Tracing route to google.com.nz [23.221.222.250]
over a maximum of 30 hops:

  1     3 ms     3 ms     3 ms  dsldevice.attlocal.net [192.168.1.254]
  2     4 ms     4 ms     4 ms  23-123-104-1.lightspeed.dybhfl.sbcglobal.net [23.123.104.1]
  3     8 ms     8 ms     7 ms  99.168.25.112
  4    11 ms    11 ms    10 ms  99.134.205.130
  5    13 ms    13 ms    10 ms  12.83.114.29
  6    27 ms    28 ms    30 ms  attga402igs.ip.att.net [12.122.117.121]
  7    24 ms    31 ms    31 ms  4.68.62.225
  8     *        *        *     Request timed out.
  9    43 ms    42 ms    43 ms  aeiclaimslaw.com [4.31.40.210]
 10     *        *        *     Request timed out.
 11     *        *        *     Request timed out.
 12     *        *        *     Request timed out.
 13    45 ms    45 ms    45 ms  a23-221-222-250.deploy.static.akamaitechnologies.com [23.221.222.250]
```

	Average	Standard deviation
1	24.38	16.19
2	22.15	13.99
3	14.08	16.25

a) There were 13 routes in the path for each of the times. There were no changes
b) 9 ISPs. Yes, in this experiment the largest delays occurred at peering interfaces between adjacent ISPs

P25. Suppose two hosts, A and B, are separated by 20,000 kilometers and are connected by a direct link of $R = 2$ Mbps. Suppose the propagation speed over the link is $2.5 \cdot 10^8$ meters/sec.

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

b. Consider sending a file of 800,000 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?

c. Provide an interpretation of the bandwidth-delay product.

d. What is the width (in meters) of a bit in the link? Is it longer than a 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.

a) 20000 km $\rightarrow 2 \times 10^7$ m

transmission rate $= 2.5 \times 10^8$ m/s

$d_{prop} = \frac{D}{S} = \frac{2 \times 10^7}{2.5 \times 10^8}$

$d_{prop} = t = 0.08$ sec

bandwidth delay product $= R \cdot d_{prop} = (2 \times 10^6)(0.08)$

$= 16 \times 10^4$ bits

b) $800\,000 \Rightarrow 8 \times 10^5$ bits $\Rightarrow$ since they are connected by a direct link, the max # of bits is independent of file size, it only depends on time & distance

transmission rate $= 2$ Mbps $= 2 \times 10^6$ bits/sec

$R \cdot d_{prop} = (2 \times 10^6)(0.08) = 16 \times 10^4$ bits

c) The bandwidth delay product is the maximum number of bits on the transmission line, its the charge

d)

$S = 2.5 \times 10^8$ meter/sec

$R = 2 \times 10^6$ bits/sec

Find meters/bit $\Rightarrow = \frac{2.5 \times 10^8}{2 \times 10^6}$

$= 125$ m/bit

The length of 1 bit is 125m.

Football field length: 91.44 m

it is longer than a football field

e) length of link $\Rightarrow D\,[m]$
propagation speed $\Rightarrow S\,[m/s]$
transmission rate $\Rightarrow R\,[bits/s]$
we need to find width of bit $\Rightarrow W\,[m/bit]$

$$\frac{S}{R} = \frac{\frac{m}{s}}{\frac{bits}{s}} = \frac{m}{bit} \Rightarrow W = \frac{m}{bit}$$

$$W = \frac{S}{R}$$

The width is not dependent on the length of the link only the propagation rate and transmission rate.