Lecture 1:

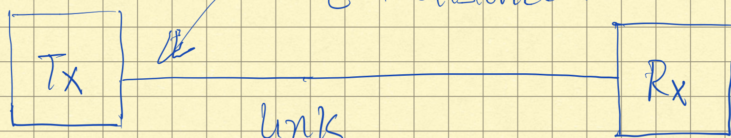
Delays

metres/sec

v is the velocity/speed of the signal propagation

$d \Rightarrow$ distance in meters

Message of size L bits



R: data rate of the link $\longrightarrow$ bits/sec

link $\rightarrow$ fiber optic

$\rightarrow$ wireless link

[$\rightarrow$ wire (string)]

{ $\rightarrow$ SONAR]

$\rightarrow$ copper wire

Electromagnetic signal

certain speed

R? data rate / transmission rate / capacity / bandwidth

rate at which the TX can transmit / inject bits into the link

Unit of R

bits/sec

R 1 kbits/sec

10^3 bits/sec

1 bit every 10^{-3} sec

R: 1 Gbps

1 bit every 10^{-9} sec

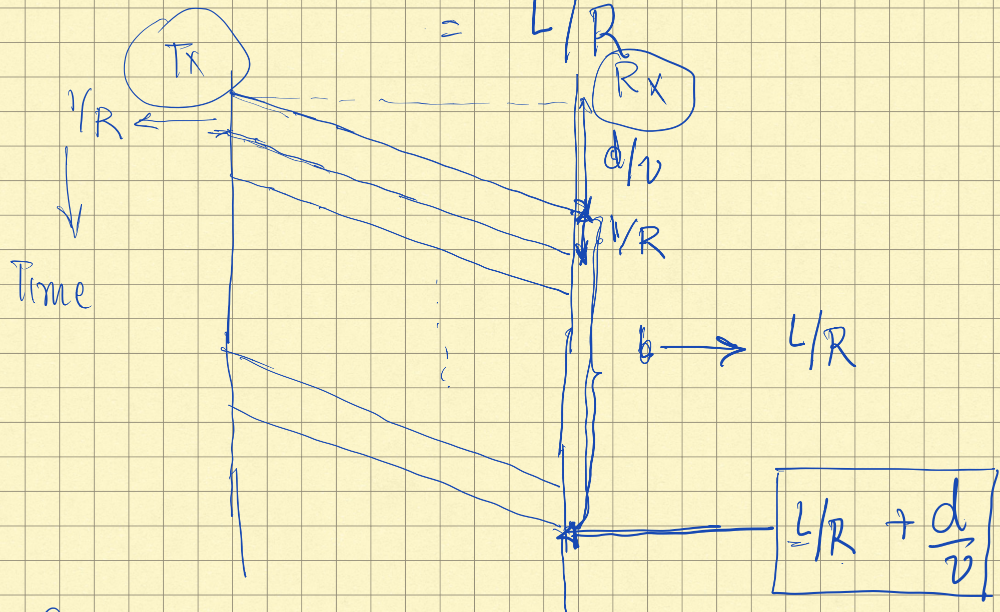
Propagation delay $= d/v$

$\Downarrow$

time for the transmitted signal to propagate to the Rx

Transmission delay

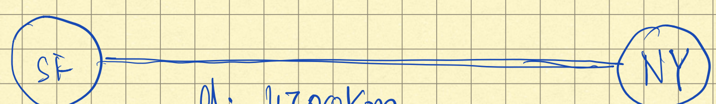
time for the Tx to transmit the message $= L/R$



Examples

L : 536 bytes   R : 10 Mbps

$\frac{L}{R} : \frac{536 \times 8}{10 \times 10^6} = 428 \times 10^{-6}$ sec



d: 4700km

v: 3×10^8 m/sec

$\frac{d}{v} = \frac{4700 \times 10^3}{3 \times 10^8} = 15.66 \times 10^{-3}$

$T = \underbrace{428 \times 10^{-6}}_{\text{Transmission delay}} + \underbrace{15.66 \times 10^{-3}}_{\text{Propagation delay}}$ sec

R = 100 Mbps

$$\frac{L}{R} = \frac{536 \times 8}{100 \times 10^{6}} = 428 * 10^{-7}$$

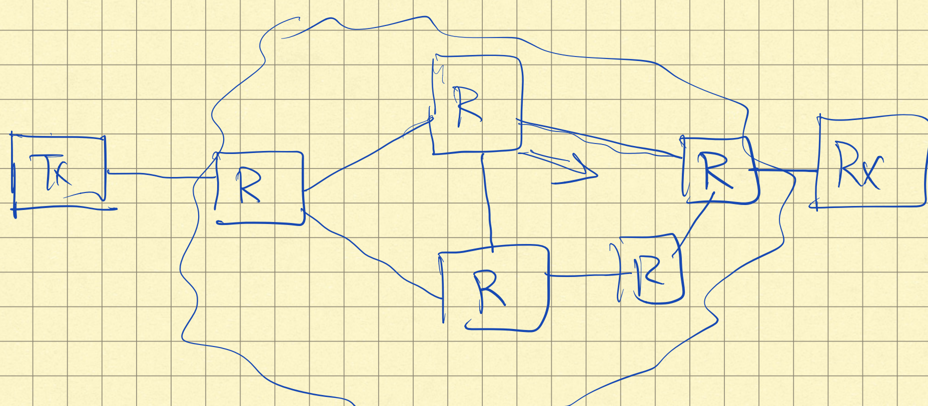
Transmission delay << Propagation delay corresponding to intercontinental distances

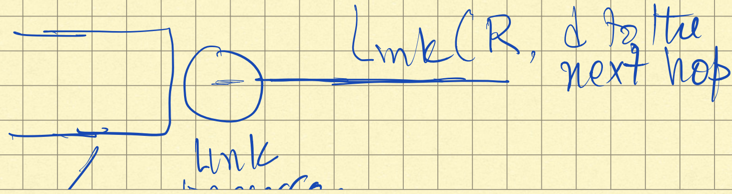
$\boxed{\text{High Speed Networks}}$

↳ increasing R

<u>Packet Switched Networks</u>

L



1. L bits are broken/divided into smaller chunks and made into packets
2. Each pkt has a header using which the Routers can route them to the destination
3. 

processor

buffer/queue

Lecture 2

Announcement

① TAs have posted office hours
② Uploaded lectures notes
③ Jupyter notebook

Recap

Transmission delay

Time to transmit the message

message L bits

Data rate R bps

Transmission ~~time~~ delay $= L/R$

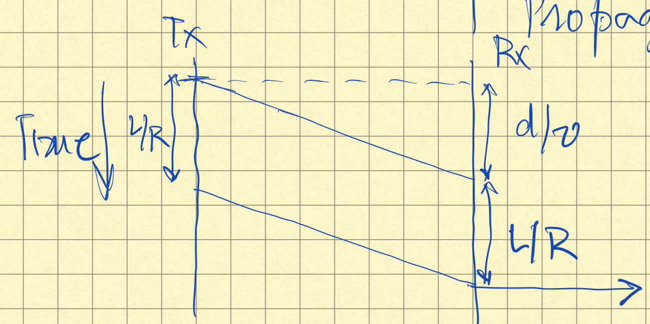
Propagation Delay

time for the signal to propagate for Tx to Rx

distance d meters

velocity v m/se

Propagation delay $= \underline{d}/\underline{v}$



$$\underline{L/R} + \boxed{\frac{d}{v}}$$

R is now ~ 100 Gbps

$$1 \text{ bit is } \frac{1}{100\text{Gbps}} = \frac{1}{100 \times 10^{+9}} \text{ sec}$$

$$= 10^{-7} \text{ sec}$$

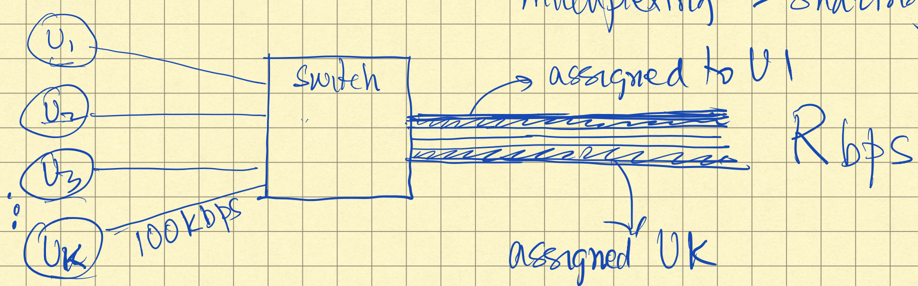
Network Architectures

packet switching
(Internet)

Circuit Switching
(Telephone n/w was implemented)

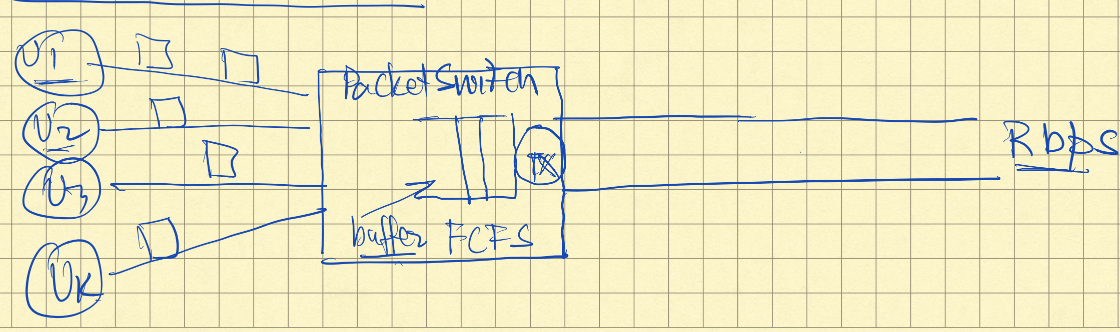
Circuit Switching

multiplexing → sharing



- Each user is assigned a smaller pipe
  date rate of R/K bps
- Each user can transmit at $\frac{R}{K}$ bps
- User has a message of size L bits
  Transmission time = $L/(R/K)$ secs
- Allocation of the smaller capacity to a user
  ✓ is done even if during certain times the user is not transmitting data

Packet Switching



1. Message is broken into smaller chunks
   chunks are added <u>header</u> → packet
2. User's can transmit the <u>pkts</u> whenever they are ready
3. Tx is transmitting each <u>packet</u> at the full link rate of R bps

<u>User behavior</u>

- User when active transmits at <u>100kbps</u>
- User is active 10% of the time
- Users are independent

<u>Link</u>

R = 1 Mbps

<u>Q.1</u>. In circuit switching how many users can we support?

⇒ 10 users

Q2. How many can we support using packet switching?

Suppose K = 10 easily possible
then it is never the case that total arrival rate is greater than R (1 Mbps)

$K = 11$ it is possible that sometime the total incoming rate is greater than 1 Mbps

$\Rightarrow$ Congestion

Given a K we can find the $P[\text{congestion}]$

$K = 35$ (just as an example)

p = probability that user is active $= 0.1$

$$P[\text{congestion}] = \sum_{i=11}^{35} \underbrace{\binom{35}{i} p^i (1-p)^{35-i}}_{\text{Binomial distribution}}$$

Probability that i out 35 are active

Sums all case when congestion will occur

$= 0.0004$

$\Rightarrow$ Leveraging the statistical behavior of the users $\rightarrow$ they are not active all the time

Congestion:

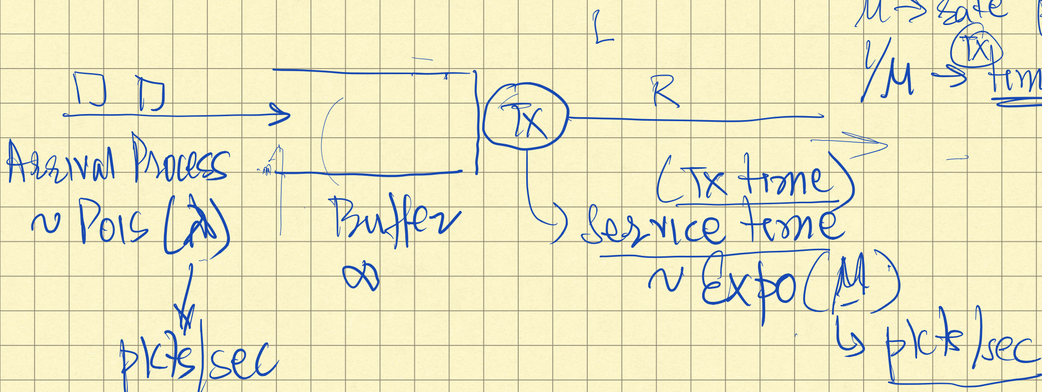
- Aggregate input rate $>$ output link capacity data rate

- Buffer to hold the excess
- Queues will form
- Queuing delays

Simple single server queue

$\mu \rightarrow$ rate pkts/se

$1/\mu \rightarrow$ Tx time



Delay : time when a pkt arrive until it is transmitted

Delay > Service time when there is congestion

Delay is going to grow as congestion increases

Markov Chains

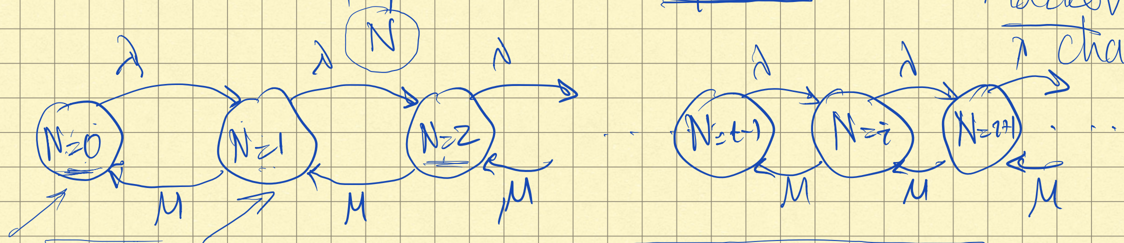
↳ . define a state that characterizes the system

- How the system moves between these states?
- steady or longrun probabilities of the

states

State $\Rightarrow$ # of pkts in the system $\rightarrow$ Buffer & Tx

Markov chain



Birth-death processes

Flow-balance equation

$\Rightarrow$ rate into a state = rate out of the state

$$\boxed{p_i = P(N=i)}$$

Lecture 3 : 4/6/2021 Announcements

1. Jupyter notebook
2. A typo in the assignment
   Image size is 12.5 Mb not 2.5 Mb
3. Office hours
   MW: 11am-12noon
4. Homework submission template
   Latex
   Overleaf
5. Draft version of Homework grading policy
   will be uploaded today

$$p_0 \lambda = p_1 \mu \Rightarrow p_1 = \left(\frac{\lambda}{\mu}\right) p_0$$

$$p_1(\lambda + \mu) = p_0 \lambda + p_2 \mu \Rightarrow p_2 = \left(\frac{\lambda}{\mu}\right)^2 p_0$$

$$\Rightarrow \quad p_i = \left(\frac{\lambda}{\mu}\right)^i p_0 \qquad E(N) = \sum_{i=0}^{\infty} i\, p_i$$

∞

$$\sum_{i=0}^{\infty} p_i = 1 \quad \Rightarrow \quad p_0 = 1 - \frac{\lambda}{\mu}$$

$$\Rightarrow \quad p_i = \left(1 - \frac{\lambda}{\mu}\right)\left(\frac{\lambda}{\mu}\right)^i \quad \forall i$$

$P[N=i]$

ρ = traffic intensity

$= \dfrac{\lambda}{\mu}$

$$\boxed{p_i = (1-\rho)\rho^i}$$

$p_0 = P[N=0]$

$p_0 > 0$

$1 - \dfrac{\lambda}{\mu} > 0$

$\Rightarrow \lambda < \mu$

$$E(N) = \sum_{i=0}^{\infty} i\, p_i = \frac{\rho}{1-\rho}$$

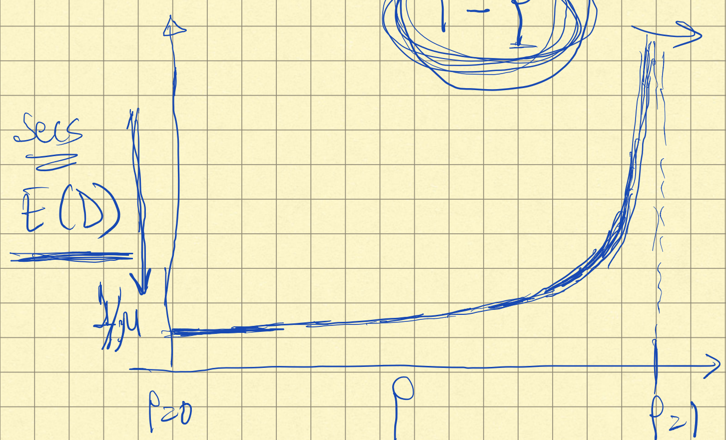
$E(D)$ D: delay

= from the moment the pkt arrives until it is completely transmitted

$$= \frac{1/\mu}{1-\rho}$$

basic delay service time ($1/\mu$)

scaling factor ($1-\rho$)



$\lambda \Rightarrow$ pkts/sec

$\mu \Rightarrow$ pkt/sec

$\rho \to 0$

$E(D) \Rightarrow 1/\mu$

$\rho = 1 \Rightarrow \lambda = \mu$

$\rho \to 1$: $1-\rho \to 0$

$E(D) \to \infty$

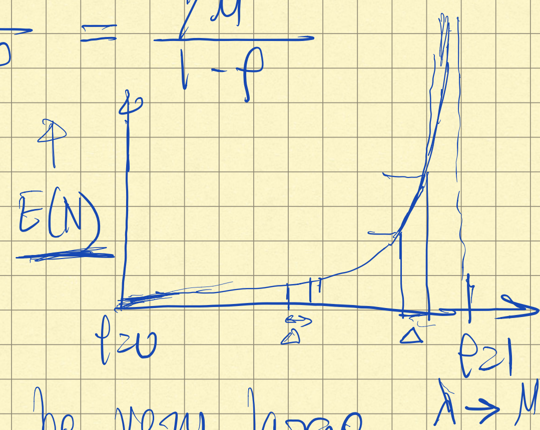
$\rho = \frac{\lambda}{\mu}$ = traffic intensity

Little's Law

$$\boxed{E(D) = \frac{E(N)}{\lambda}} \Rightarrow E(N) = \boxed{\lambda \cdot E(D)}$$

$$E(D) = \frac{1}{\lambda} \cdot \frac{\rho}{1-\rho} = \frac{1/\mu}{1-\rho}$$

$$E(N) = \frac{\rho}{1-\rho}$$

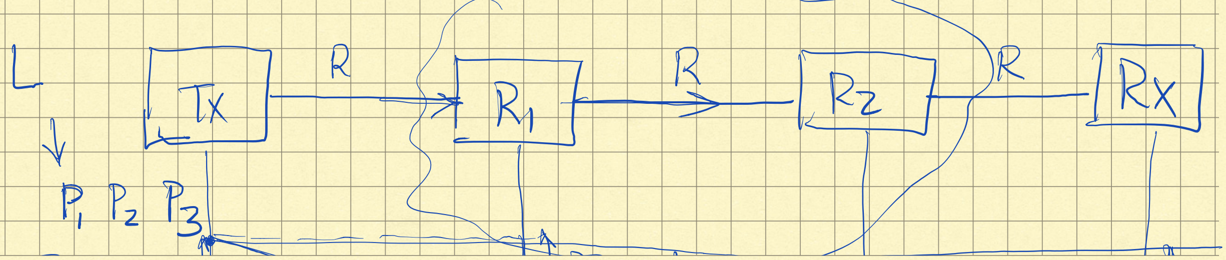


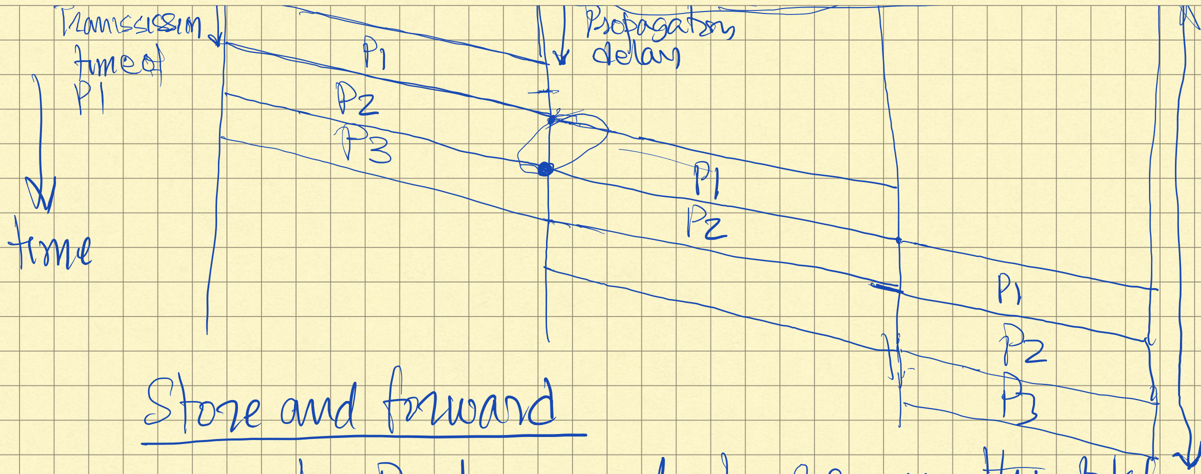
Queueing delay can be very large and can change a lot when at times the input rate becomes greater than the output rate

$\lambda \rightarrow$ pkts/sec $\qquad \mu \rightarrow$ pkt/sec

$\rho \rightarrow \frac{\lambda}{\mu}$ unitless

Packet Switching over multiple hops





Store and forward

↳ Router needs to receive the pkt completely before it can forward to the next hop

Remember → the router can rx on an interface and tx on another interface simultaneously

Important to compute the total time to transfer a message (using multiple pkts) over a multihop network