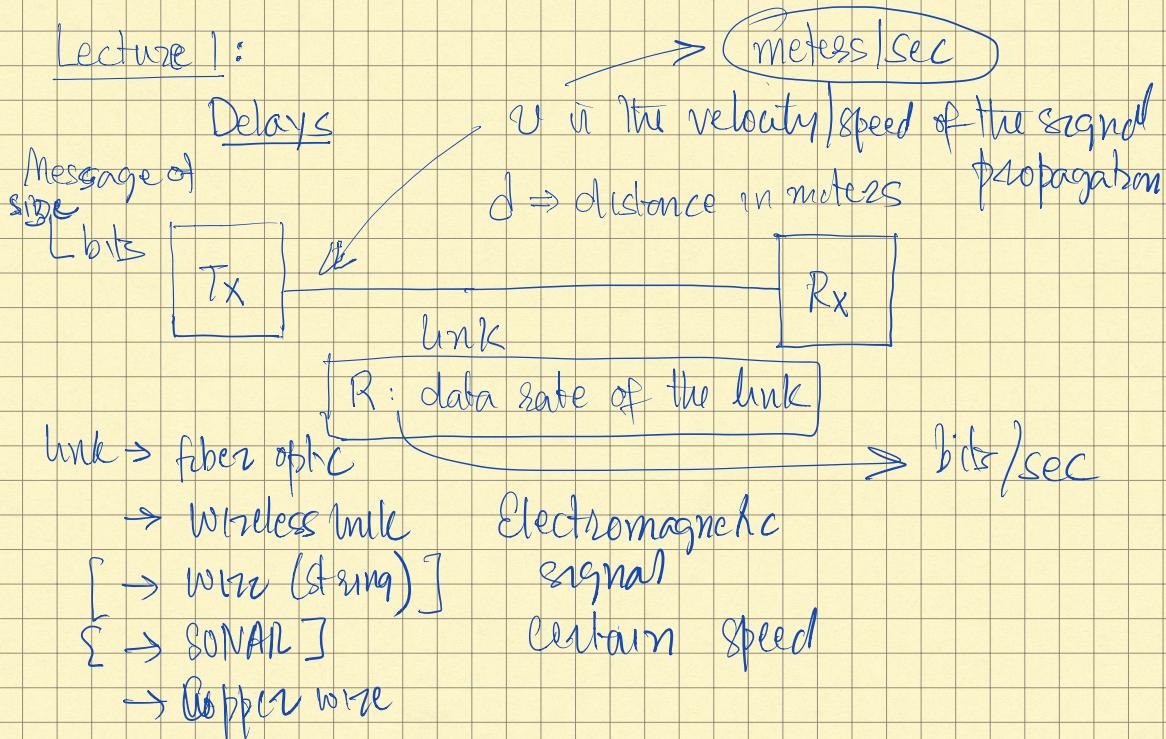


## Lecture 1:



$R$ : data rate / transmission rate / capacity / bandwidth

Rate at which the Tx can transmit  
inject bits into the link

Unit of  $R$   
bits/sec

$R = 1 \text{ kbit/sec}$

$10^3 \text{ bit/sec}$

1 bit every  $10^{-3} \text{ sec}$

$R = 1 \text{ Gbps}$

1 bit every  $10^{-9} \text{ sec}$

Propagation Delay

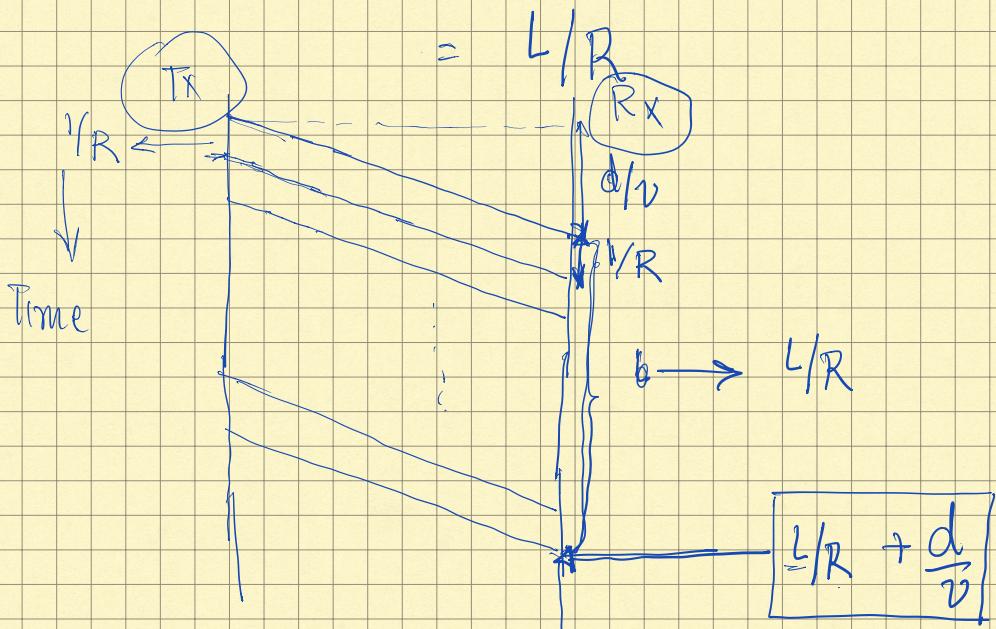
$$\Downarrow = d/v$$

time for the transmitted signal to propagate

To the rx

### Transmission delay

Time for the Tx to transmit the message

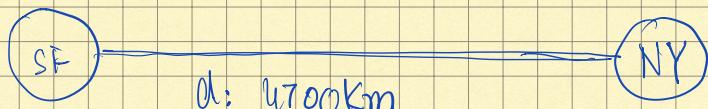


### Examples

$$L : 536 \text{ bytes}$$

$$R : 10 \text{ Mbps}$$

$$\frac{L}{R} : \frac{536 \times 8}{10 \times 10^6} = 4.28 \times 10^{-6} \text{ sec}$$



$$v: 3 \times 10^8 \text{ m/sec}$$

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

$$T = 4.28 \times 10^{-6} + 15.66 \times 10^{-3} \text{ sec}$$

$$R = 100 \text{ Mbps}$$

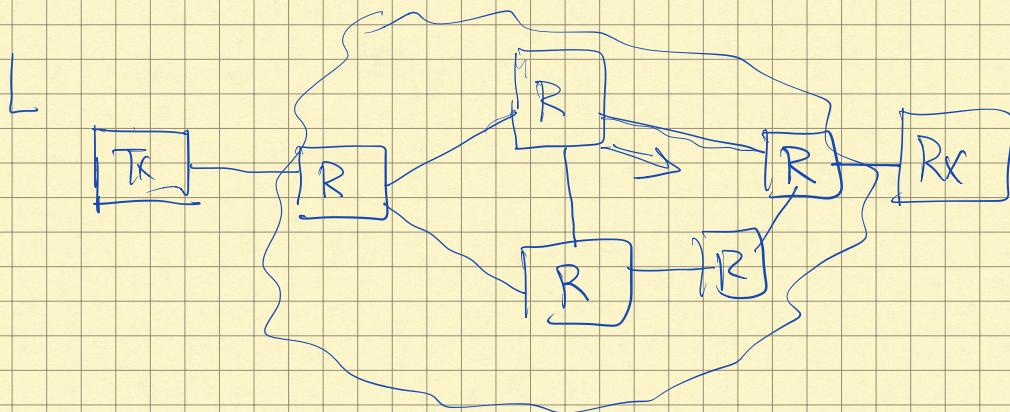
Transmission delay → Propagation delay

$$\frac{L}{R} = \frac{536 \times 8}{100 \times 10^6} = 4.28 \times 10^{-7}$$

Transmission delay << Propagation delay  
corresponding to continental distances

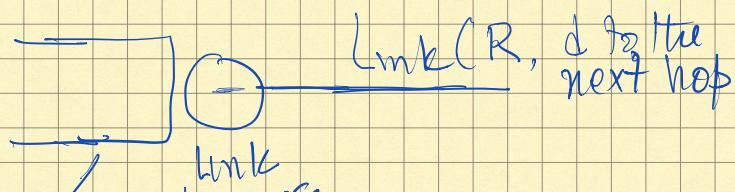


### Packet Switched Networks



- ① L bits are broken/divided into smaller chunks and made into packets
- ② Each pkt has a header w/ info which the routers can route them to the destination

③



# Professor buffer/queue

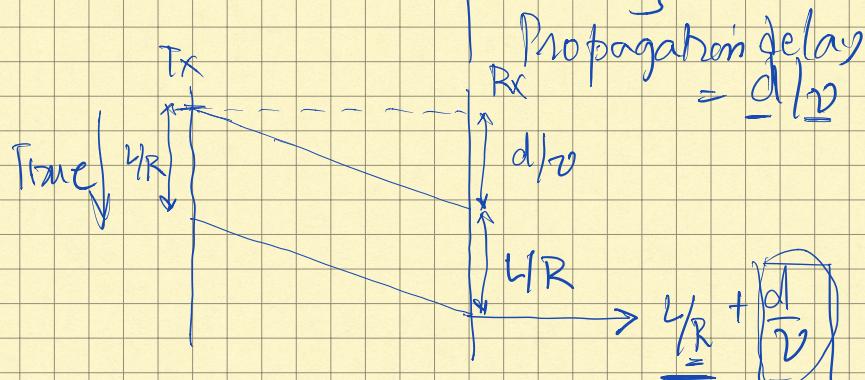
## Lecture 2

### Announcement

- ① TAC have posted office hours
- ② Uploaded lectures notes
- ③ Duyter notebook

### Recap

Transmission Delay	Propagation Delay
Time to transmit the message message L bits	time for the signal to propagate from TX to RX
Data rate R bps	distance d meters
Transmission time = $\frac{L}{R}$	velocity v m/se



R is now  $\approx 100$  bps

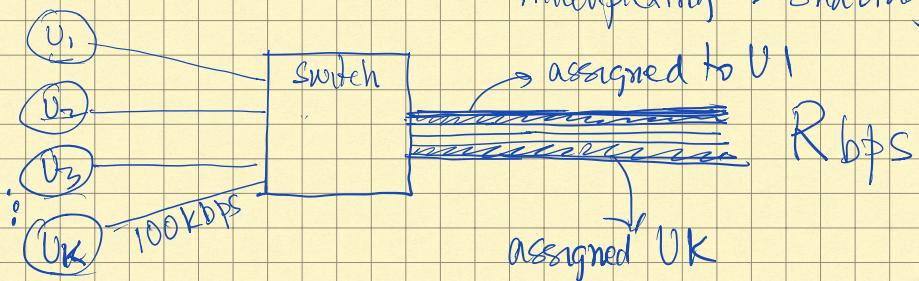
$$1 \text{ bit in } \frac{1}{100 \text{ bps}} = \frac{1}{100 \times 10^9} \text{ sec} \\ = 10^{-7} \text{ sec}$$

## Network Architectures

packet switching  
(Internet)

circuit switching  
(Telephone w/w was implemented)

### Circuit Switching



- Each user is assigned a smaller pipe date rate of  $R/K$  bps

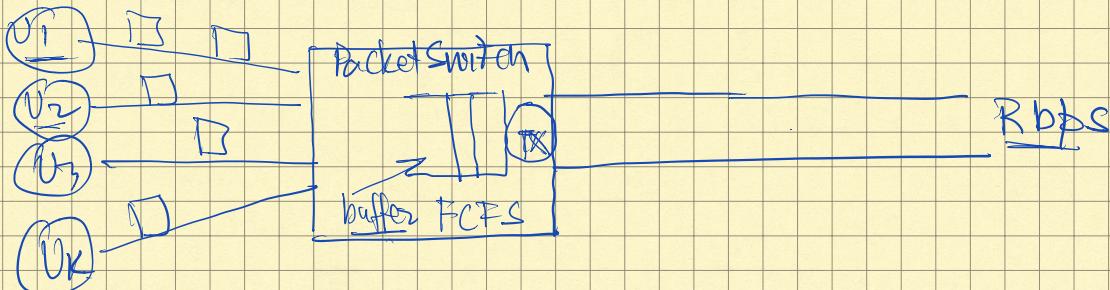
- Each user can transmit at  $\frac{R}{K}$  bps

- User has a message of size  $L$  bits

$$\text{Transmission time} = L / (R/K) \text{ secs}$$

- Allocation of the 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 header  $\rightarrow$  packet
2. Users can transmit the packet whenever they are ready
3. Tx is transmitting each packet at the full link rate of  $R$  bps

### User behavior

- User when active transmits at 100 Kbps
- User is active 10% of the time
- Users are independent

### Link

$$R = 1 \text{ Mbps}$$

Q.1. In circuit switching how many users can we support?

$\Rightarrow 10$  users

Q.2. How many can we support using packet switching?

Suppose  $K = 10$  easily possible

then it is never the case that total user rate is greater than  $R$  (1 Mbps)

$K = 11$  it is possible that sometimes 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)

$$p = \text{probability that user is active} \\ = 0.1$$

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

↙  
Probability that  $i$  out of 35 are active

↙  
Sum all cases when congestion will occur

$$= 0.0004$$

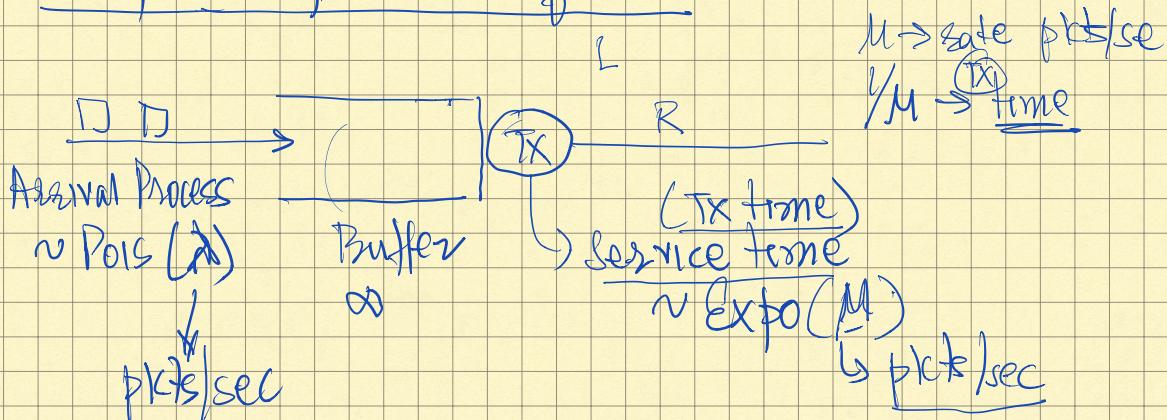
$\Rightarrow$  Leveraging the statistical behavior of the users  $\rightarrow$  they are not active all the time

Congestion:

- Aggregate input rate  $\rightarrow$  output link saturation

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

### Simple single server queue



Delay : time when a pkt arrives 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

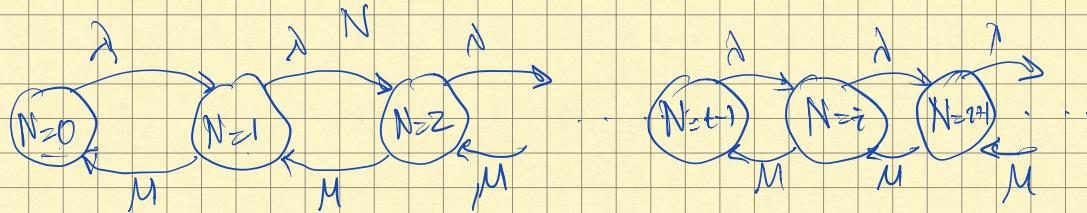
- How the system moves between these states?

- Steady or long-run probabilities of the

States

State  $\Rightarrow$  # of pkts in the system

→ Buffer & Tx



Birth-death processes

$$P_i = P(N=i)$$

Flow-balance equations

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

$P_0$