$T_f = \frac{L}{R}$ $T_{prop} = \frac{d}{v}$

$a = \frac{T_{prop}}{T_f}$

P[frame has no errors] = $(1-p)^n$

P[frame has errors] = FER = $P_e = 1-(1-p)^n$

$C_{max} = R \times S$

$P[1 \text{ bit received in error}] = \binom{n}{1} p(1-p)^{n-1}$

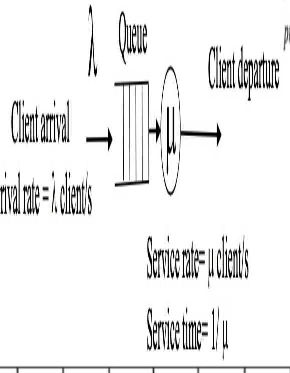
$P[i \text{ bits received in error}] = \binom{n}{i} p^i (1-p)^{n-i}$

$\mu = \frac{C}{L}$

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

λ - arrival cli
μ - service ra
ρ - traffic int

- **N=λT**
  - N- avera
  - T – aver
  - λ – arriv
- $T = T_w + T_s$
  - T_w – tim
  - T_s – serv
- $N = N_w + N_s$
  - N_w – nu
  - N_s – nur
- **$N_w = \lambda T_w$**



Subnet	1	2	4	8	16	32	64	128	256
Host	256	128	64	32	16	8	4	2	1
Subnet Mask	/24	/25	/26	/27	/28	/29	/30	/31	/32

Stop and Wait ARQ

Efficiency

$$S = \frac{T_f}{T_f + 2T_{prop}} = \frac{1}{1+2a}$$

Efficiency (with Error)

$$S = \frac{1-p_e}{1+2a}$$

M/M/1

Poisson arrival, exponential service time

$T = N/\lambda = \frac{1}{\mu - \lambda}$

$T_w = T - T_s = \frac{1}{\mu - \lambda} - \frac{1}{\mu} = \frac{\rho}{\mu(1-\rho)}$

$N_w = T_w \lambda = \frac{\lambda}{\mu - \lambda} - \frac{\lambda}{\mu} = N - \rho$

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Probability of queue having n clients

$P(n) = \rho^n (1-\rho)$

P(n) - probability of the Markov chain be in state n
n - number of clients in the queue

Go-Back-N ARQ

$W = M-1 = 2^k - 1$

Efficiency

If $W \geq 1+2a$ ➔ $S = 1$

If $W < 1+2a$ ➔ $S = W/(1+2a)$

Efficiency (with Error)

$$S = \begin{cases} \frac{1-p_e}{1+2ap_e} & ,W \geq 1+2a \\ \frac{W(1-p_e)}{(1+2a)(1-p_e+Wp_e)} & ,W < 1+2a \end{cases}$$

M/M/1/B

Poisson arrival, exponential service time

$P(B) = \frac{(1-\rho)\rho^B}{1-\rho^{B+1}}$

- P(B) - Probability of packet being lost
- B - Number of buffers

If $\rho = 1$, $P(B) = \frac{1}{B+1}$

If $\rho >> 1$, $P(B) = \frac{\rho - 1}{\rho} = \frac{\mu - \lambda}{\lambda}$

Selective Repeat ARQ

$W = \frac{M}{2} = 2^{k-1}$

Efficiency (with Error)

$$S = \begin{cases} 1-p_e & ,W \geq 1+2a \\ \frac{W(1-p_e)}{1+2a} & ,W < 1+2a \end{cases}$$

M/D/1

Poisson arrival, deterministic (constant) service time 1/μ

$T_w = \frac{\lambda}{2\mu^2(1-\rho)} = \frac{\rho}{2\mu(1-\rho)}$

Kendall Notation
A/S/s/K

A – arrival
S – service
s - number of servers
K – buffer capacity

$T_f = \frac{L}{R}$ $T_{prop} = \frac{d}{v}$

$a = \frac{T_{prop}}{T_f}$ $C_{max} = R \times S$

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$\binom{n}{i} = \frac{n!}{(i!(n-i)!)}$

Stop and Wait ARQ

Efficiency

$$S = \frac{T_f}{T_{prop} + T_f + T_{prop}} = \frac{1}{1+2a}$$

Efficiency (with Error)

$$S = \frac{T_f}{E[A](T_f + 2T_{prop})} = \frac{1}{E[A](1+2a)} = \frac{1-p_e}{1+2a}$$

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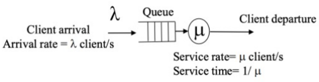

λ - arrival client rate (client/s)
μ - service rate (client/s)
ρ - traffic intensity, how busy the server is (%)

- **N=λT**
  - » N- average number of clients in a system
  - » T – average amount of time a client spends in the system
  - » λ – arrival rate of clients to the system
- $T = T_w + T_s$
  - » T_w – time a client waits in the queue for being served
  - » T_s – service time
- $N = N_w + N_s$
  - » N_w – number of clients waiting in the queue for being served
  - » N_s – number of clients being served
- $N_w = \lambda T_w$

M/M/1
Poisson arrival, exponential service time

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- Signals should be reconstructed on the receiver side
- **Nyquist** showed that a signal having a bandwidth of B Hz, can be fully reconstructed, with a sampling rate of 2B sample/s

$C = 2B \log_2(M)$

- 2B - channel capacity baudrate (symbol/s or baud)
- M - levels are encoded, M = 4 (-5V(00) , -2V(01) , -2V(10), 5V(11))

- Samping at a higher rate does not bring additional information

Baseband transmission
- signal has frequencies from zero up to a maximum BH

Passband transmission
- signal uses band of frequencies around the frequency of the carrier f_c

- M-QAM(Quadrature Amplitude Modulation), M = 4

- In a stable M/D/1, $\mu = \lambda$

Shannon's Theorem
- The maximum capacity of a channel is said to be:

$$C = B_c \log_2\left(1 + \frac{P_r}{N_0 B_c}\right)$$

- B_c - bandwidth of the channel (Hz), sampling rate
- Pr - Signal power as seen by the receiver (W)
- N_0B_c - noise power within the bandwidth Bc, seen by the receiver (W)
- N_0 - White noise; noise power per unit bandwidth (W/Hz)

which can be also be expressed as:

$$C = B \log_2\left(1 + \frac{S}{N}\right)$$

- where, S/N is the Signal to Noise Ratio
- SNR = Pr (dB) - N (dB)

If a bandpass channel has a bandwidth B_c= 100 kHz and Signal to Noise ratio (SNR) at the receiver is

» $P_r/(N_0B_c)=7$ ➔ $C = 100k \log_2(1+7) = 300 kbit/s$

» $P_r/(N_0B_c)=255$ ➔ $C = 100k \log_2(1+255) = 800 kbit/s$

Power expressed in **W**, **dBW**, or **dBm**

» $P_{dBW} = 10\log_{10}P$: P=100mW ➔ $P_{dBW} = 10\log_{10}(100 \cdot 10^{-3}) = -10$ dBW

» $P_{dBm} = 10\log_{10}(P/1mW)$: P=100mW ➔ $P_{dBm} = 10\log_{10}(100) = 20$ dBm

Internet transport-layer protocols

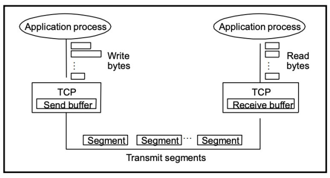
TCP service:
- connection-oriented: setup required between client and server processes
- reliable transport between sending and receiving process
- flow control: sender won't overwhelm receiver
- congestion control: throttle sender when network overloaded
- does not provide: timing, minimum throughput guarantees, security

UDP service:
- unreliable data transfer between sending and receiving process
- does not provide: connection setup, reliability, flow control, congestion control, timing, throughput guarantee, or security
- Q: why bother? Why is there a UDP?

UDP - User Datagram Protocol (UDP)
- Allows applications
  - to interface directly to IP
  - with minimal additional protocol overhead
- often used for streaming multimedia apps
  - loss tolerant
  - rate sensitive
- other UDP uses
  - DNS
  - SNMP
- reliable transfer over UDP: add reliability at application layer
  - application-specific error recovery!

TCP – Transmission Control Protocol

- full duplex data:
  - bi-directional data flow in same connection
- connection-oriented:
  - handshaking (exchange of control msgs) inits sender, receiver state before data exchange
- flow controlled:
  - sender will not overwhelm receiver
  - ARQ mechanism
- Congestion control
  - Avoids network's congestion
- point-to-point:
  - one sender, one receiver
- reliable, in-order *byte stream:*
  - no "message boundaries"
- pipelined:
  - TCP congestion and flow control set window size
- *send & receive buffers*



Packets may be lost
- Receiver confirms (ACK) reception of each segment
- If sender does not receive confirmation within a time limit ➔ re-sends segment

Receiving duplicated segments:
- generated by the network of retransmissions by lost ACKs
- Segments are numbered
- ACK identifies the number of the last received segment
- It also solves the re-ordering problem

Packets may contain errors
- Detected using checksum
- Packets with errors are ignored ➔ handled as lost packets

- RTT → Round Trip Time
- `sampleRTT` measured for each segment/ACK pair
- Moving average (smooth RTT) of SRTT
  - $SRTT_{new} = (1-\alpha) \times SRTT_{old} + \alpha \times sampleRTT$
    - α = 1/8
- Variation of **RTT**
  - $RTTVAR_{new} = (1 - \beta) * RTTVAR_{old} + \beta * |SRTT_{old} - sampleRTT|$
    - β = ¼
- `RTO = SRTT + max (G, K*RTTVAR)`
  - clock granularity of G seconds
  - K = 4
  - RTO - retransmission timeout

MAC

Datalink has 2 sub-layers:
- LLC (Logical Link Control)
  - interface for network layer, error and flow control
  - Error and flow control
- MAC (Medium Access Control)
  - Access control to the shared medium
  - Frame transmission/reception
  - Addressing and Error control

ideal Multiple Access Protocol
- one station wants to transmit -> it uses the R bit/s
- m stations want to transmit -> each station uses an average rate R/m bit/s

MAC Protocols:
- Channel Partitioning
  - Time Division Multiplexing | Frequency Division Multiplexing
- Random Access
  - channel not divided, collisions allowed
- Taking turns
  - stations take turns
  - stations with more data to send can take longer turns

Channel partitioning

MAC protocols (TDM, FDM)

» share channel efficiently and fairly at high loads

» are inefficient at low loads

- delay in channel access; 1/N bandwidth allocated even if only 1 active node!

Random access MAC protocols (Aloha, CSMA, CSMA/CD, CSMA/CA)

» efficient at low load -> single node can fully utilize the channel

» high load -> collisions -> inefficiency

Taking turns protocols

» look for best of both worlds!

What Are Random Access Protocols?
- When station has packet to send
  - transmits at channel data rate R bit/s
  - no a priori coordination among stations
- If two or more stations transmit simultaneously ➔ collision
- It defines:
  - when to send data
  - how to detect collision
  - how to recover from collisions
- Examples:
  - ALOHA, CSMA, CSMA/CD, CSMA/CA

1. ALOHA
- When packet transmission fails, it will delay a random period of time before next transmission
- Pure Aloha (unslotted)
  - Station transmits when it has a frame to transmit
  - S_{max} = 18.4%
- Slotted Aloha
  - Time divided into time slots
  - Tslot = Tframe
  - (Re)transmissions only the beginning of a slot
  - S_{max} = 36.8%

2. CSMA (Carrier Sense Multiple Access)
- Listens before transmit
  - If channel sensed free → transmit frame
  - If channel sensed busy → defer transmission
- Collisions can still occur (entire packet is lost)
- vulnerability time = 2*Tprop = rtt (round trip time)
- Determine collision probability
- a = T_{prop}/T_{frame} <<1

3. CSMA/CD – Carrier Sense Multiple Access / Collision Detection
- Carrier Sense
  - station senses medium before transmitting
    - If free → station starts transmission
    - If busy → waits until free and then transmits
- Collision Detection
  - station listens medium while transmitting
  - if collision is detected
    - transmission is aborted
    - retransmission delayed using
    - a Binary Exponential Back-off algorithm
      - time modeled in time slots; Tslot= 2*Tprop
      - after the ith consecutive collision → the station attempts to transmit, after waiting, a random number of slots uniformly distributed in [0, 2^i-1]
  - No ACK is needed
    - It can detect itself for collisions
  - however, a minimum frame size is required for collision detection

4. CSMA/CA - CSMA with Collision Avoidance
- CSMA/CD cannot be used for wireless transmission
- Therefore it is more commonly used in wireless networking
- CSMA / CA is effective before a collision.
  - whereas, CSMA/CD is effective after a collision.
- Station with a frame to transmit
  - monitors the channel activity → until an idle period equal to a Distributed Inter-Frame Space (DIFS) has been observed
    - then if medium remains free → transmits frame
- If the medium is sensed busy
  - random backoff interval is selected
  - backoff time counter is decremented as long as the channel is sensed idle
  - stopped when a transmission is detected on the channel
  - reactivated when the channel is sensed idle again for more than a DIFS
  - the station transmits when the backoff time reaches 0
- to avoid channel capture
  - station waits random backoff time between two consecutive frame transmissions
  - even if the medium is sensed idle in the DIFS time
- ACK will be required for CSMA/CA
  - Since it cannot locally detect if there is a collision
- S_{max} = 60% commonly found

Taking turns Mac Protocols

1. Polling
- master station invites slave stations to transmit in turn
- concerns
  - polling overhead
  - latency
  - single point of failure (master)

2. Token Passing

» control token
- passed from one station to next sequentially

» token message

» concerns
- token overhead
- latency
- single point of failure (token)

Hub
- Has repeaters, repeats bits received on one port to all other ports
- Layer 1 device (does not know addresses)
- if collision detected on one port -> repeats random bits on other port
- 1 Collision Domain and half duplex

Bridge

» Layer 2 device

» forwards MAC frames to destinations based on MAC addresses

» Packet received on one port -> analyzed by bridge -> re-sent on some other port

» Bridge separates collision domains
- a bridged LAN maybe larger than a repeated LAN
- several frames may be transmitted simultaneously

Note: Switches not need a MAC Address (transparent bridging), but routers do have.

Services provided by network layer

Virtual Circuit network	Datagram network
- connection-oriented service	- connectionless service

Virtual Circuit
1. circuit establishment
2. data transference
3. circuit termination

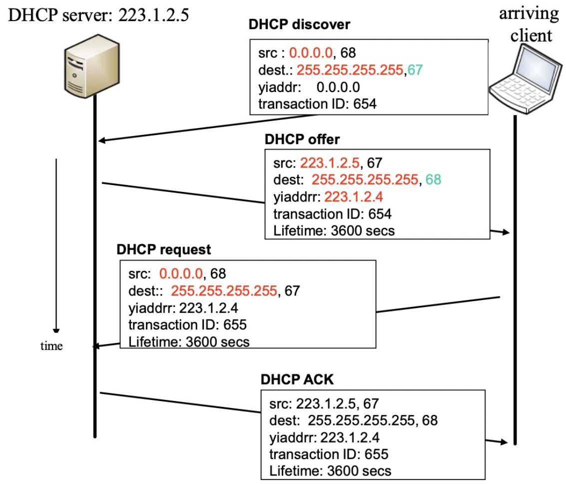
- Packet carries identifier of Virtual Circuit
- Path defined from source to destination
  - -sequence of VC identifiers, one for each link along path
- Router
  - -maintains "state" for every supported circuit
  - -may allocate resources (bandwidth, buffers) per Virtual Circuit

Datagram
- No circuit establishment; no circuit concept
- Packets
  - -forwarded using destination host address
  - -packets between same source-destination pair may follow different paths

Issue	Datagram subnet	Virtual-circuit subnet
Circuit setup	Not needed	Required
Addressing	Each packet contains the full source and destination address	Each packet contains a short VC number
State information	Routers do not hold state information about connections	Each VC requires router table space per connection
Routing	Each packet is routed independently	Route chosen when VC is set up; all packets follow it
Effect of router failures	None, except for packets lost during the crash	All VCs that passed through the failed router are terminated
Quality of service	Difficult	Easy if enough resources can be allocated in advance for each VC
Congestion control	Difficult	Easy if enough resources can be allocated in advance for each VC

What is ARP needed for?
- On the same LAN you need to connect on the link layer
  - Known: IP address of destination (packet from Network Layer)
  - Unknown: MAC address of destination
- Protocol used to obtain the MAC address associated to a given IP address
- RARP – Reverse ARP - Protocol used to obtain the IP address associated to a MAC address

DHCP allows
- host to dynamically obtain its IP address (assigns a dynamic IP address) from network server when it joins network
- It supports address reuse



NAT
- To overcome IP address shortage
- Uses private IP address
- Converts an internal private IP address and port to a public one, to be used in the public network

ICMP - Internet Control Message Protocol
- Ping request
- Used by router or host
  - to send layer 3 error or control messages
  - to other hosts or routers
- Carried in IP datagrams

• Link-Local
  - Used for communication between hosts in the same LAN/link
  - Address built from MAC address
  - Routers do not forward packets having Link-Local destination addresses

• Global Unicast
  - Global addresses
  - Address: network prefix + computer identifier
  - Structured prefixes
  - Network aggregation; less entries in the router forwarding tables

• Anycast
  - Group address; packet is received by any (only one) member of the group

• Multicast
  - Group address; packet received by all the members of the group