MAC (Medium Access Control)
Two Types of Networks

- Switched networks
  - Users are interconnected by transmissions lines, multiplexers, and switches.

- Broadcast networks
  - A single transmission medium is shared by a community of users.
  - The information from a user is broadcast to the medium, and all the users listen to all the transmissions.
  - **LAN (Local Area Network)**, with emphasis on low-cost and simplicity, have been based on the broadcast approach.
Multiple Access Network

- Broadcast networks are also referred to as multiple access networks.

- There is potential for user transmissions interfering or “colliding” with each other.

- A medium access control (MAC) protocol is required to prevent or minimize such interference.
Schemes for Medium Sharing

Medium sharing techniques

Static channelization
- Partitioning of medium into separate channels (FDMA, TDMA)
- Different channels are dedicated to different users
- Satellite Communication
- Cellular Communication

Dynamic medium access control

Scheduling
- Use scheduling to coordinate the access to the shared medium
- Token-ring

Random access
- Loose coordination
- Send, wait, retry if necessary
- ALOHA
- CSMA/CD for Ethernet
Two-Station MAC Example

Two stations are trying to share a common medium

Distance \( d \) meters

\[ t_{\text{prop}} = \frac{d}{\nu} \] seconds

Case 1

- B does not transmit before \( t = t_{\text{prop}} \)
- A captures channel

Case 2

- B transmits before \( t = t_{\text{prop}} \) and detects collision soon thereafter
- A detects collision at \( t = 2t_{\text{prop}} \)

The station that began transmitting earlier is the winner.
Efficiency of Two-Station MAC Example

- Each frame transmission requires $2t_{prop}$ to coordinate
  - $R$ transmission bit rate
  - $L$ bits/frame

Max Throughput = $R_{ef,f} = \frac{L}{L/R + 2t_{prop}} = \frac{1}{1 + 2a} R$ bits/second

$$a = \frac{t_{prop} R}{L} = \frac{t_{prop}}{L/R} = \frac{t_{prop}}{X}$$

Normalized Max Throughput = Efficiency = $\rho_{max} = \frac{R_{ef,f}}{R} = \frac{1}{1 + 2a}$
The *a* Parameter

- *a* -- normalized delay-bandwidth product
  - Defined as the ratio of the one-way delay-bandwidth product to the average frame length
  - Key parameter in system performance of broadcast networks

- The efficiency for Ethernet: \(1/(1+6.44a)\)
- The efficiency for token-ring networks: \(1/(1+a')\)
  - *a'* is the ratio of the latency of the ring in bits to the average frame length

- If *a* << 1, efficiency is close to 1
- If *a* → 1, efficiency is low

- Consequently, broadcast networks are used primarily in LANs and other networks with small delay-bandwidth products.
Factors Considered to Select a MAC Protocol

- Efficiency/Throughput
- Transfer delay
- Fairness
  - Stations are provided with treatment that is consistent with policies set by the network administrator.
- Reliability
- Quality-of-Service guarantee
- Scalability
- Cost
Throughput

- The **throughput** is defined as the actual rate at which information is transmitted through the shared medium.
- It is measured in frames/second or bits/second.

**Assume** $R$ bits/second and $L$ bits/frame
- The maximum possible throughput is $R/L$ frames/second.
- In practice each MAC protocol has a maximum throughput less than $R/L$.
- The **normalized throughput** or **load** is defined as the actual throughput divided by the maximum possible throughput.
Transfer Delay

- Frame transfer delay
  - From first bit of frame arrives at source MAC
  - To last bit of frame delivered at destination MAC

- Assume $R$ bits/second and $L$ bits/frame
  - Average frame transmission time
    $$X = \frac{L}{R} \text{ seconds/frame}$$
  - Average frame arrival rate
    $$\lambda \text{ frames/second}$$
  - Load
    $$\rho = \frac{\lambda}{R/L} = \lambda X$$
Normalized Delay vs. Load

\[ E[T]/X \]

- **E[T]** = average frame transfer delay
- **X** = average frame transmission time
- **E[T]/X**: average frame transfer delay in multiples of a single average frame transmission time

- At low arrival rates, only frame transmission time
- At high arrival rates, increasingly longer waits to access channel
- Max efficiency typically less than 100%
Dependence on $a$ Parameter

$E[T/X]$

$a' > a$

Transfer Delay

$\rho'_{\text{max}}$

Load

$\rho_{\text{max}}$

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Random Access
ALOHA

- Wireless data transfer between main campus & remote campuses (on different islands) of University of Hawaii
- Simplest solution: just do it
  - A station transmits whenever it has data to transmit
  - If more than one frames are transmitted, they interfere with each other (collide) and are lost
  - If ACK is not received within timeout, then the station picks random backoff time (to avoid repeated collision)
  - The station retransmits frame after backoff time

![Diagram of ALOHA](image)
ALOHA Model

- Definitions and Assumptions
  - $X$: frame transmission time (assume constant)
  - $S$: throughput (average # of successful frame transmissions per $X$ seconds)
  - $G$: load (average # of transmission attempts per $X$ seconds)
  - $P_{success}$: probability that a frame transmission is successful

- Any transmission that begins during *vulnerable period* ($2X$ seconds) leads to collision
- Success if no arrivals during $2X$ seconds

\[ S = GP_{success} \]
Abramson’s Assumption

- What is probability of no arrivals in vulnerable period?

- Abramson assumption: Effect of backoff algorithm is that transmission attempts are equally likely to occur at any time interval

- $G$ is average # of transmission attempts per $X$ seconds

- $A(T)$ is # of transmission attempts per $T$ seconds

- $A(T)$ is Poisson with rate $G/X$
Poisson

- The Poisson distribution predicts the number of events to occur in a time period.

  \[ \lambda = \text{the arrival rate} = \text{the number of frames per unit of time} \]

  \[ T = \text{time duration} \]

  Poisson distribution: \[ Pr(A(T)=k) = (\lambda T)^k e^{-\lambda T} /k! \]

  \[ E[A(T)] = \lambda T \]

So, if we know the rate of occurrence of some event, we can predict the likelihood of exactly \( k \) occurrences in a period of time = \( T \)

Note that the occurrences are random, not regularly scheduled. There will be periods of time with no occurrences, and others with many occurrences.
Poisson model for Aloha

- What is probability of no arrivals in vulnerable period?
  - $\lambda = G/X$
  - $T = 2X$
  - $E[A(T)] = \lambda T = 2G$

\[
\Pr_{\text{success}} = \Pr(\text{no transmission attempts in } 2X \text{ seconds})
= \frac{(2G)^0}{0!} e^{-2G}
\]

\[
S = G \Pr_{\text{success}} = Ge^{-2G}
\]
Throughput of ALOHA

\[ S = GP_{\text{success}} = Ge^{-2G} \]

- Collisions are means for coordinating access
- Max throughput is \( S_{\text{max}} = 1/2e \) (18.4%)
- \( G = 1/2 \) for max throughput, one transmission per vulnerable period
- Bimodal behavior:
  - Small \( G \), \( S \approx G \)
  - Large \( G \), \( S \downarrow 0 \)
- Collisions can snowball and drop throughput to zero
Slotted ALOHA

- Time is slotted in $X$-second slots
- Packets are assumed to be constant and to occupy one time slot.
- All the stations keep track of transmission time slots and are allowed to initiate transmissions only at the beginning of a time slot.
- Backoff intervals are in multiples of slots.

**Vulnerable period**

- Only frames that arrive during prior $X$ seconds collide
- **Vulnerable period now becomes $X$-second long!**
Slotted ALOHA

- What is probability of no arrivals in vulnerable period?
  - \( \lambda = \frac{G}{X} \)
  - \( T = X \)
  - \( E[A(T)] = \lambda T = G \)

\[
\Pr_{\text{success}} = \Pr(\text{no transmission attempts in } X \text{ seconds}) = \frac{(G)^0}{0!} e^{-G}
\]

\[
S = G \Pr_{\text{success}} = Ge^{-G}
\]
CSMA (Carrier Sensing Multiple Access)

- A station **senses** the channel before it starts transmission
  - If busy, either wait or schedule backoff (different options)
  - If idle, start transmission
  - Vulnerable period is reduced to $t_{prop}$
  - If $a>1$, no gain compared to ALOHA or slotted ALOHA
CSMA Options

Transmitter behavior when busy channel is sensed

- **1-persistent CSMA** (most greedy)
  - Start transmission as soon as the channel becomes idle
  - Low delay and low efficiency

- **Non-persistent CSMA** (least greedy)
  - Wait for a backoff period, then sense carrier again
  - High delay and high efficiency

- **p-persistent CSMA** (adjustable greedy)
  - Wait till channel becomes idle, transmit with prob. $p$; or wait an additional propagation delay & re-sense with prob. $1-p$
  - Delay and efficiency can be balanced
Performance of CSMA

- CSMA schemes are sensitive to the end-to-end propagation delay of the medium.

- The normalized delay-bandwidth product ($a$) has a significant impact on the maximum achievable throughput.
  - For very small values of $a$, non-persistent CSMA has higher maximum achievable throughput than 1-persistent CSMA.
  - As $a$ approaches 1, both 1-persistent and non-persistent CSMA schemes have maximum achievable throughput that are even lower than the ALOHA schemes.
CSMA/CD (CSMA with Collision Detection)

- In both ALOHA and CSMA schemes, collisions involve entire frame transmissions.
- The amount of wasted bandwidth can be reduced by aborting the transmission when a collision is detected.
- If a collision is detected during transmission, then a short jamming signal is transmitted to ensure that other stations know that a collision has occurred before aborting the transmission.
- A backoff algorithm is used to schedule a future re-sensing time.
CSMA/CD Reaction Time

- It takes $2t_{prop}$ time to find out if channel has been captured
- A may abort its transmission at $2t_{prop}$ if collision is detected
CSMA/CD Model

- Assumptions
  - Collisions can be detected and resolved in $2t_{prop}$
  - Time is divided into $2t_{prop}$–long time slots during contention periods
  - Assume $n$ busy stations, and each may transmit with probability $p$ in each contention time slot
  - Once the contention period is over (when a station successfully captures the channel), it takes $X$ seconds for a frame to be transmitted
  - It takes $t_{prop}$ before the next contention period starts.
Contention Resolution

- How long does it take to resolve contention?
  - Contention is resolved ("success") if exactly 1 station transmits in a slot:
    \[ P_{success} = np(1 - p)^{n-1} \]
  - By taking derivative of \( P_{success} \), we find max occurs at \( p = 1/n \)
    \[ P_{max}^{success} = n \frac{1}{n} \left( 1 - \frac{1}{n} \right)^{n-1} = \left( 1 - \frac{1}{n} \right)^{n-1} \rightarrow \frac{1}{e} \]
  - So, on average, it takes \( e = 2.718 \) time slots to resolve contention
CSMA/CD Throughput

- At maximum throughput, system alternates between contention periods and frame transmission times

\[
\rho_{\text{max}} = \frac{X}{X + t_{\text{prop}} + 2et_{\text{prop}}} = \frac{1}{1 + (2e + 1)a} = \frac{1}{1 + (2e + 1)Rd / \nu L}
\]

where:

- \( R \) bits/sec, \( L \) bits/frame, \( X = L/R \) seconds/frame
- \( a = t_{\text{prop}}/X \)
- \( \nu \) m/s, speed of light in medium
- \( d \) meters is diameter of system
- \( 2e + 1 = 6.44 \)
Throughput Comparison of Random Access MACs

- For small $a$: CSMA/CD has the best throughput
- For larger $a$: ALOHA & Slotted ALOHA yield better throughput
Ethernet and IEEE 802.3
802.3 MAC Protocol

- 1-persistent CSMA/CD

- Truncated Binary Exponential Backoff
  - If a frame is about to undergo its $n^{th}$ retransmission attempt, then its retransmission time (in unit of minislot = $2 \times t_{prop}$) is determined by selecting an integer between 0 and $2^k-1$, where $k = \min(n, 10)$.
  - The increased retransmission range after each collision is intended to increase the likelihood that retransmissions will succeed.
  - Up to 16 retransmissions will be attempted, after which the system gives up.
Ethernet Scalability

- CSMA/CD maximum throughput depends on the normalized delay-bandwidth product \( a = \frac{t_{\text{prop}}}{X} \)
- When the transmission speed is increased, in order for CSMA/CD to operate correctly
  - Increase min packet size or reduce max distance between stations
Scheduling
Scheduling Approaches

- The randomness in the random access approaches can limit the maximum achievable throughput and can result in large variability in packet delays under heavier traffic load.

- **Scheduling approaches** attempt to produce an orderly access to the transmission medium.
  - Reservation systems
  - Polling systems
    - Special form of reservation systems
  - Token-passing ring
    - An extension of the polling concept to ring topology
Basic Reservation System

Transmissions are organized into cycles
Cycle: reservation interval + frame transmissions
Reservation interval has a minislot for each station to request reservations for frame transmissions
Operation of Reservation System

(a) negligible propagation delay

(b) non-negligible propagation delay

The reservation does not take effect until some fixed number of cycles later.
Assume that packet transmission times are $X = 1$ time unit, and that a reservation minislot requires $\nu \ (<1)$ time units.

The maximum throughput occurs when all stations are busy.

- For one packet reservation per minislot,
  \[ \rho_{\text{max}} = \frac{1}{1 + \nu} \]

- For $k$ packet reservations per minislot,
  \[ \rho_{\text{max}} = \frac{1}{1 + \nu/k} \]

Very high throughput is achievable when $\nu \ll 1$. 
If the number of stations becomes very large, the reservation interval \( M\nu \) becomes significant.

This becomes a serious problem when a very large number of stations transmit infrequently.

This problem can be addressed by making stations contend for a reservation minislot by using a random access scheme.

- If slotted ALOHA is used, then each successful reservation will require \( e = 2.71 \) minislots.
- The maximum achievable throughput for a reservation ALOHA system is \( \rho_{\text{max}} = 1 / (1 + 2.71\nu) \)
The Impact of the Non-Negligible Delays

- With non-negligible delays, slots may go unused because reservations cannot take effect quickly enough.
  - Reduction in the maximum achievable throughput

- Reservation systems can be modified so that packets that arrive during a frame can attempt to “cut ahead of the line.”
  - Packets are transmitted during periods that all stations know have not been reserved.
  - If a packet is successfully transmitted this way, its reservation in a following cycle is canceled.
Polling Systems

- Polling can be centralized or decentralized.
  - Centralized polling
    - Master asks each station in turn if it wants to send.
  - Decentralized polling
    - Assume that all stations can receive the transmission from all other stations.
    - The stations have a polling order list.
    - After a station is done transmitting, it is responsible for transferring a polling message to the next station on the polling list.
Examples of Polling Systems
Interaction of Polling Messages and Transmissions

Walk time (t’): the time elapses from when a station completes transmission to when the next station starts transmission

Cycle time (T_c): the time that elapses between two consecutive polls of the same station

Total walk time (τ’): the sum of the walk times in one cycle and represents the minimum time for one round of polling of all the stations.
Average Cycle Time

- Assume walk times all equal to \( t' \)
- Assume exhaustive service: stations empty their buffers per polled
- Cycle time = \( M t' \) + time to empty \( M \) station buffers
- \( \lambda / M \): the frame arrival rate at a station
- \( N_C \): average number of frame arrivals to a station in one cycle time

- Time to empty one station buffer:

\[
T_{\text{station}} = N_C X = \left( \frac{\lambda}{M} T_c \right) X = \frac{\rho T_c}{M} \quad \rho = \lambda X
\]

- Average Cycle Time:

\[
T_c = M t' + M T_{\text{station}} = M t' + \rho T_c \quad \Rightarrow \quad T_c = \frac{M t'}{1 - \rho}
\]
Efficiency of Polling Systems

- Exhaustive Service
  - Cycle time increases as traffic increases, so delays become very large
  - Walk time per cycle becomes negligible compared to cycle time:

\[
\text{Efficiency} = \frac{T_c - Mt'}{T_c} = \rho
\]

Can approach 100%!

- Limited Service
  - Many applications cannot tolerate extremely long delays
  - Time or transmissions per station are limited
  - This limits the cycle time and hence delay
  - Efficiency of 100% is not possible
  - E.g., if single frame per poll

\[
\text{Efficiency} = \frac{MX}{MX + Mt'} = \frac{1}{1 + t'/X}
\]
Application: Token-Passing Rings

Free Token = Poll

Listen mode
- Ready station looks for free token
- Change free token to busy

Transmit mode
- Ready station inserts its frames
- Reinserts free token when done

Input from ring → Delay → Output to ring

To device → Delay → From device
Token Passing

- Polling can be implemented in a distributed fashion on a ring.
- Receiving a free token corresponds to receiving a polling message.

- Two approaches to remove a packet that is inserted into the ring:
  - the destination station removes the packet
  - the packet is allowed to travel back to the transmitting station
    - a form of acknowledgment

- **Ring Latency**: the number of bits that can be simultaneously in transit around the ring
Methods of Token Re-insertion

- Multi-Token Operation
  - Free token is transmitted immediately after last bit of the data frame

- Single-Token Operation
  - Free token is inserted after last bit of the busy token is received back and the last bit of the frame is transmitted
  - If frame is longer than ring latency, it is equivalent to multi-token operation
  - Effective frame duration = \(\text{max(frame transmission time, ring latency)}\)

- Single-Frame Operation
  - Free token is inserted after the transmitting station has received the last bit of its frame
  - It allows the transmitting station to do error checking
Transmission Limit

- If a station is allowed to transmit an unlimited number of frames each time a token is received,
  - the delay experienced by frames is minimized, but
  - the cycle time is unbounded.

- A limit is usually placed either
  - on the number of frames that can be transmitted each time a token is received or
  - on the total time that a station may transmit information.

- This limit places a bound on the time that elapses between consecutive arrivals of a free token at given station.
Ring Latency

Suppose that a maximum of one frame can be transmitted per token.

- Let $\tau'$ be the ring latency in seconds and $a'$ be the ring latency normalized to the frame transmission time.

We have:

$$
\tau' = \tau + \frac{Mb}{R} \\
a' = \frac{\tau'}{X}
$$

- where $\tau$ is the total propagation time around the ring, $b$ is the number of bit delays in an interface, $Mb$ is the total delay introduced by the $M$ station interfaces, and $R$ is the speed of the transmission lines.
The maximum throughput occurs when all stations transmit a frame, i.e., no idle stations.

The total time taken to transmit the frames from the $M$ stations is $MX + \tau'$.

The maximum throughput is then

$$\rho_{\text{max}} = \frac{MX}{MX + \tau'} = \frac{1}{1 + \tau'/MX} = \frac{1}{1 + \alpha'/M}$$
Assume that packets are of constant length and their transmission time is $X$.

The effective frame duration is the maximum of $X$ and $\tau'$.

The maximum throughput is

$$\rho_{\text{max}} = \frac{MX}{M \max\{X, \tau\}' + \tau'} = \frac{1}{\max\{1, a'\} + \tau'/MX} = \frac{1}{\max\{1, a'\} + a'/M}$$

- When $X > \tau'$, that is $1 > a'$, single-token operation has the same maximum throughput as multi-token operation.
- When $X < \tau'$, that is $a' > 1$, then the maximum throughput is less than that of multi-token operation.
Throughput for Single-Frame Operation

- The effective frame duration is always $X + \tau'$.
- The maximum throughput is
  \[
  \rho_{\text{max}} = \frac{MX}{M(X + \tau') + \tau'} = \frac{1}{1 + a'(1 + \frac{1}{M})}
  \]
  which is the lowest of the three approaches.
- When $a' >> 1$, the maximum throughput of both single-token and single-frame approaches is approximately $1/ a'$.
- This occurs when the distance of the ring becomes large or the transmission speed becomes very high.
Throughput Comparison

Maximum throughput

Single-Token Operation

Multi-Token Operation

$M = 50$

$M = 10$

$M = 50$

$M = 10$
Token-Ring, IEEE 802.5, and FDDI
Token Ring

- The ring topology provides for fairness in access and for a fully distributed implementation.
- The token mechanism allows for the introduction of access priorities as well as the control of the token circulation time.
- IEEE 802.5 standard defines token-ring network, operating at 4 Mbps and 16 Mbps transmission.
- The rings are formed by twisted-pair cables using differential Manchester line coding.
- The maximum number of stations is set to 250.
Star-Topology Token Ring

- Stations connected in star fashion to wiring closet
  - Ring is implemented inside the wiring closet
  - Relay circuits can bypass failed links or stations
  - Can use existing telephone wiring arrangements
The transmitter station has the responsibility of removing the frame from the ring and of reinserting a free token in the ring.

All three of the token reinsertion strategies have been incorporated into token-ring LAN standards.

- Single-Frame
  - IEEE 802.5 standard at 4 Mbps

- Single-Token
  - IBM token-ring at 4 Mbps

- Multi-Token
  - IEEE 802.5 and IBM token-ring at 16 Mbps

IEEE 802.5 standard imposes a maximum token-holding-time limit of 10 ms.
Fiber Distributed Data Interface (FDDI)

- Token-ring protocol to interconnect various Ethernet LAN
- Counter-rotating dual ring topology
- 100 Mbps on optical fiber
- 4B5B binary line code and NRZ-inverted signaling
- Up to 200 km diameter, up to 500 stations
- FDDI has option to operate in multi-token mode
Dual Ring Topology

Dual ring becomes a single ring
802.11 Wireless LAN
Wireless Data Communications

- Wireless communications compelling
  - Easy, low-cost deployment

- Mobility & roaming: Access information anywhere

- Supports personal devices
  - PDAs, laptops, data-cell-phones

- Spectrum is limited & usually regulated
Ad Hoc Communications

- Temporary association of group of stations
  - Within range of each other
  - Need to exchange information
  - E.g. Presentation in meeting, or distributed computer game, or both
Infrastructure Network

- Permanent Access Points provide access to Internet
Why not CSMA/CD?

- It is difficult to detect collisions in a radio environment, so it is not possible to abort transmission that collided.
- The radio environment is not as well controlled as a wired broadcast medium, and transmissions from users in other WLANs can interfere with the operation of CSMA/CD.
- WLANs are subject to the hidden-station problem.
CSMA with Collision Avoidance

(a) RTS requests to send

(b) clear to send
B announces A ok to send

(c) Data Frame
A sends

C remains quiet
Summary of Random Access Approaches

- **ALOHA & Slotted ALOHA**
  - Simple & quick transfer at very low load
  - Accommodates large number of low-traffic bursty users
  - Highly variable delay at moderate loads
  - Efficiency does not depend on $a$.

- **CSMA/CD**
  - Quick transfer and high efficiency for low delay-bandwidth product
  - Can accommodate large number of bursty users
  - Variable and unpredictable delay
Summary of Scheduling Approaches

- Reservation
  - On-demand transmission of bursty or steady streams
  - Accommodates large number of low-traffic users with Slotted ALOHA reservations
  - Can incorporate QoS
  - Handles large delay-bandwidth product via delayed grants

- Polling
  - Special form of reservation systems
  - Provides fairness through regular access opportunities
  - Can provide bounds on access delay
  - Performance deteriorates with large delay-bandwidth product
Random Access vs. Scheduling

- The **scheduling approach** provides methodical orderly access to the medium, whereas **random access** provides a somewhat chaotic, uncoordinated, and unordered access.

- The **scheduling approach** has less variability in the delays encountered by packets and therefore has an edge in supporting applications with stringent delay requirements.

- When bandwidth is plentiful, **random access** systems can provide very small delays as long as the systems are operated with light load.

- Both approaches use channel bandwidth to provide information that controls the access to the channel.

- Any attempt to improve the throughput uses some form of coordination and is sensitive to the reaction time.