

ECE 683-001 Fall 2005 Computer Network Design and Analysis Lecture 6

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Sources:

- **Communication Networks 2nd Edition Chapter 6**
by Alberto Leon-Garcia and Indra Widjaja



Medium Access Control
Multiple Access Communications
Random Access
Scheduling



Lecture 6 Medium Access Control Protocols



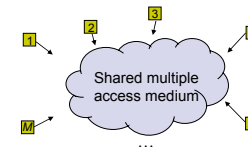
**Multiple Access
Communications**



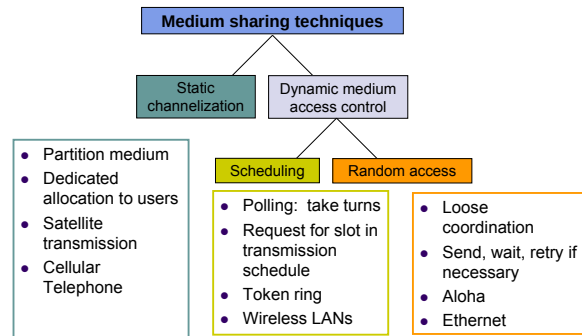
Multiple Access Communications



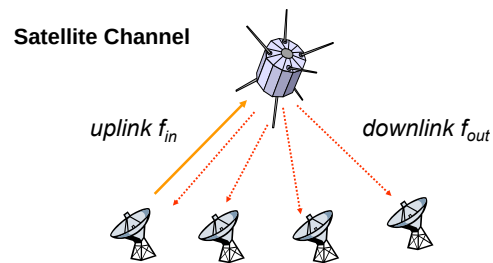
- Shared media basis for broadcast networks
 - Inexpensive: radio over air; copper or coaxial cable
 - M users communicate by broadcasting into medium
- Key issue: How to share the medium?



Approaches to Media Sharing



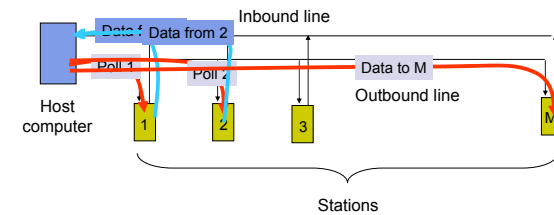
Channelization: Satellite



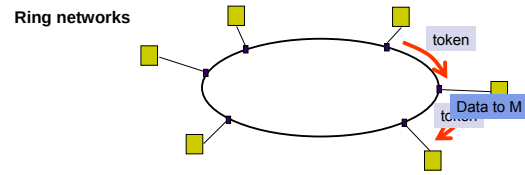
Channelization: Cellular



Scheduling: Polling



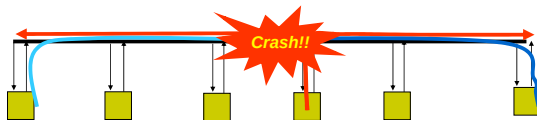
Scheduling: Token-Passing



Station that holds token transmits into ring

Random Access

Multitapped Bus



Transmit when ready

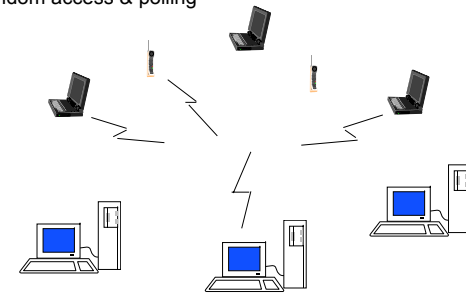
Transmissions can occur; need retransmission strategy

Wireless LAN

AdHoc: station-to-station

Infrastructure: stations to base station

Random access & polling



Selecting a Medium Access Control

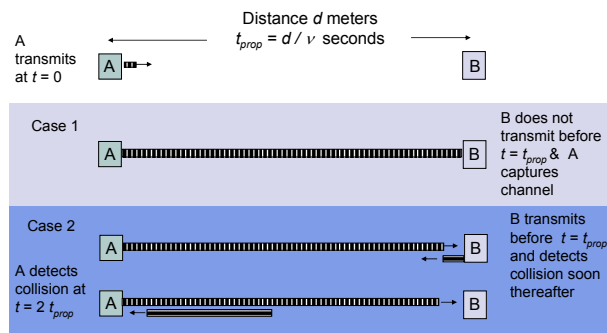
- Applications
 - What type of traffic?
 - Voice streams? Steady traffic, low delay/jitter
 - Data? Short messages? Web page downloads?
 - Enterprise or Consumer market? Reliability, cost
- Scale
 - How much traffic can be carried?
 - How many users can be supported?
- Current Examples:
 - Design MAC to provide wireless DSL-equivalent access to rural communities
 - Design MAC to provide Wireless-LAN-equivalent access to mobile users (user in car travelling at 130 km/hr)

Delay-Bandwidth Product

- *Delay-bandwidth* product key parameter
 - Coordination in sharing medium involves using bandwidth (explicitly or implicitly)
 - Difficulty of coordination commensurate with delay-bandwidth product
- Simple two-station example
 - Station with frame to send listens to medium and transmits if medium found idle
 - Station monitors medium to detect collision
 - If collision occurs, station that begin transmitting earlier retransmits (propagation time is known)

Two-Station MAC Example

Two stations are trying to share a common medium



Efficiency of Two-Station Example

- Each frame transmission requires $2t_{prop}$ of quiet time
 - Station B needs to be quiet t_{prop} before *and* after time when Station A transmits
 - R transmission bit rate
 - L bits/frame

$$Efficiency = \rho_{max} = \frac{L}{L + 2t_{prop}R} = \frac{1}{1 + 2t_{prop}R/L} = \frac{1}{1 + 2a}$$

$$MaxThroughput = R_{eff} = \frac{L}{L/R + 2t_{prop}} = \frac{1}{1 + 2a} R \text{ bits/second}$$

Normalized
Delay-Bandwidth
Product

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

← Propagation delay
 ← Time to transmit a frame

Typical MAC Efficiencies

Two-Station Example:

$$Efficiency = \frac{1}{1 + 2a}$$

CSMA-CD (Ethernet) protocol:

$$Efficiency = \frac{1}{1 + 6.44a}$$

Token-ring network

$$Efficiency = \frac{1}{1 + a'}$$

a' = latency of the ring (bits)/average frame length

- If $a < 1$, then efficiency close to 100%
- As a approaches 1, the efficiency becomes low

Typical Delay-Bandwidth Products

Distance	10 Mbps	100 Mbps	1 Gbps	Network Type
1 m	3.33×10^{-02}	3.33×10^{-01}	3.33×10^0	Desk area network
100 m	3.33×10^{01}	3.33×10^{02}	3.33×10^{03}	Local area network
10 km	3.33×10^{02}	3.33×10^{03}	3.33×10^{04}	Metropolitan area network
1000 km	3.33×10^{04}	3.33×10^{05}	3.33×10^{06}	Wide area network
100000 km	3.33×10^{06}	3.33×10^{07}	3.33×10^{08}	Global area network

- Max size Ethernet frame: 1500 bytes = 12000 bits
- Long and/or fat pipes give large a

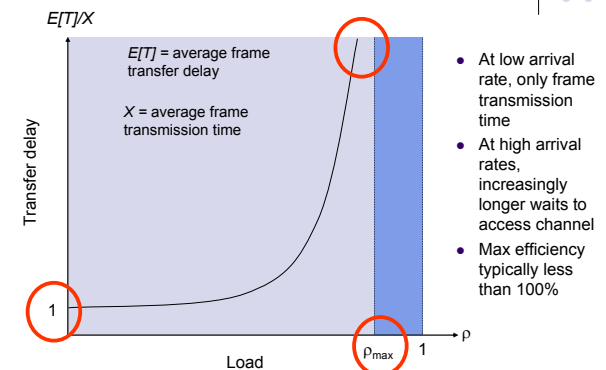
MAC protocol features

- Delay-bandwidth product
- Efficiency
- Transfer delay
- Fairness
- Reliability
- Capability to carry different types of traffic
- Quality of service
- Cost

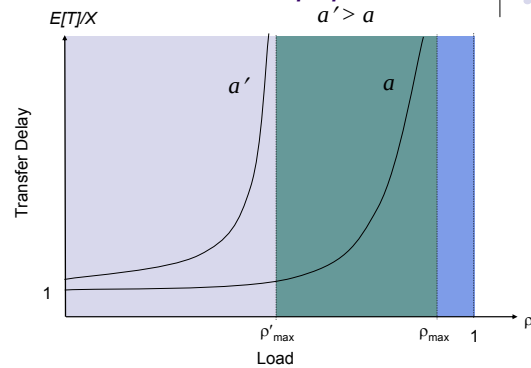
MAC Delay Performance

- Frame transfer delay
 - From first bit of frame arrives at source MAC
 - To last bit of frame delivered at destination MAC
- Throughput
 - Actual transfer rate through the shared medium
 - Measured in frames/sec or bits/sec
- Parameters
 - R bits/sec & L bits/frame
 - $X = L/R$ seconds/frame
 - λ frames/second average arrival rate
 - Load $\rho = \lambda X$, rate at which "work" arrives
 - Maximum throughput (@100% efficiency): R/L fr/sec

Normalized Delay versus Load



Dependence on Rt_{prop}/L



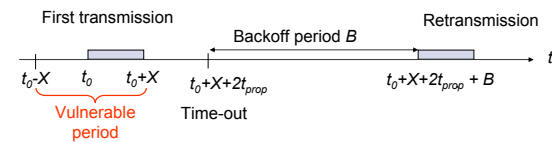
Lecture 6 Medium Access Control Protocols

Random Access



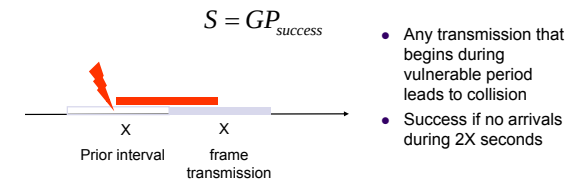
ALOHA

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



ALOHA Model

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



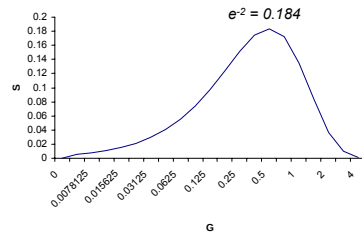
Abramson's Assumption

- What is probability of no arrivals in vulnerable period?
- Abramson assumption: Effect of backoff algorithm is that frame arrivals are equally likely to occur at any time interval
- G is avg. # arrivals per X seconds
- Divide X into n intervals of duration $\Delta = X/n$
- p = probability of arrival in Δ interval, then
 $G = n p$ since there are n intervals in X seconds

$$\begin{aligned}
 P_{\text{success}} &= P[0 \text{ arrivals in } 2X \text{ seconds}] = \\
 &= P[0 \text{ arrivals in } 2n \text{ intervals}] \\
 &= (1-p)^{2n} = \left(1 - \frac{G}{n}\right)^{2n} \rightarrow e^{-2G} \text{ as } n \rightarrow \infty
 \end{aligned}$$

Throughput of ALOHA

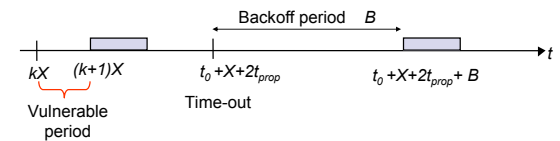
$$S = GP_{\text{success}} = Ge^{-2G}$$



- Collisions are means for coordinating access
- Max throughput is $\rho_{\text{max}} = 1/2e$ (18.4%)
- Bimodal behavior:
 Small G , $S \approx G$
 Large G , $S \rightarrow 0$
- Collisions can snowball and drop throughput to zero

Slotted ALOHA

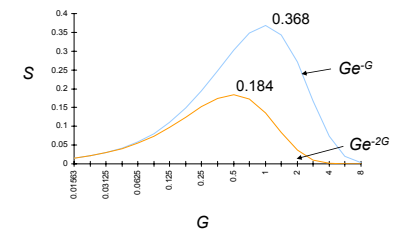
- Time is slotted in X seconds slots
- Stations synchronized to frame times
- Stations transmit frames in first slot after frame arrival
- Backoff intervals in multiples of slots



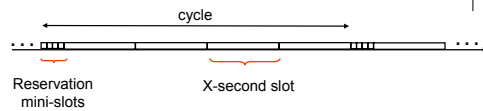
Only frames that arrive during prior X seconds collide

Throughput of Slotted ALOHA

$$\begin{aligned}
 S &= GP_{\text{success}} = GP[\text{no arrivals in } X \text{ seconds}] \\
 &= GP[\text{no arrivals in } n \text{ intervals}] \\
 &= G(1-p)^n = G\left(1 - \frac{G}{n}\right)^n \rightarrow Ge^{-G}
 \end{aligned}$$



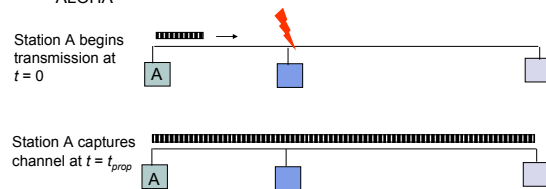
Application of Slotted Aloha



- Reservation protocol allows a large number of stations with infrequent traffic to reserve slots to transmit their frames in future cycles
- Each cycle has mini-slots allocated for making reservations
- Stations use slotted Aloha during mini-slots to request slots

Carrier Sensing Multiple Access (CSMA)

- 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} (due to channel capture effect)
 - When collisions occur they involve entire frame transmission times
 - If $t_{prop} > X$ (or if $a > 1$), no gain compared to ALOHA or slotted ALOHA

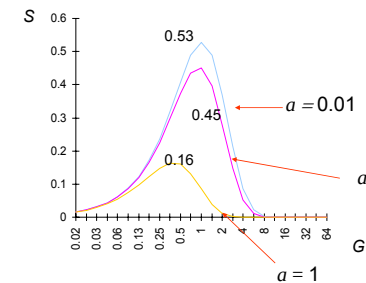


CSMA Options

- 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 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 one mini-slot time & re-sense with probability $1-p$
 - Delay and efficiency can be balanced

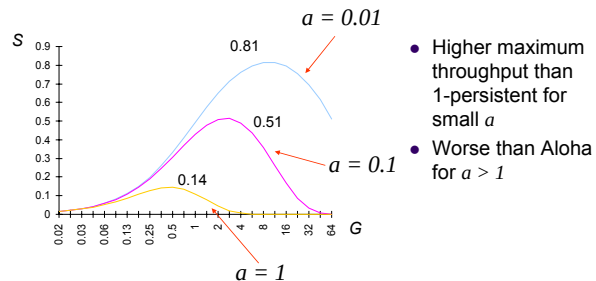


1-Persistent CSMA Throughput



- Better than Aloha & slotted Aloha for small a
- Worse than Aloha for $a > 1$

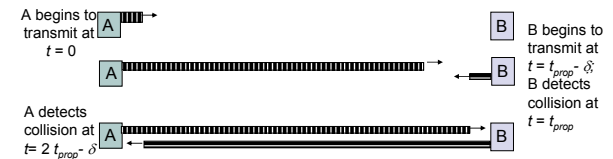
Non-Persistent CSMA Throughput



CSMA with Collision Detection (CSMA/CD)

- Monitor for collisions & abort transmission
 - Stations with frames to send, first do carrier sensing
 - After beginning transmissions, stations continue listening to the medium to detect collisions
 - If collisions detected, all stations involved stop transmission, reschedule random backoff times, and try again at scheduled times
- In CSMA collisions result in wastage of X seconds spent transmitting an entire frame
- CSMA-CD reduces wastage to time to detect collision and abort transmission

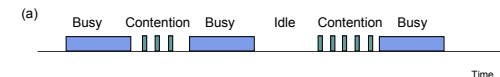
CSMA/CD reaction time



It takes $2t_{prop}$ to find out if channel has been captured

CSMA-CD Model

- Assumptions
 - Collisions can be detected and resolved in $2t_{prop}$
 - Time slotted in $2t_{prop}$ 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 (a station successfully occupies 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:

$$P_{\text{success}} = np(1-p)^{n-1}$$

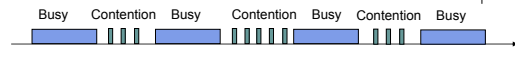
- By taking derivative of P_{success} we find max occurs at $p=1/n$

$$P_{\text{success}}^{\text{max}} = n \frac{1}{n} \left(1 - \frac{1}{n}\right)^{n-1} = \left(1 - \frac{1}{n}\right)^{n-1} \rightarrow \frac{1}{e}$$

- On average, $1/P^{\text{max}} = e = 2.718$ time slots to resolve contention

$$\text{Average Contention Period} = 2t_{\text{prop}}e \text{ seconds}$$

CSMA/CD Throughput



- At maximum throughput, systems 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

$a = t_{\text{prop}}/X$

ν meters/sec. speed of light in medium

d meters is diameter of system

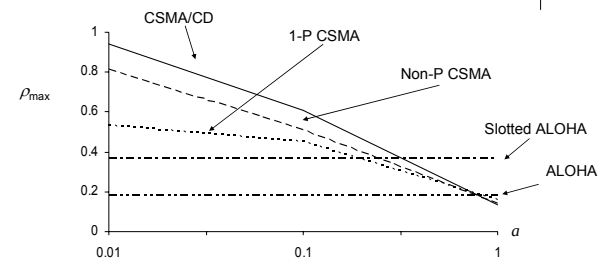
$2e+1 = 6.44$

CSMA-CD Application: Ethernet



- First Ethernet LAN standard used CSMA-CD
 - 1-persistent Carrier Sensing
 - $R = 10$ Mbps
 - $t_{\text{prop}} = 51.2$ microseconds
 - 512 bits = 64 byte slot
 - accommodates 2.5 km + 4 repeaters
- Truncated Binary Exponential Backoff
 - After n th collision, select backoff from $\{0, 1, \dots, 2^k - 1\}$, where $k = \min(n, 10)$

Throughput for Random Access MACs



- For small a : CSMA-CD has best throughput
- For larger a : Aloha & slotted Aloha better throughput

Carrier Sensing and Priority Transmission



- Certain applications require faster response than others, e.g. ACK messages
- Impose different interframe times
 - High priority traffic sense channel for time τ_1
 - Low priority traffic sense channel for time $\tau_2 > \tau_1$
 - High priority traffic, if present, seizes channel first
- This priority mechanism is used in IEEE 802.11 wireless LAN

Lecture 6 Medium Access Control Protocols and Local Area Networks



Scheduling



Scheduling for Medium Access Control

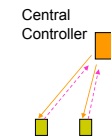
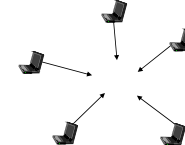


- Schedule frame transmissions to avoid collision in shared medium
 - ✓ More efficient channel utilization
 - ✓ Less variability in delays
 - ✓ Can provide fairness to stations
 - ✗ Increased computational or procedural complexity
- Two main approaches
 - Reservation
 - Polling

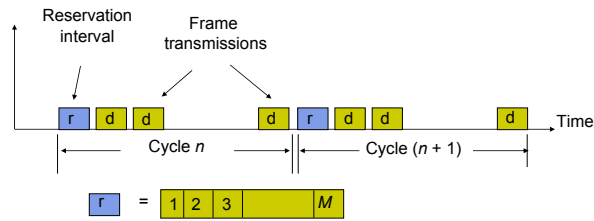
Reservations Systems



- *Centralized systems*: A central controller accepts requests from stations and issues grants to transmit
 - Frequency Division Duplex (FDD): Separate frequency bands for uplink & downlink
 - Time-Division Duplex (TDD): Uplink & downlink time-share the same channel
- *Distributed systems*: Stations implement a decentralized algorithm to determine transmission order



Reservation Systems



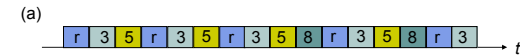
- Transmissions organized into cycles
- Cycle: reservation interval + frame transmissions
- Reservation interval has a minislot for **each** station to request reservations for frame transmissions

Reservation System Options

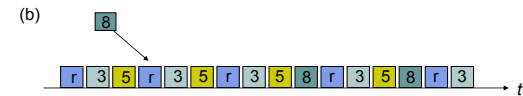
- Centralized or distributed system
 - *Centralized systems*: A central controller listens to reservation information, decides order of transmission, issues grants
 - *Distributed systems*: Each station determines its slot for transmission from the reservation information
- Single or Multiple Frames
 - *Single frame reservation*: Only one frame transmission can be reserved within a reservation cycle
 - *Multiple frame reservation*: More than one frame transmission can be reserved within a frame
- Channelized or Random Access Reservations
 - *Channelized (typically TDMA) reservation*: Reservation messages from different stations are multiplexed without any risk of collision
 - *Random access reservation*: Each station transmits its reservation message randomly until the message goes through

Example

- Initially stations 3 & 5 have reservations to transmit frames



- Station 8 becomes active and makes reservation
- Cycle now also includes frame transmissions from station 8



Efficiency of Reservation Systems

- Assume minislot duration = vX
- TDM single frame reservation scheme
 - If propagation delay is negligible, a single frame transmission requires $(1+v)X$ seconds
 - Link is fully loaded when all stations transmit, maximum efficiency is:

$$\rho_{\max} = \frac{MX}{Mv + MX} = \frac{1}{1 + v}$$

- TDM k frame reservation scheme
 - If k frame transmissions can be reserved with a reservation message and if there are M stations, as many as Mk frames can be transmitted in $XM(k+v)$ seconds
 - Maximum efficiency is:

$$\rho_{\max} = \frac{MkX}{Mv + MkX} = \frac{1}{1 + \frac{v}{k}}$$

Random Access Reservation Systems



- *Large number of light traffic stations*
 - Dedicating a minislot to each station is inefficient
- **Slotted ALOHA reservation scheme**
 - Stations use slotted Aloha on reservation minislots
 - On average, each reservation takes at least e minislot attempts
 - Effective time required for the reservation is $2.71vX$

$$\rho_{\max} = \frac{X}{X(1+ev)} = \frac{1}{1+2.71v}$$

Example: GPRS



- **General Packet Radio Service**
 - Packet data service in GSM cellular radio
 - GPRS devices, e.g. cellphones or laptops, send packet data over radio and then to Internet
 - Slotted Aloha MAC used for reservations
 - Single & multi-slot reservations supported

Reservation Systems and Quality of Service



- Different applications; different requirements
 - Immediate transfer for ACK frames
 - Low-delay transfer & steady bandwidth for voice
 - High-bandwidth for Web transfers
- Reservation provide direct means for QoS
 - Stations makes requests per frame
 - Stations can request for persistent transmission access
 - Centralized controller issues grants
 - Preferred approach
 - Decentralized protocol allows stations to determine grants
 - Protocol must deal with error conditions when requests or grants are lost

Polling Systems



- *Centralized polling systems*: A central controller transmits polling messages to stations according to a certain order
- *Distributed polling systems*: A permit for frame transmission is passed from station to station according to a certain order
- A signaling procedure exists for setting up order

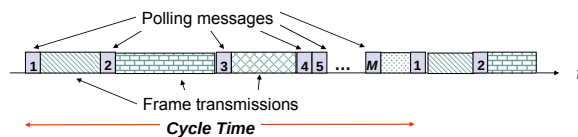


Polling System Options

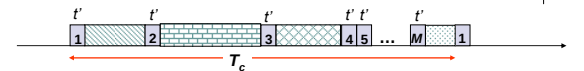
- Service Limits: How much is a station allowed to transmit per poll?
 - *Exhaustive*: until station's data buffer is empty (including new frame arrivals)
 - *Gated*: all data in buffer when poll arrives
 - *Frame-Limited*: one frame per poll
 - *Time-Limited*: up to some maximum time
- Priority mechanisms
 - More bandwidth & lower delay for stations that appear multiple times in the polling list
 - Issue polls for stations with message of priority k or higher

Walk Time & Cycle Time

- Assume polling order is round robin
- Time is "wasted" polling stations
 - Time to prepare & send polling message
 - Time for station to respond
- *Walk time*: from when a station completes transmission to when next station begins transmission
- *Cycle time* is between consecutive polls of a station
- Overhead/cycle = total walk time/cycle time



Average Cycle Time



- Assume walk times all equal to t'
- Exhaustive Service: stations empty their buffers
- Cycle time = $Mt' +$ time to empty M station buffers
- λ/M be frame arrival rate at a station
- N_c average number of frames transmitted from a station
- Time to empty one station buffer:

$$T_{station} = N_c X = \left(\frac{\lambda}{M} T_c\right) X = \frac{\rho T_c}{M} \quad \rho = \lambda X$$

- Average Cycle Time:

$$T_c = Mt' + MT_{station} = Mt' + \rho T_c \Rightarrow T_c = \frac{Mt'}{1 - \rho}$$

Efficiency of Polling Systems

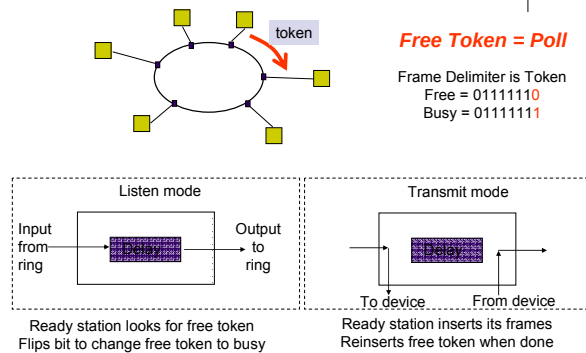
- Exhaustive Service
 - Cycle time increases as traffic increases, so delays become very large
 - Walk time per cycle becomes negligible compared to cycle time:

$$Efficiency = \frac{MX - Mt'}{T_c} = \rho \quad \text{Can approach 100\%}$$

- 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

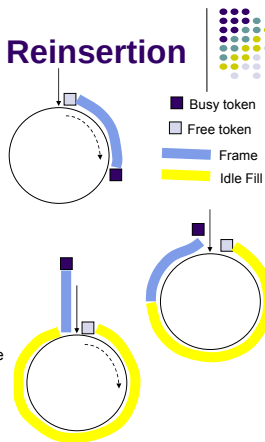
$$Efficiency = \frac{MX}{MX + Mt'} = \frac{1}{1 + t' / X} \quad \text{Single frame per poll}$$

Application: Token-Passing Rings



Methods of Token Reinsertion

- Ring latency: number of bits that can be simultaneously in transit on ring
- Multi-token operation
 - Free token transmitted immediately after last bit of data frame
- Single-token operation
 - Free token inserted after last bit of the busy token is received back
 - Transmission time at least ring latency
 - If frame is longer than ring latency, equivalent to multi-token operation
- Single-Frame operation
 - Free token inserted after transmitting station has received last bit of its frame
 - Equivalent to attaching trailer equal to ring latency



Token Ring Throughput

- Definition
 - τ' : ring latency (time required for bit to circulate ring)
 - X : maximum frame transmission time allowed per station
- Multi-token operation
 - Assume network is fully loaded, and all M stations transmit for X seconds upon the reception of a free token
 - This is a polling system with limited service time:

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

$$a' = \frac{\tau'}{X} \text{ is the normalized ring latency}$$

Token Ring Throughput

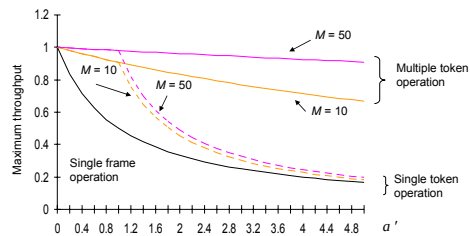
- Single-frame operation
 - Effective frame transmission time is maximum of X and τ' , therefore

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

- Single-token operation
 - Effective frame transmission time is $X + \tau'$, therefore

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

Token Reinsertion Efficiency Comparison



- $a < 1$, any token reinsertion strategy acceptable
- $a \approx 1$, single token reinsertion strategy acceptable
- $a > 1$, multitoken reinsertion strategy necessary

Application Examples

- Single-frame reinsertion
 - IEEE 802.5 Token Ring LAN @ 4 Mbps
- Single token reinsertion
 - IBM Token Ring @ 4 Mbps
- Multitoken reinsertion
 - IEEE 802.5 and IBM Ring LANs @ 16 Mbps
 - FDDI Ring @ 50 Mbps
- All of these LANs incorporate token priority mechanisms

Comparison of MAC 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

Comparison of MAC 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
 - Generalization of time-division multiplexing
 - Provides fairness through regular access opportunities
 - Can provide bounds on access delay
 - Performance deteriorates with large delay-bandwidth product