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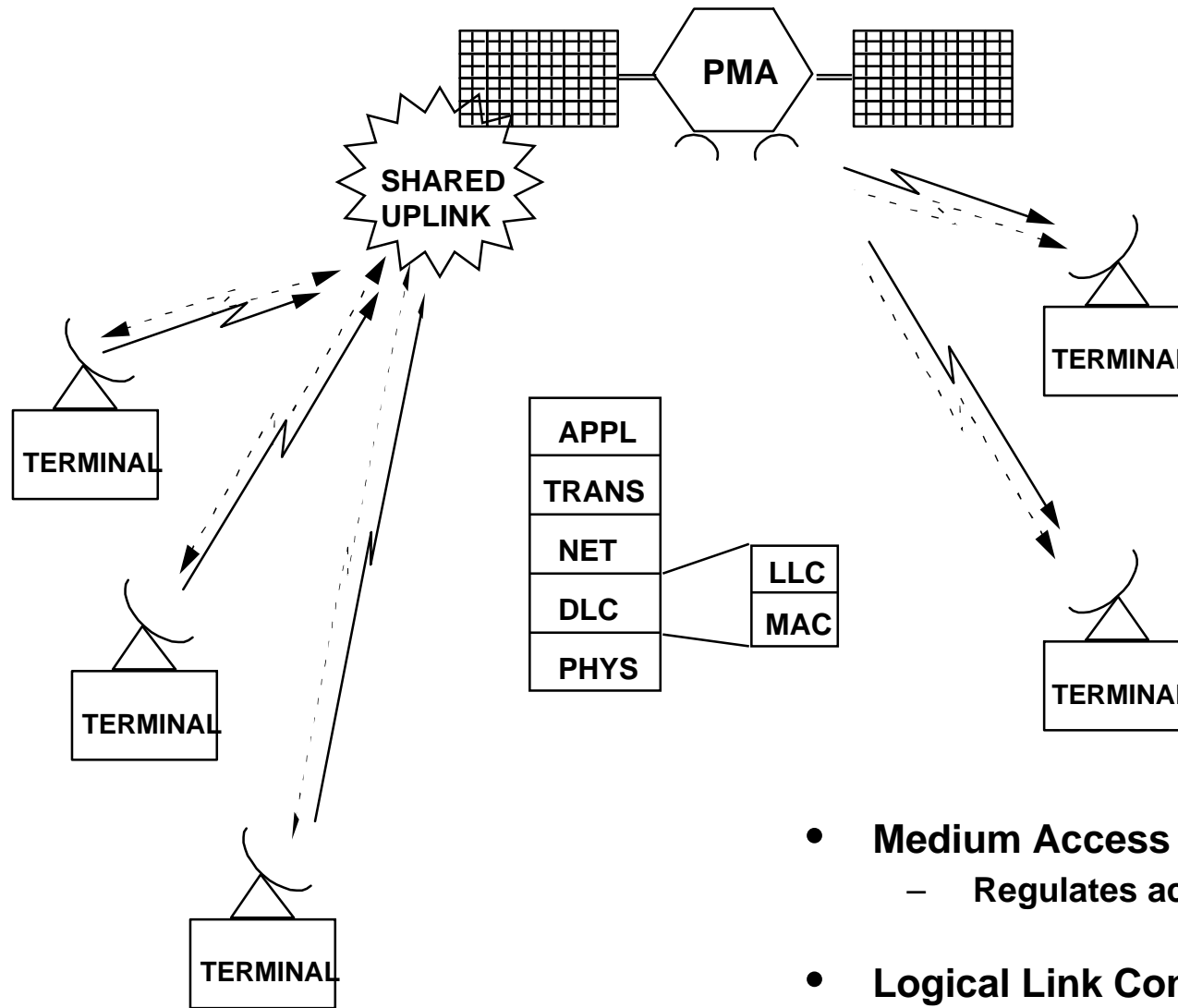
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# Packet multiple access: The Aloha Protocol

**Eytan Modiano**  
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# Packet Multiple Access



- **Medium Access Control (MAC)**
  - Regulates access to channel
- **Logical Link Control (LLC)**
  - All other DLC functions



# Examples of Multiple Access Channels

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- **Local area networks (LANs)**
- **Satellite channels**
- **Wireless radio**
- **Characteristics of Multiple Access Channel**
  - **Shared Transmission Medium**
    - A receiver can hear multiple transmitters
    - A transmitter can be heard by multiple receivers
  - **The major problem with multiple access is allocating the channel between the users**
    - Nodes do not know when other nodes have data to send
    - Need to coordinate transmissions



# Approaches to Multiple Access

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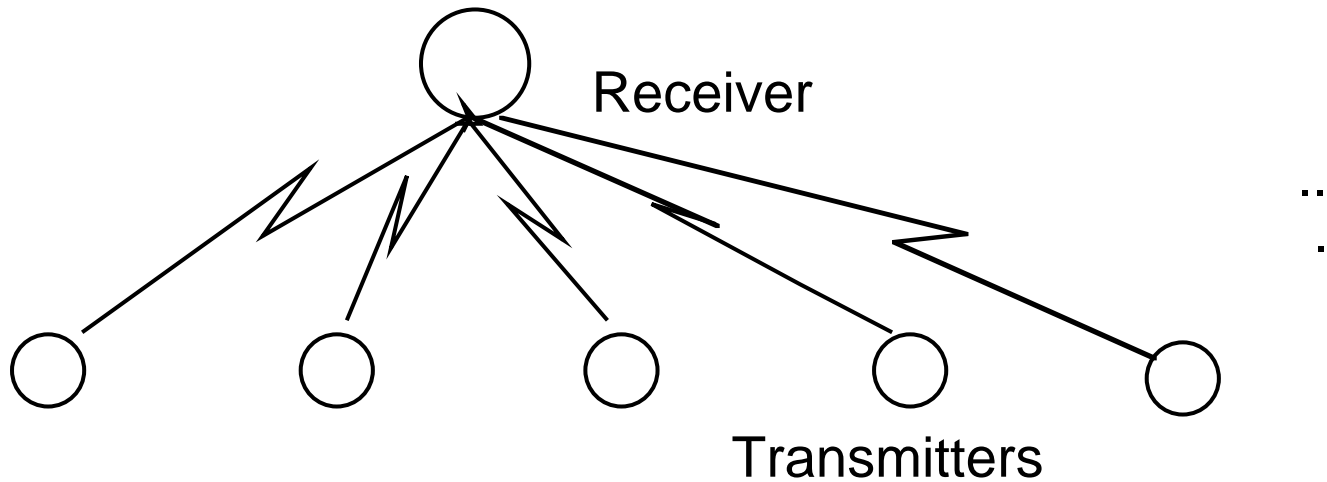
- **Fixed Assignment (TDMA, FDMA, CDMA)**
  - Each node is allocated a fixed fraction of bandwidth
  - Equivalent to circuit switching
  - very inefficient for low duty factor traffic
- **Packet multiple access**
  - Polling
  - Reservations and Scheduling
  - Random Access



# Aloha



Single receiver, many transmitters

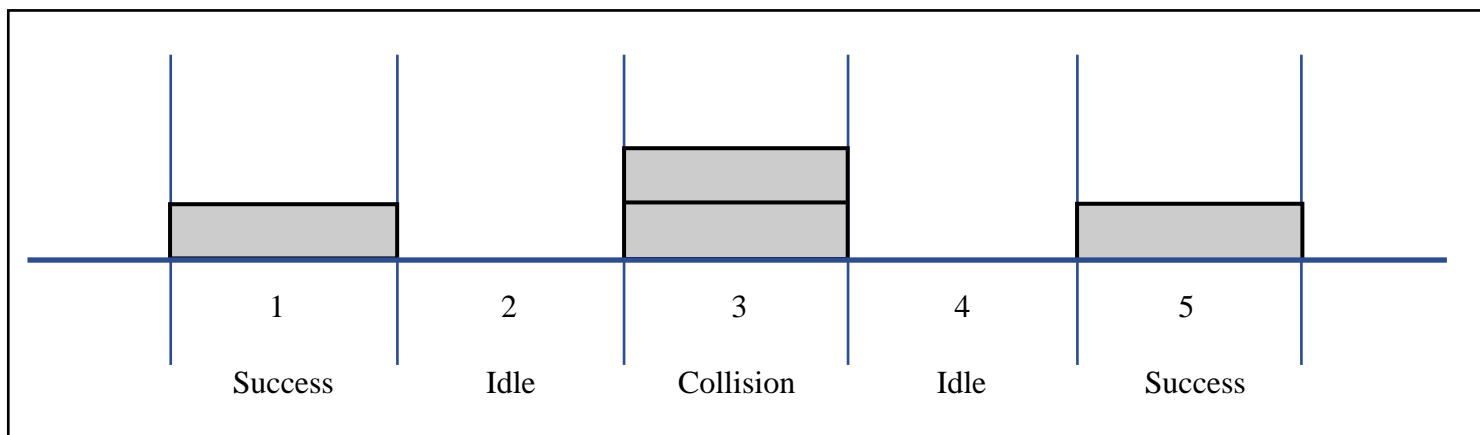


E.g., Satellite system, wireless



# Slotted Aloha

- Time is divided into “slots” of one packet duration
  - E.g., fixed size packets
- When a node has a packet to send, it waits until the start of the next slot to send it
  - Requires synchronization
- If no other nodes attempt transmission during that slot, the transmission is successful
  - Otherwise “collision”
  - Collided packet are retransmitted after a random delay





# Slotted Aloha Assumptions

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- **Poisson external arrivals**
- **No capture**
  - Packets involved in a collision are lost
  - Capture models are also possible
- **Immediate feedback**
  - Idle (0) , Success (1), Collision (e)
- **If a new packet arrives during a slot, transmit in next slot**
- **If a transmission has a collision, it becomes backlogged and retransmitted after a random delay**
  - Let  $n$  be the number of backlogged nodes





# slotted aloha



- **Let  $g$  be the attempt rate (the expected number of packets transmitted in a slot)**
  - **The number of attempted packets per slot is approximately a Poisson random variable of mean  $g = \lambda + n \cdot q_r$** 
    - $q_r$  = probability that a backlogged packet is retransmitted in a slot
    - $n$  = number of backlogged packets
  - **$P(m \text{ attempts}) = g^m e^{-g} / m!$**
  - **$P(\text{idle}) = \text{probability of no attempts in a slot} = e^{-g}$**
  - **$p(\text{success}) = \text{probability of one attempt in a slot} = g e^{-g}$**
  - **$P(\text{collision}) = P(\text{two or more attempts}) = 1 - P(\text{idle}) - P(\text{success})$**



# Throughput of Slotted Aloha

- The throughput is the fraction of slots that contain a successful transmission =  $P(\text{success}) =$

arrival rate ( $\lambda$ )

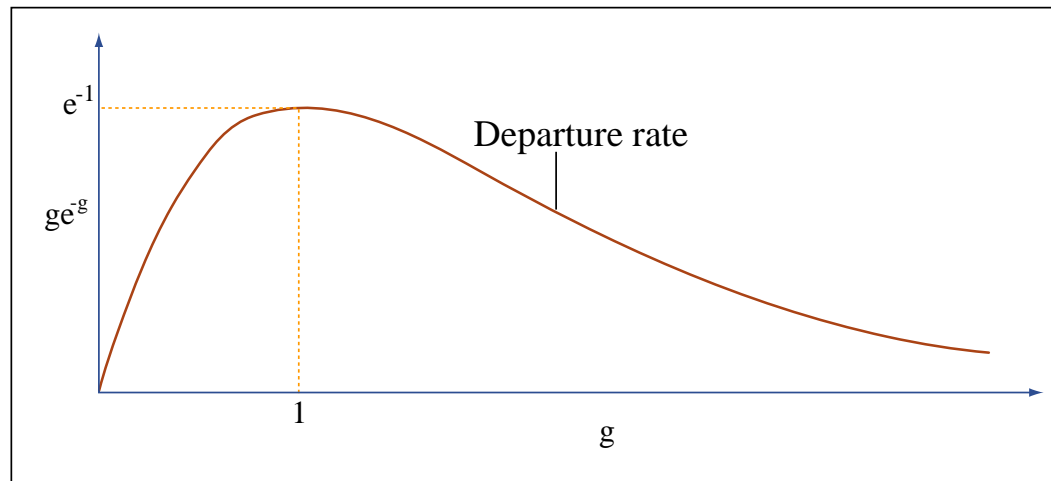


Figure by MIT OpenCourseWare.

- What value of  $g$  maximizes throughput?

$$\frac{d}{dg(n)} ge^{-g} = e^{-g} - ge^{-g} = 0$$

$$\Rightarrow g = 1$$

- $g < 1 \Rightarrow$  too many idle slots
- $g > 1 \Rightarrow$  too many collisions

$$\Rightarrow P(\text{success}) = ge^{-g} = 1/e \approx 0.36$$

- If  $g$  can be kept close to 1, an external arrival rate of  $1/e$  packets per slot can be sustained



# Instability of slotted aloha



- if backlog increases beyond unstable point (bad luck) then it tends to increase without limit and the departure rate drops to 0
  - Aloha is inherently unstable and needs algorithm to keep it stable
- Drift in state  $n$ ,  $D(n)$  is the expected change in backlog over one time slot
  - $D(n) = \lambda - P(\text{success}) = \lambda - g(n)e^{-g(n)}$

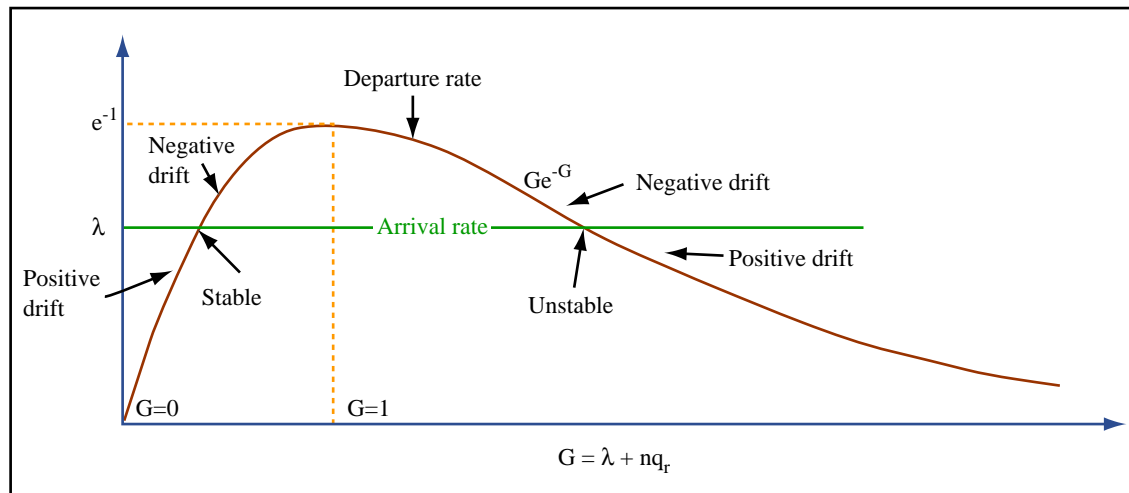
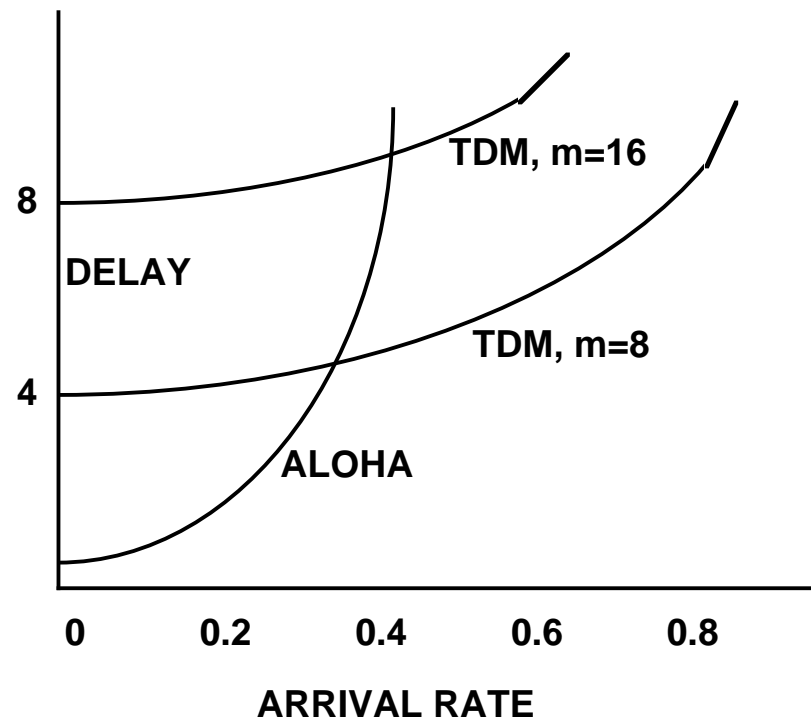


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# TDM vs. slotted aloha

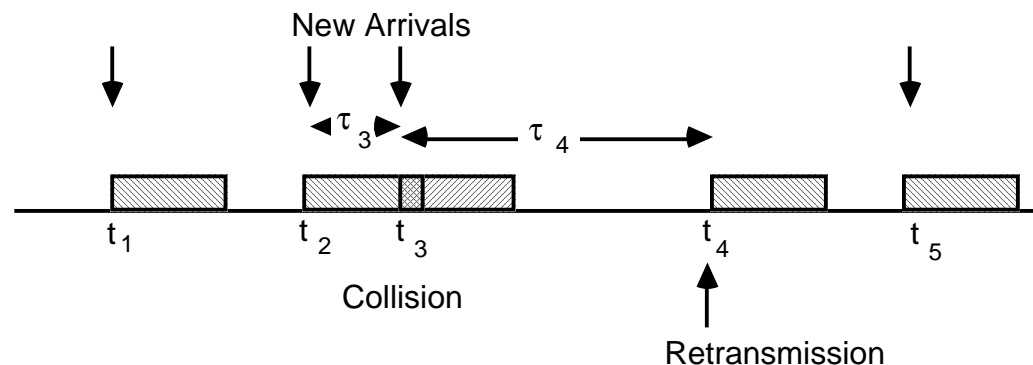


- Aloha achieves lower delays when arrival rates are low
- TDM results in very large delays with large number of users, while Aloha is independent of the number of users



# Pure (unslotted) Aloha

- **New arrivals are transmitted immediately (no slots)**
  - No need for synchronization
  - No need for fixed length packets
- **A backlogged packet is retried after an exponentially distributed random delay with some mean  $1/x$**
- **The total arrival process is a time varying Poisson process of rate  $g(n) = \lambda + nx$  ( $n = \text{backlog}$ ,  $1/x = \text{ave. time between retransmissions}$ )**
- **Note that an attempt suffers a collision if the previous attempt is not yet finished ( $t_i - t_{i-1} < 1$ ) or the next attempt starts too soon ( $t_{i+1} - t_i < 1$ )**





# Throughput of Unslotted Aloha

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- **An attempt is successful if the inter-attempt intervals on both sides exceed 1 (for unit duration packets)**
  - **$P(\text{success}) = e^{-g} \times e^{-g} = e^{-2g}$**
  - **Throughput (success rate) =  $ge^{-2g}$**
  - **Max throughput at  $g = 1/2$ , Throughput =  $1/2e \sim 0.18$**
  - **Stabilization issues are similar to slotted aloha**
  - **Advantages of unslotted aloha are simplicity and possibility of unequal length packets**



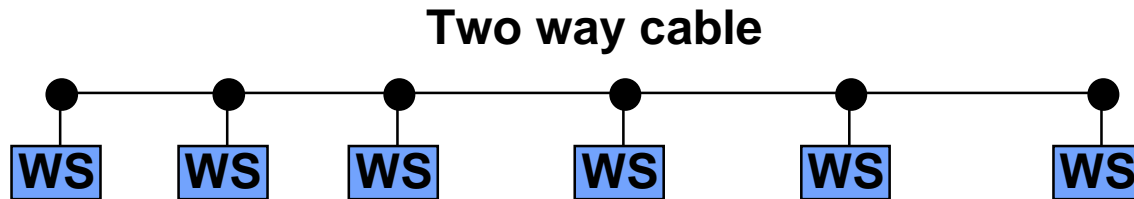
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# **Packet Multiple Access: CSMA/CD and the Ethernet**

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# CSMA/CD and Ethernet

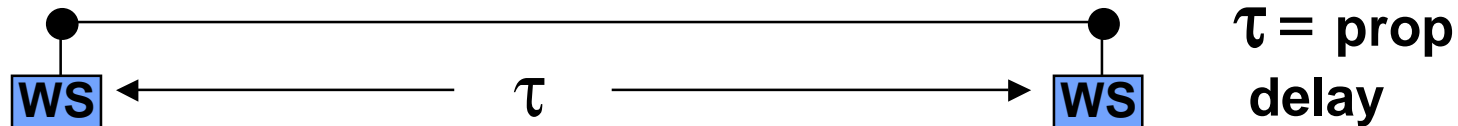


- **CSMA with Collision Detection (CD) capability**
  - Nodes able to detect collisions
  - Upon detection of a collision nodes stop transmission
    - Reduce the amount of time wasted on collisions
  
- **Protocol:**
  - All nodes listen to transmissions on the channel
  
  - When a node has a packet to send:
    - Channel idle  $\Rightarrow$  Transmit
    - Channel busy  $\Rightarrow$  wait a random delay (binary exponential back-off)
  
  - If a transmitting node detects a collision it stops transmission
    - Waits a random delay and tries again





# Time to detect collisions



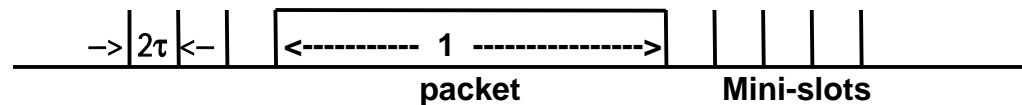
- A collision can occur while the signal propagates between the two nodes
- It would take an additional propagation delay for both users to detect the collision and stop transmitting
- If  $\tau$  is the maximum propagation delay on the cable then if a collision occurs, it can take up to  $2\tau$  seconds for all nodes involved in the collision to detect and stop transmission



# Approximate model for CSMA/CD



- Simplified approximation for added insight
- Consider a slotted system with “mini-slots” of duration  $2\tau$



- If a node starts transmission at the beginning of a mini-slot, by the end of the mini-slot either
  - No collision occurred and the rest of the transmission will be uninterrupted
  - A collision occurred, but by the end of the mini-slot the channel would be idle again
- Hence a collision at most affects one mini-slot



# Analysis of CSMA/CD

- Assume  $N$  users and that each attempts transmission during a free “mini-slot” with probability  $p$ 
  - $P$  includes new arrivals and retransmissions

$$P(i \text{ users attempt}) = \binom{N}{i} P^i (1-P)^{N-i}$$

$$P(\text{exactly 1 attempt}) = P(\text{success}) = NP(1-P)^{N-1}$$

To maximize  $P(\text{success})$ ,

$$\frac{d}{dp} [NP(1-P)^{N-1}] = N(1-P)^{N-1} - N(N-1)P(1-P)^{N-2} = 0$$

$$\Rightarrow P_{\text{opt}} = \frac{1}{N}$$

$\Rightarrow$  Average attempt rate of one per slot

$\Rightarrow$  Notice the similarity to slotted Aloha



## Analysis of CSMA/CD, continued

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$$P(\text{success}) = NP(1-p)^{N-1} = \left(1 - \frac{1}{N}\right)^{N-1}$$

$$P_s = \lim_{N \rightarrow \infty} P(\text{success}) = \frac{1}{e}$$

Let  $X$  = Average number of slots per successful transmission

$$P(X=i) = (1-P_s)^{i-1}P_s$$

$$\Rightarrow E[X] = \frac{1}{P_s} = e$$

- Once a mini-slot has been successfully captured, transmission continues without interruption
- New transmission attempts will begin at the next mini-slot after the end of the current packet transmission



# Analysis of CSMA/CD, continued



- Let  $S$  = Average amount of time between successful packet transmissions

$$S = (e-1)2\tau + D_{Tp} + \tau$$

Idle/collision Mini-slots      Packet transmission time      Ave time until start of next Mini-slot

- Efficiency =  $D_{Tp}/S = D_{Tp} / (D_{Tp} + \tau + 2\tau(e-1))$
- Let  $\beta = \tau / D_{Tp} \Rightarrow$  Efficiency  $\approx 1/(1+4.4\beta) = \lambda < 1/(1+4.4\beta)$



# Notes on CSMA/CD

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- **Can be viewed as a reservation system where the mini-slots are used for making reservations for data slots**
- **In this case, Aloha is used for making reservations during the mini-slots**
- **Once a users captures a mini-slot it continues to transmit without interruptions**
- **In practice, of course, there are no mini-slots**
  - **Minimal impact on performance but analysis is more complex**



# CSMA/CD examples

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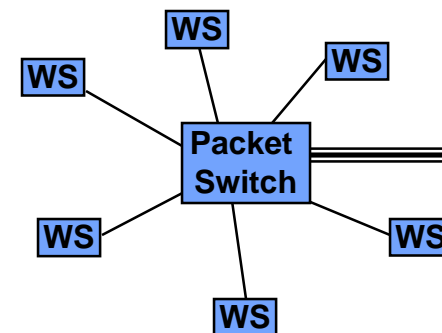
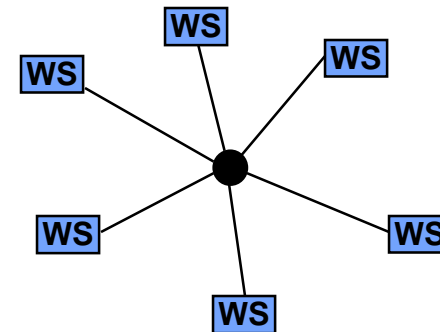
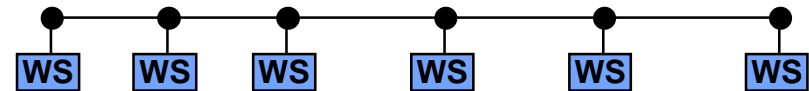
- **Example (Ethernet)**
  - Transmission rate = 10 Mbps
  - Packet length = 1000 bits,  $D_{Tp} = 10^{-4}$  sec
  - Cable distance = 1 mile,  $\tau = 5 \times 10^{-6}$  sec
  - ➔  $\beta = 5 \times 10^{-2}$  and  $E = 80\%$
- **Example (GEO Satellite) - propagation delay 1/4 second**
  - $\beta = 2,500$  and  $E \sim 0\%$
- **CSMA/CD only suitable for short propagation scenarios!**
- **How is Ethernet extended to 100 Mbps?**
- **How is Ethernet extended to 1 Gbps?**



# Migration to switched LANs



- **Traditional Ethernet**
  - Nodes connected with coax
    - Long “runs” of wire everywhere
  - CSMA/CD protocol
- **“Hub” Ethernet**
  - Nodes connected to hub
    - Hub acts as a broadcast repeater
    - Shorted cable “runs”, Useful for 100 Mbps
  - CSMA/CD protocol
  - Easy to add/remove users
  - Easy to localize faults
  - Cheap cabling (twisted pair, 10baseT)
- **Switched Ethernet**
  - No CSMA/CD
    - Easy to increase data rate (e.g., Gbit Ethernet)
  - Nodes transmit when they want
  - Switch queues the packets and transmits to destination
  - Typical switch capacity of 20-40 ports
  - Each node can now transmit at the full rate of 10/100/Gbps
  - **Modularity:** Switches can be connected to each other using high rate ports

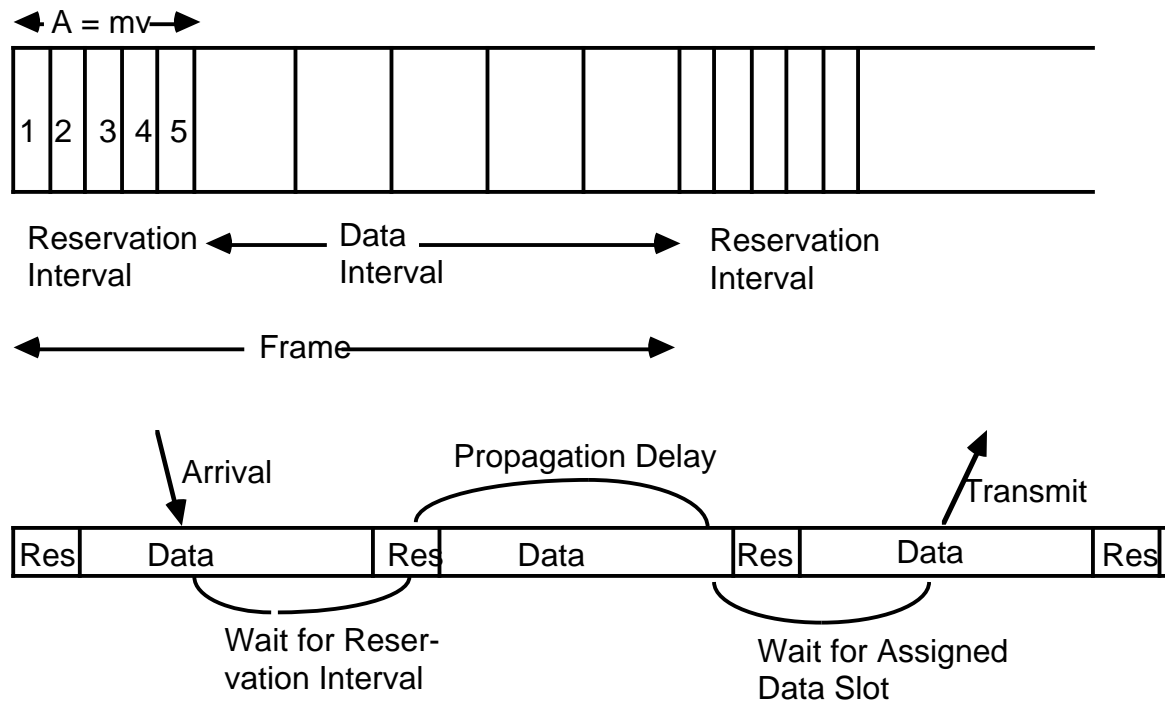


Connect To other Switches





# Large propagation delay (satellite networks)



- **Satellite reservation system**
  - Use mini-slots to make reservation for longer data slots
  - Mini-slot access can be inefficient (Aloha, TDMA, etc.)
- To a crude approximation, delay is  $3/2$  times the propagation delay plus ideal queuing delay.



# Satellite Reservations



- **Frame length must exceed round-trip delay**
  - Reservation slots during frame  $j$  are used to reserve data slots in frame  $j+1$
  - Variable length: serve all requests from frame  $j$  in frame  $j+1$ 
    - Difficult to maintain synchronization
    - Difficult to provide QoS (e.g., support voice traffic)
  - Fixed length: Maintain a virtual queue of requests
- **Reservation mechanism**
  - Scheduler on board satellite
  - Scheduler on ground
  - Distributed queue algorithm
    - All nodes keep track of reservation requests and use the same algorithm to make reservation
- **Control channel access**
  - TDMA: Simple but difficult to add more users
  - Aloha: Can support large number of users but collision resolution can be difficult and add enormous delay



# Packet multiple access summary

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- **Latency: Ratio of propagation delay to packet transmission time**
  - GEO example:  $D_p = 0.5$  sec, packet length = 1000 bits,  $R = 1$  Mbps  
Latency = 500 => very high
  - LEO example:  $D_p = 0.1$  sec  
Latency = 100 => still very high
  - Over satellite channels data rate must be very low to be in a low latency environment
- **Low latency protocols**
  - CSMA, Polling, Token Rings, etc.
  - Throughput  $\sim 1/(1+a\alpha)$ ,  $\alpha$  = latency,  $a$  = constant
- **High latency protocols**
  - Aloha is insensitive to latency, but generally low throughput  
Very little delays
  - Reservation system can achieve high throughput  
Delays for making reservations
  - Protocols can be designed to be a hybrid of Aloha and reservations  
Aloha at low loads, reservations at high loads



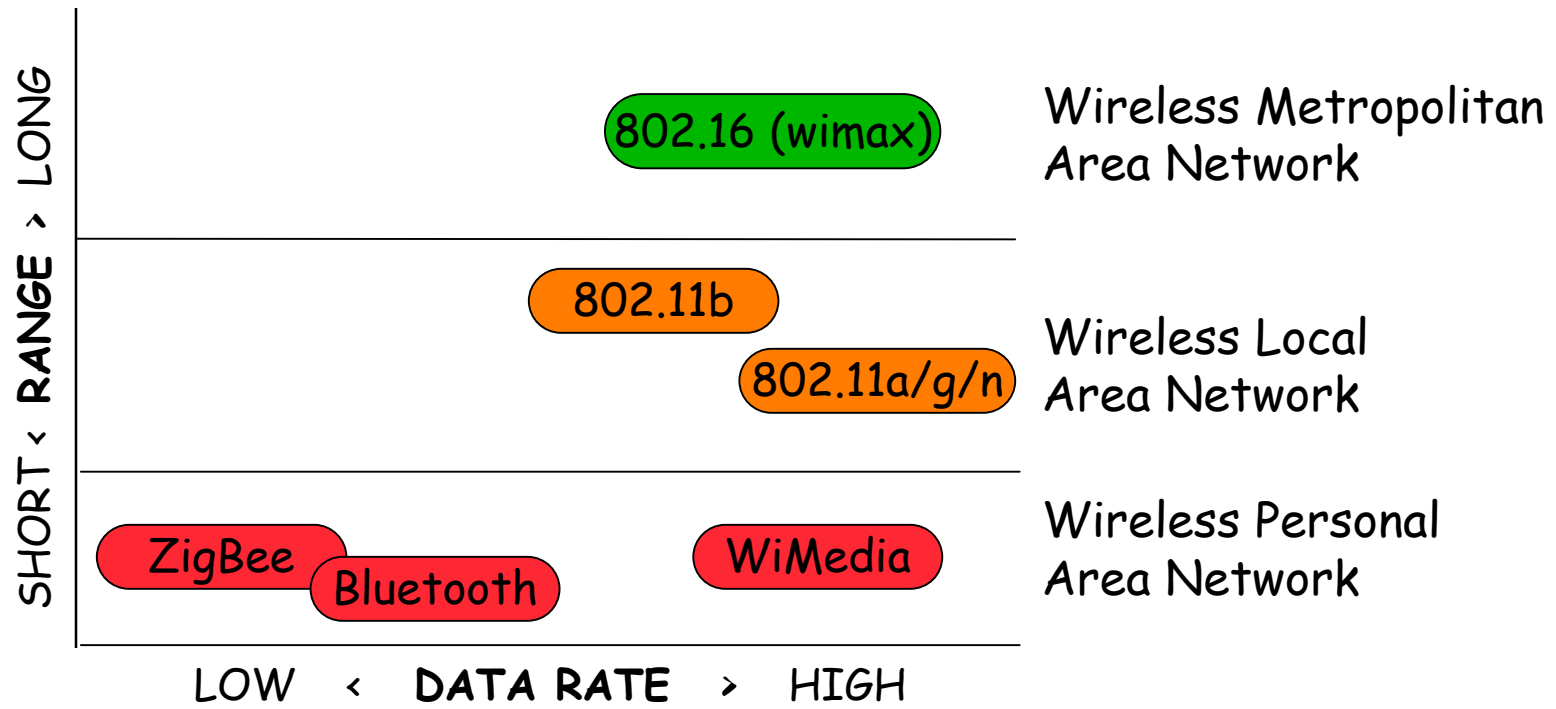
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# **Packet Multiple Access: Wireless LANs**

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# Wireless Networking Technologies



- Standards typically define the Medium Access Control (MAC) and the Physical layers

	Bluetooth	WiFi (802.11)	WiMax (802.16)
Data rate	2.1 Mbps	54 Mbps	70 Mbps
Link length	10 meters	100 meters	10 km
application	Peripheral devices	LAN	Access

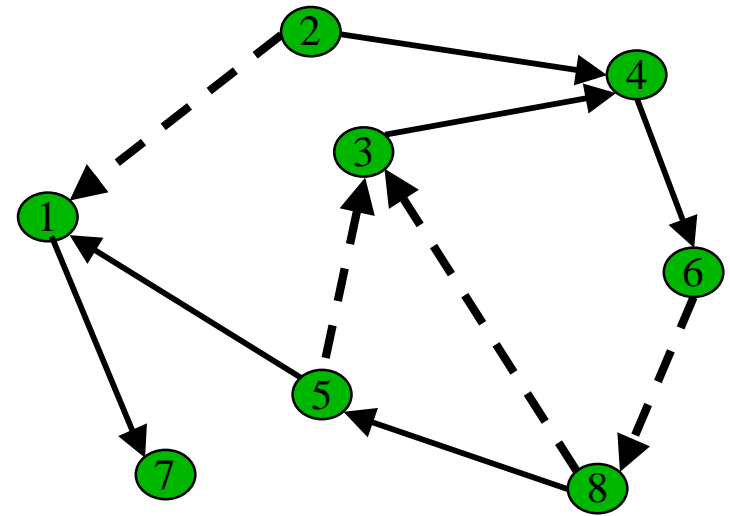


# Medium Access Control (MAC)



- Nodes are scattered in a geographic area
- Need to somehow coordinate the access to channel
  - Transmission time, power, rate, etc.

- Centralized
  - Managed by an Access Point/Base Station
- Distributed
  - Random access (Aloha, CSMA, Ethernet)
  - Scheduled access



- Requirements
  - Throughput, delay, fairness, energy efficiency



# IEEE 802.11 / WiFi

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- **Set of standards for Wireless Local Area Networks (WLANs)**
  - Define Medium Access Control (MAC)
  - Physical layer
- **Most common 802.11g**
  - Maximum data rate: 54Mb/s
  - Frequency band: 2.4 Ghz
- **Other variations 802.11a,b,e,n**
  - Different bands, physical layers, data rates, QoS, etc.



# Ad Hoc and Infrastructure Modes



- **Ad Hoc mode**
  - The stations communicate with one another
  - Not connected to a larger network
- **Infrastructure mode**
  - An Access Point connects Stations to a wired network
  - Overlapping Access Points connected to each other
  - Allows Stations to roam between Access Points

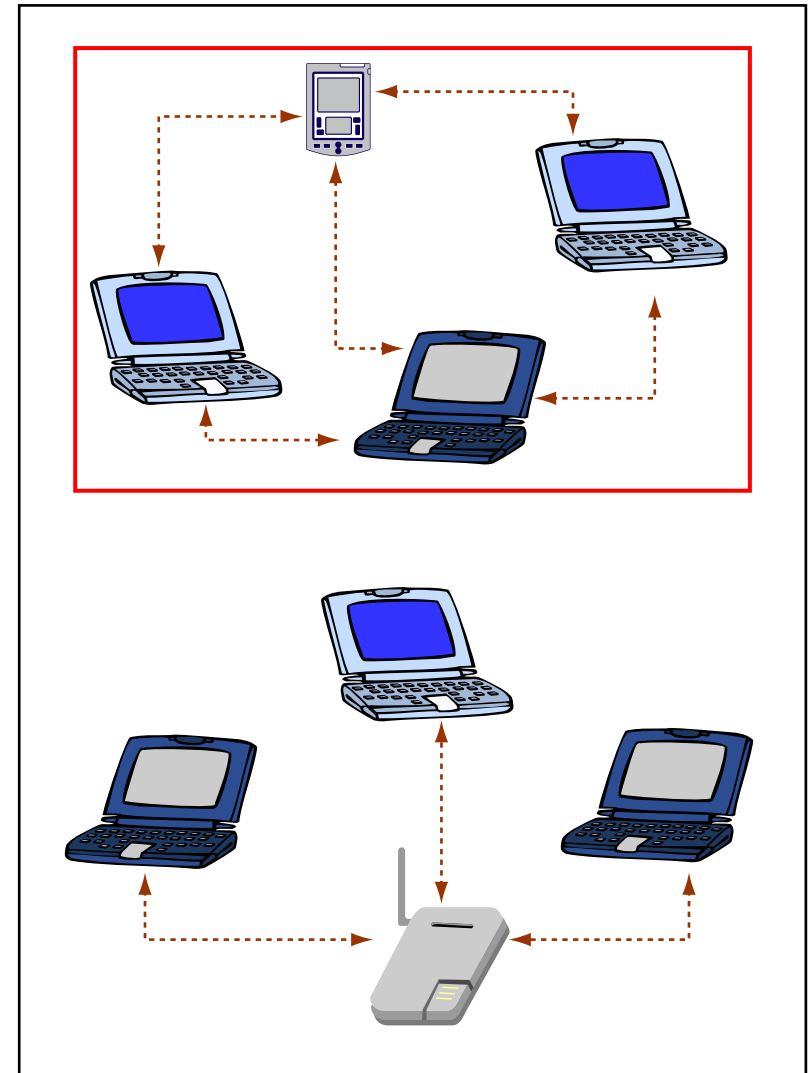


Figure by MIT OpenCourseWare.





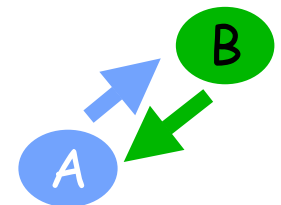
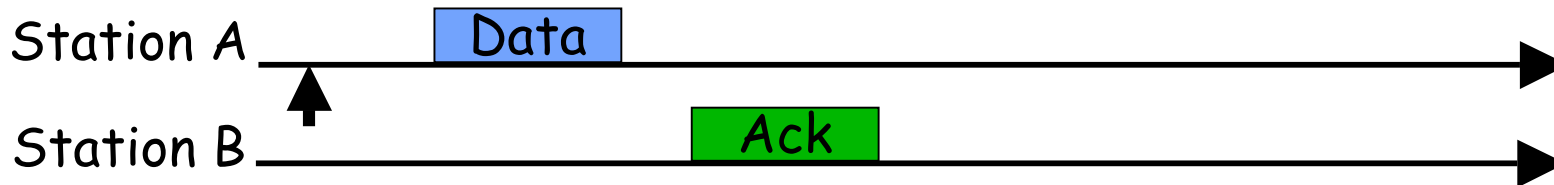
# Medium Access Control - CSMA/CA



## Carrier Sense Multiple Access \ Collision Avoidance

- Station wishing to transmit a Data packet senses the medium
- If it is idle for a given period - Transmits
- ACK packet is sent by the receiving station
- Collision assumed if sending station doesn't get ACK
  - Data is retransmitted after a random time

} CSMA

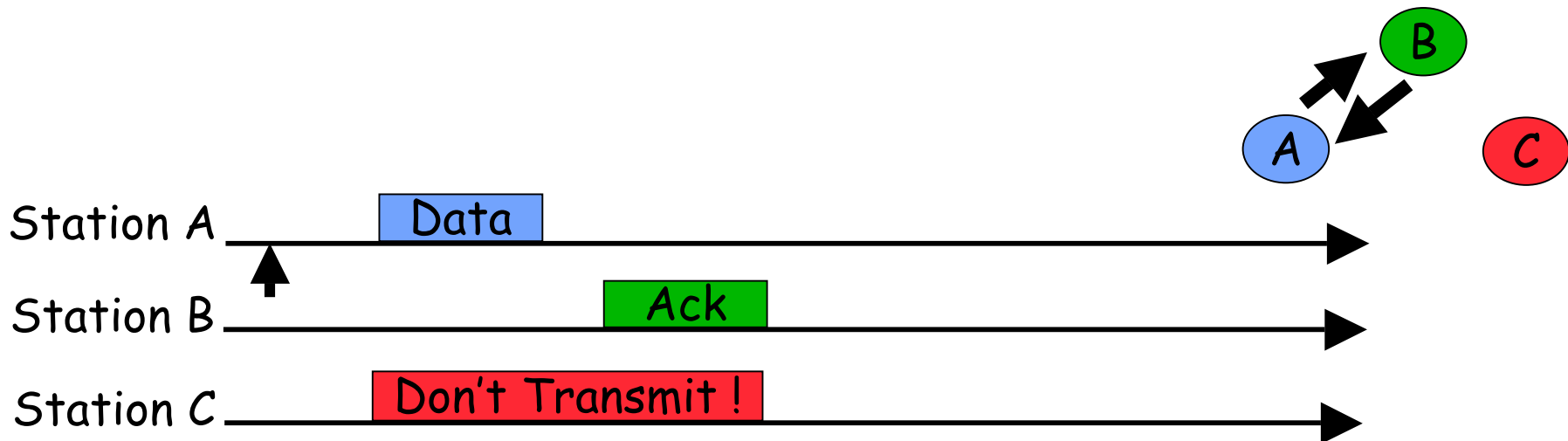




# Medium Access Control - CSMA/CA



## Carrier Sense Multiple Access \ Collision Avoidance



- CA {
- A station that heard the Data or the ACK, knows the time remaining until the medium will become available
    - Will not try to transmit during that time
  - Carrier Sensing
    - Physical
    - Virtual: using RTS/CTS procedure and NAV values within



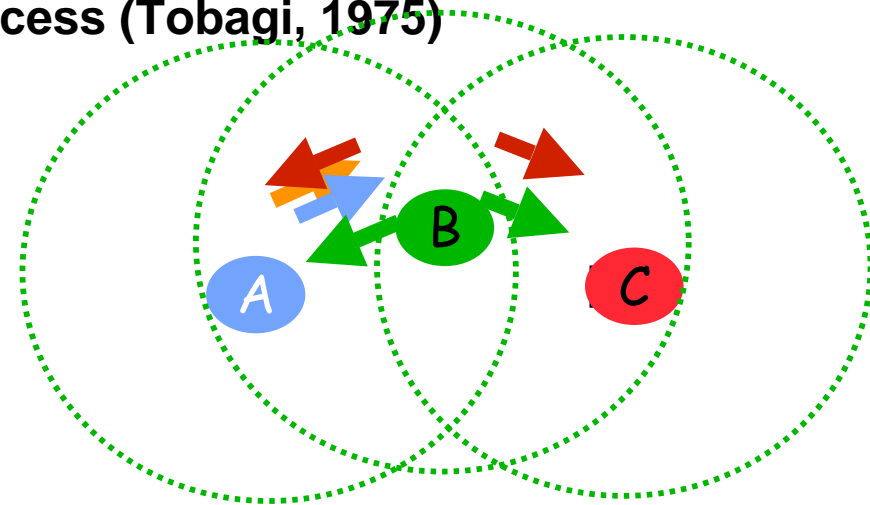
# Hidden Node Problem

- **Hidden Node** - A node that a station does not hear but can interfere with its transmissions

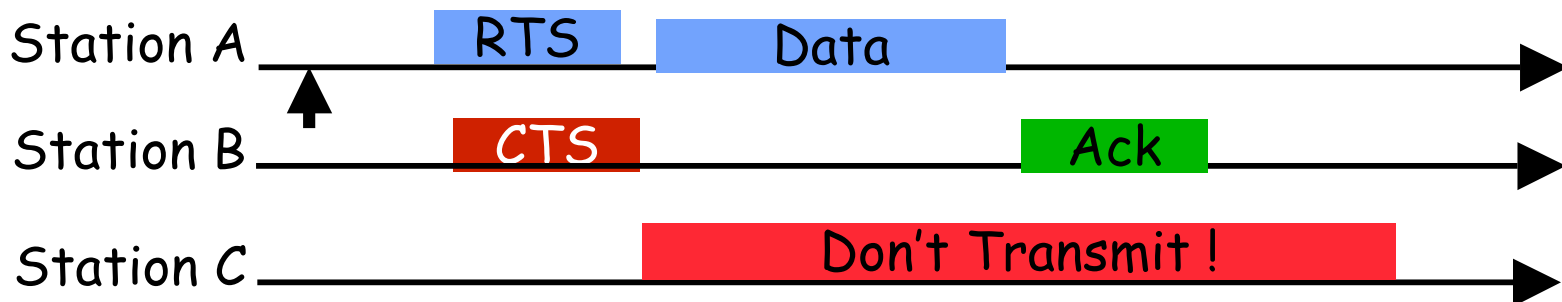
- Solution: Busy tone multiple access (Tobagi, 1975)

- **Enhancement:**

- CA {
- A → B Request to Send (RTS)
  - B → A Clear to Send (CTS)
  - A → B Data
  - B → A ACK



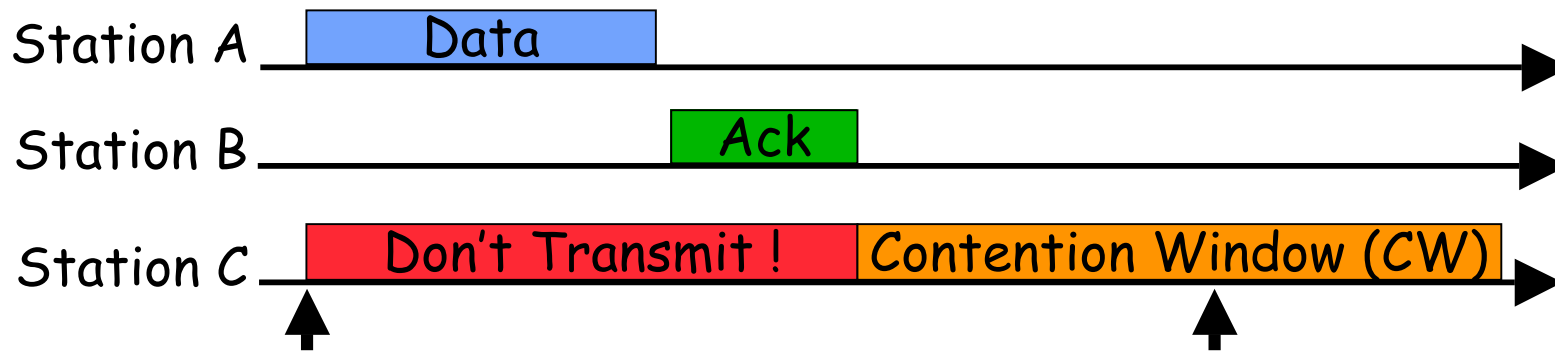
- **Neighboring nodes will keep quiet for the duration of the transfer**
  - Network allocation vector (NAV) - specifies duration of transfer



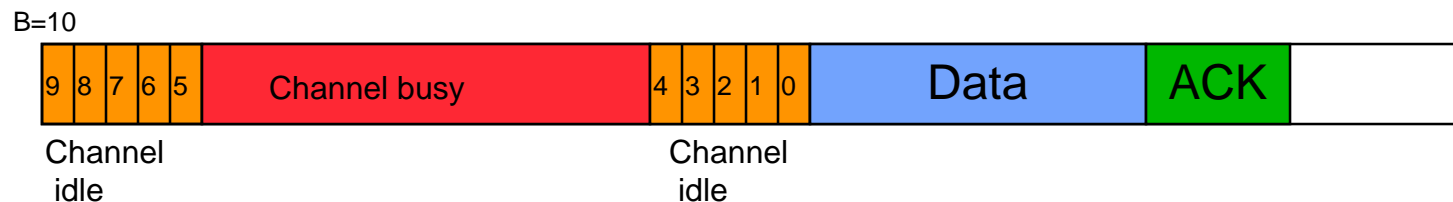


# Contention Window

- A station that sensed the medium busy or did not receive an ACK will try to retransmit



- The back-off interval is uniformly distributed within the CW
- The window is doubled every time there is a need to retransmit
  - Upper limit on CW
  - Count down back-off interval when channel idle
  - Stop counting when busy (resume when idle again)
  - Transmit when back-off interval reaches 0





# Bluetooth



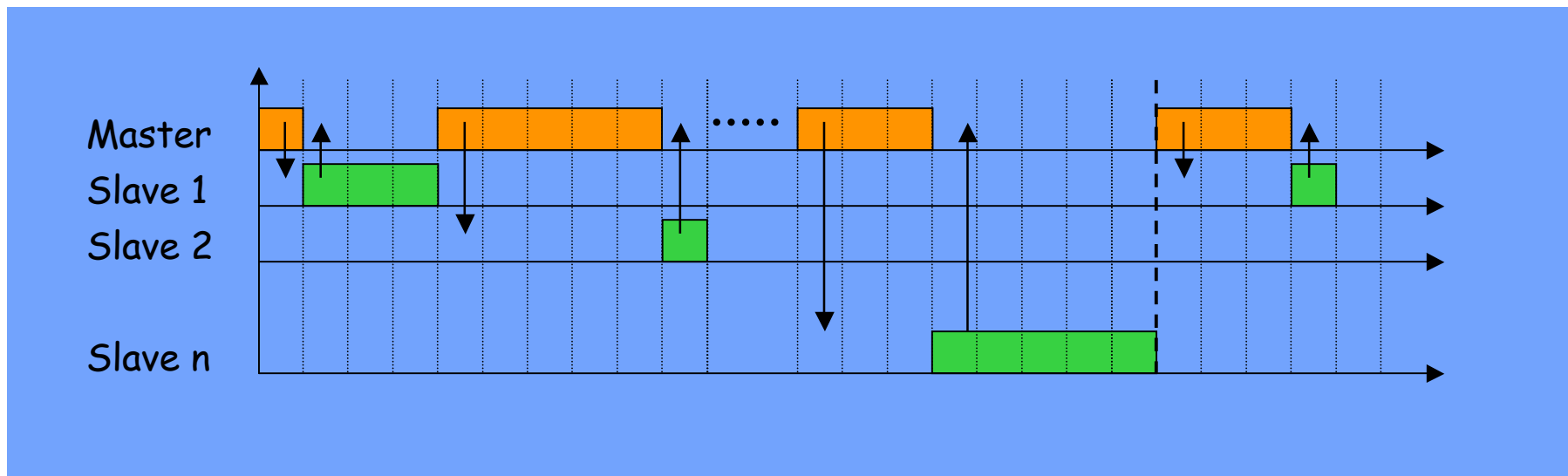
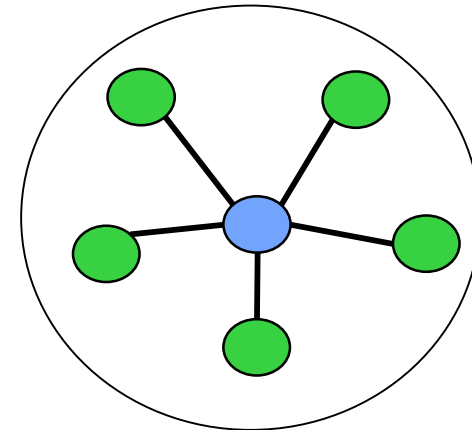
- **Very short-range communications between computers and peripheral devices**
  - E.g., replace connector cables such as usb
- **Operates in 2.4 GHz unlicensed band**
  - **Uses spread-spectrum communications**
    - Frequency hopping between 79 frequency channels
    - New frequency every slot (625  $\mu$ s)
- **Piconet: master and 7 slave devices**
  - All communication goes through the master
- **ZigBee - a competing technology (will not discuss much)**
  - Newer technology for low bandwidth, low power applications
  - Very simple and inexpensive
  - Designed for sensor networks; and communications between very inexpensive devices (e.g., appliances)



# Bluetooth MAC

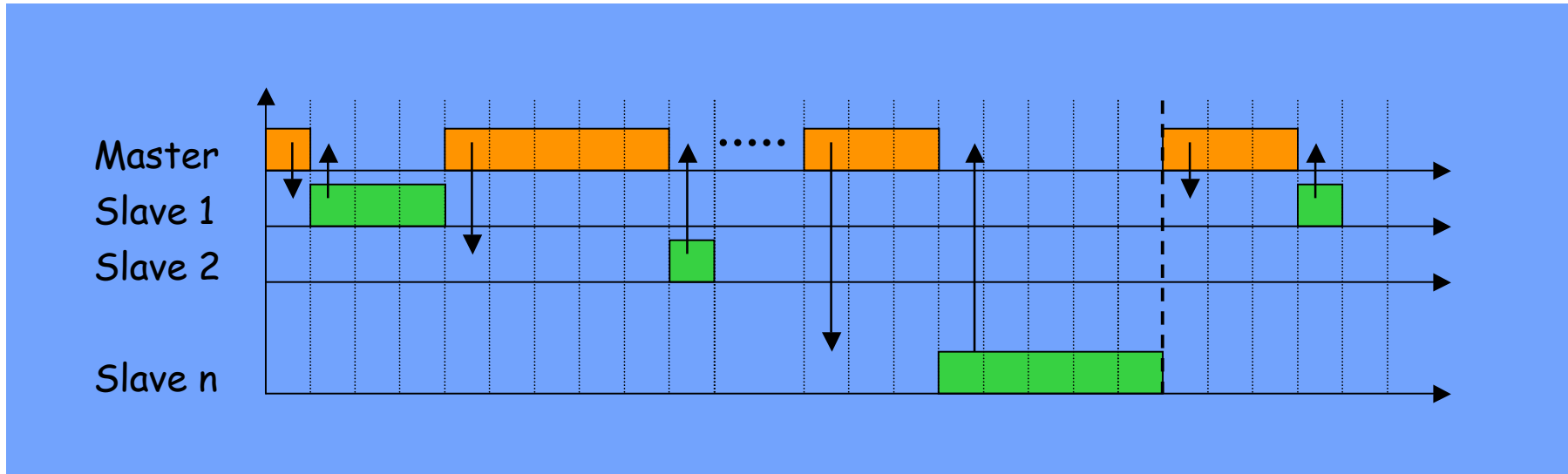


- **Frequency Hop / Time Division Duplex Scheme**
  - Frequency band: 2.4 GHz ISM Band
  - 1,600 slots per second (625  $\mu$ s/slot)
- **Piconet - A Master and up to 7 Slaves sharing a common hopping pattern**
- **Intra-Piconet Communication (TDD):**

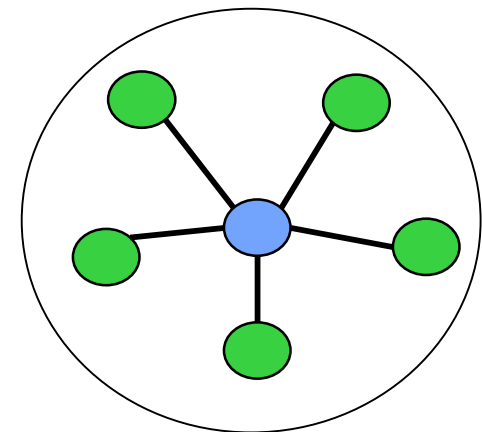




# Bluetooth MAC



- 1, 3, and 5-slot data frames
- If the master has no data to transmit, it can address a slave by sending a 1-slot POLL packet
- If a slave has nothing to send, it must respond by sending a 1-slot NULL packet

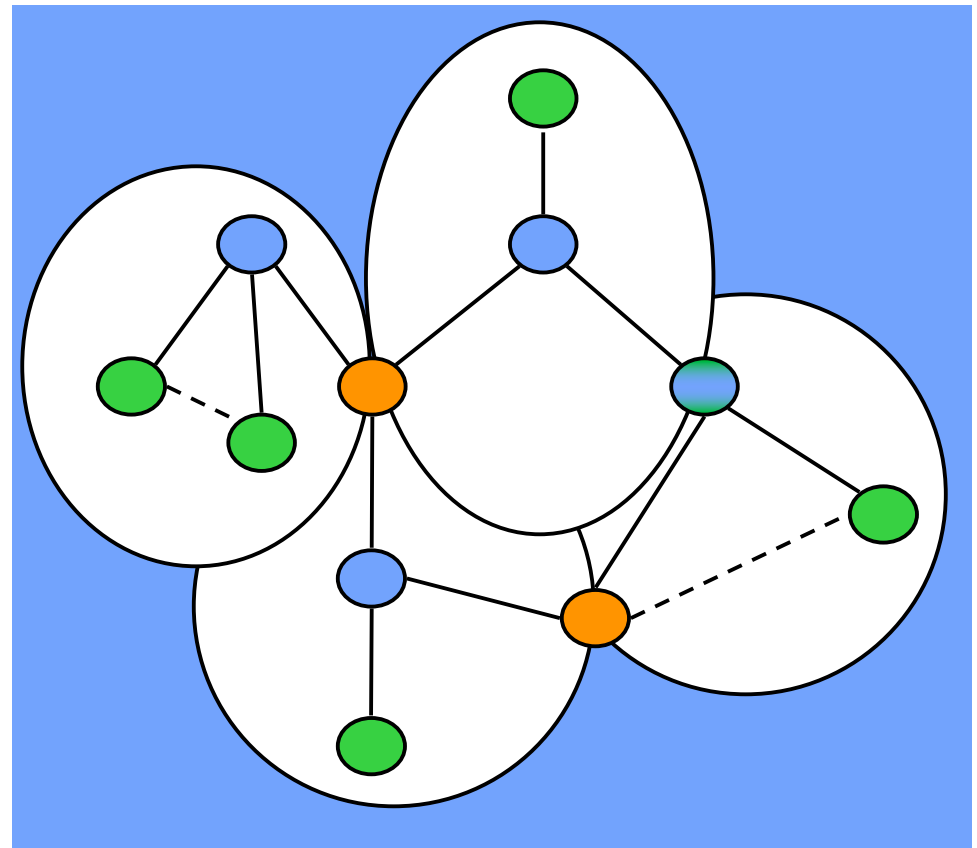




# Multi-hop Topology



- **Several piconets may coexist in the same coverage area with minimal interference**
- **A unit can be:**
  - **Piconet Coordinator / Device / Bridge**
- **There are links and neighbors**







# WiMAX (802.16)

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- **Access technology - metro area**
  - Last (few) miles to home or business
- **Data rates of up to 70 Mbps**
- **Physical layer**
  - Microwave band: 10 to 66 GHz (line of sight)
  - Other bands also possible
- **Connection oriented to offer QoS guarantees**
- **Medium access**
  - Fixed assignment (guaranteed rate)
  - Reservations (polling)
  - Contention mechanism for best effort services