# Network System Capstone @CS.NCTU

## Lecture 4: MAC Protocols for WLANs

Instructor: Kate Ching-Ju Lin (林靖茹)

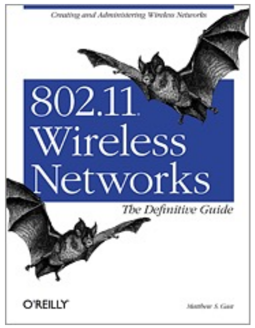
# Reference

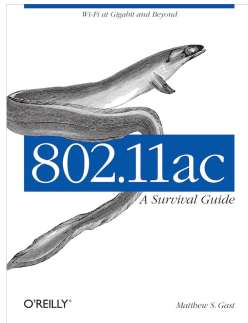

1. A Technical Tutorial on the IEEE 802.11 Protocol
   By Pablo Brenner
   online: http://www.sss-mag.com/pdf/802_11tut.pdf

2. IEEE 802.11 Tutorial
   By Mustafa Ergen
   online:
   http://wow.eecs.berkeley.edu/ergen/docs/ieee.pdf

3. 802.11 Wireless Networks: The Definitive Guide
   By Matthew Gast

4. 802.11ac: A Survival Guide
   By Matthew Gast
   online:
   http://chimera.labs.oreilly.com/books/1234000001739

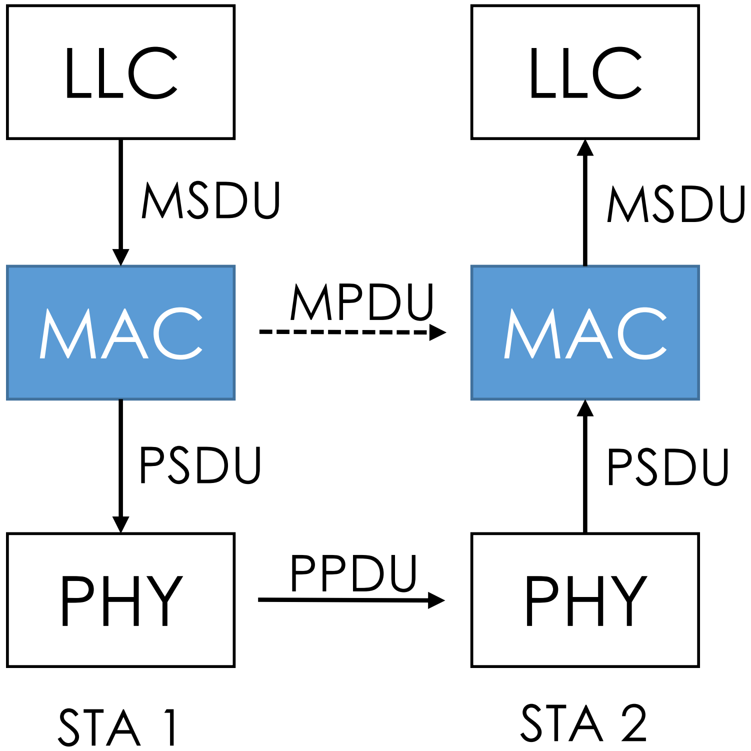



# Agenda

- **Medium Access Control**
- WiFi
  - Basic 802.11 Operation
  - Collision Avoidance (CSMA/CA)
  - Hidden Terminal
  - QoS guarantee
  - Other Issues
  - Performance Analysis
- Bluetooth

# What is MAC?

- Medium access control
- Layer 2 (link layer)
- Allowing multiple stations in a network to share the spectrum resources and communicate (1-hop)
- Type of communications
  - Unicast: one-to-one
  - Multicast: one-to-many
  - Broadcast: one-to-all



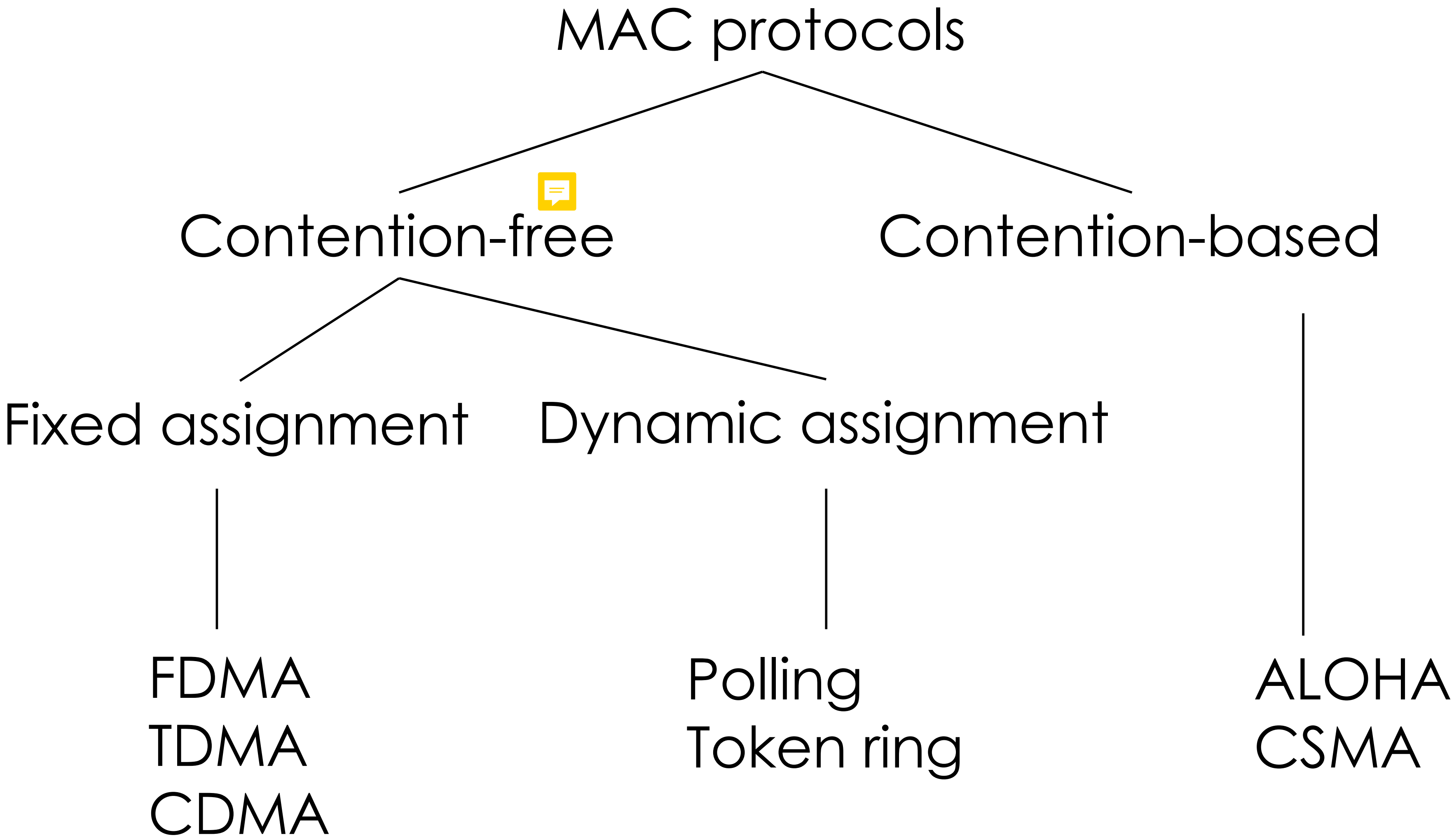
# MAC Protocols

- Multiple access
  - Several stations connected to the same physical medium to share it
  - Requirements:
    - High bandwidth utilization
    - Fair
    - Low protocol overhead
    - Dynamic and adaptive
    - Energy efficient
- MAC protocols
  - Primarily responsible for regulating access to the shared medium

# Why MAC for WLANs is Challenging?

- Wireless medium is prone to errors
- One station cannot “hear” all other stations
  - Local view != global view
- Channel quality, and thereby the achievable data rate, is closely related to link distance, and could change with time due to mobility
- Again, because of mobility, need management mechanisms to (de)associating with APs as location changes
  - Need efficient handoff to ensure seamless access

# MAC Categorization

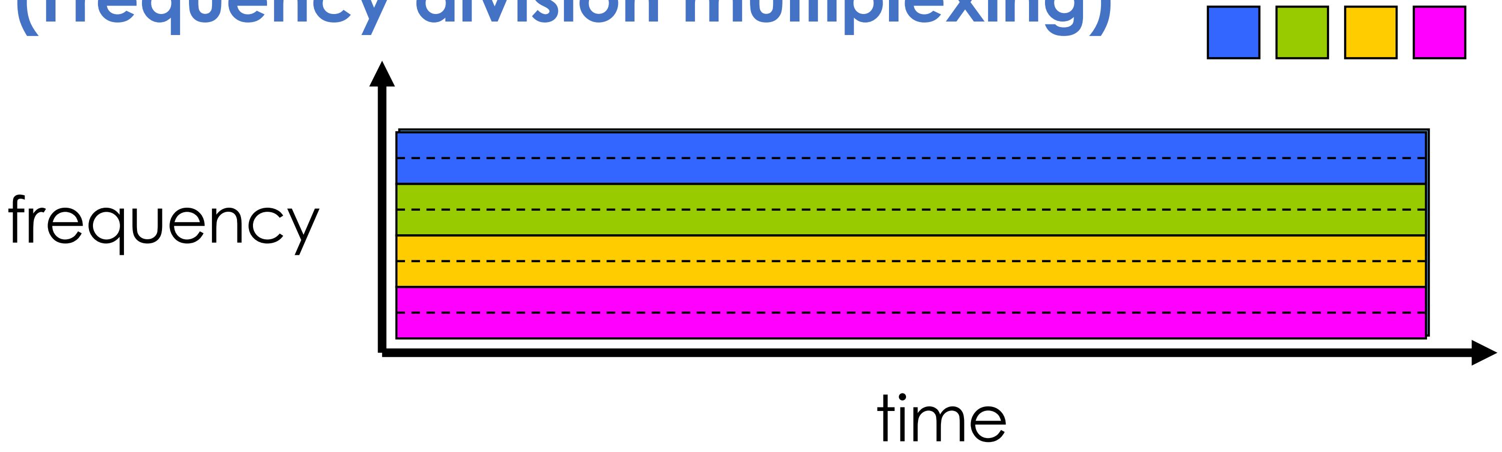


# Contention-Free: FDM vs. TDM

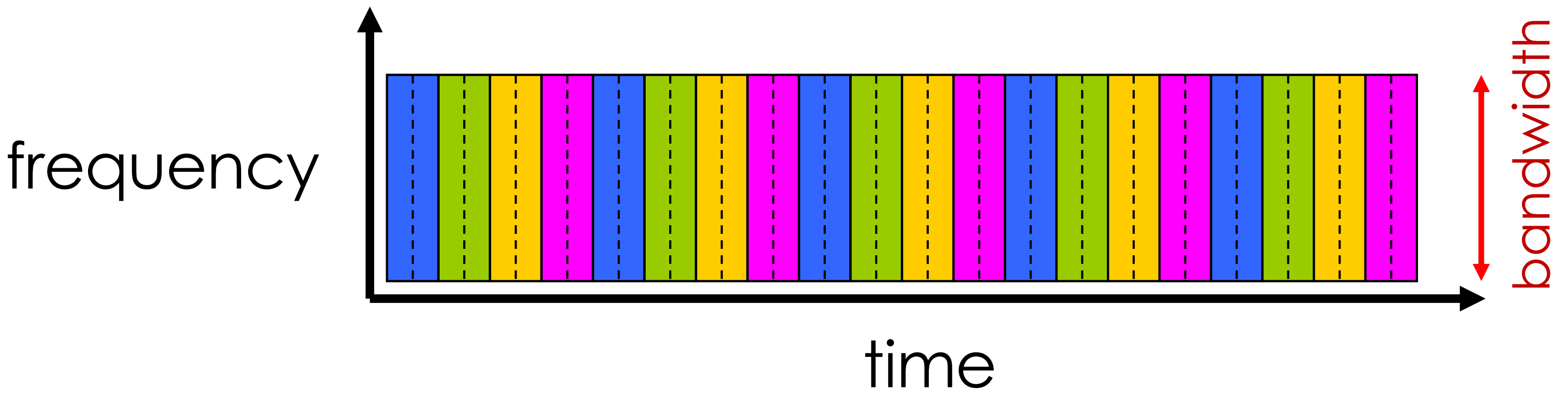
- **Multiplexing**: allocate resources to multiple users

Example: 4 users

## FDM (Frequency division multiplexing)



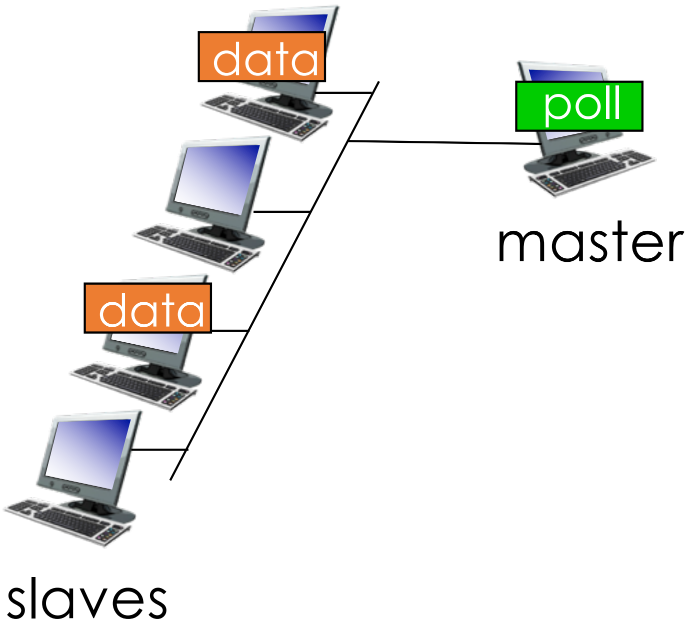

## TDM (Time division multiplexing)

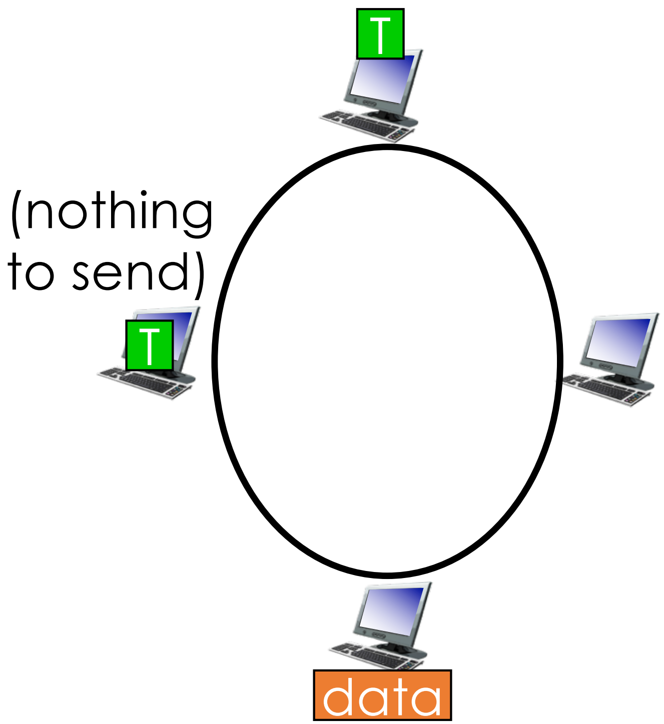


# Contention-Free: Polling and Token

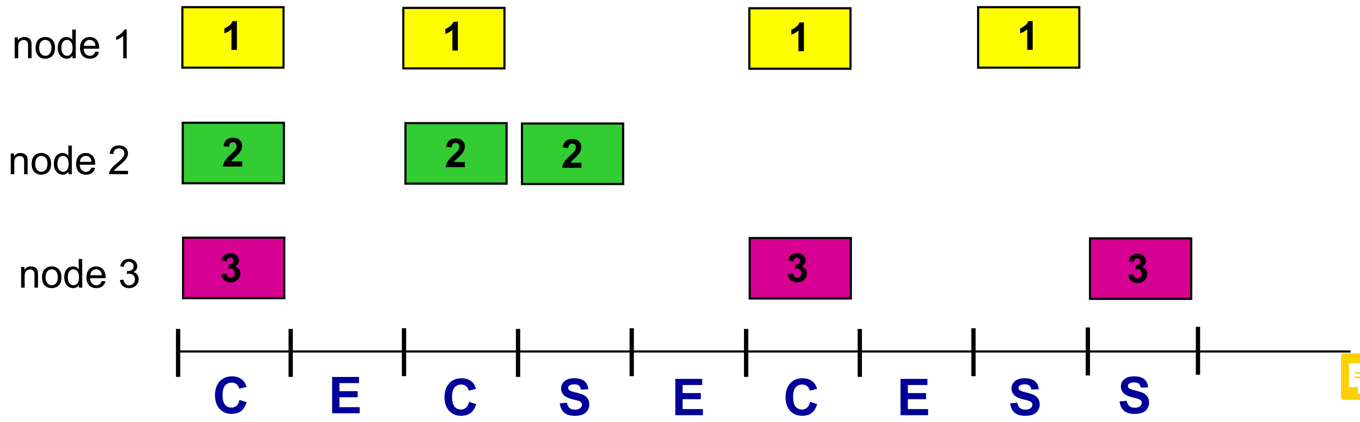
- Polling
  - Master schedules for slaves
  - Polling overhead
  - Single-point failuer problem

- Token Ring
  - Token passing
  - Message overhead
  - Single-point failuer problem



# Contention-Based: ALOHA




- Assumptions
  - All frames are of equal size
  - Time divided into equal size slots (1 slot 1 frame)
  - Node start transmitting in the beginning of a slot
  - Nodes are synchronized
- Protocol
  - If a node has a frame, transmit in the next slot
  - If collisions, retransmit in the following slots with probability p until success

# Agenda

- Medium Access Control
- **WiFi**
  - Basic 802.11 Operation
  - Collision Avoidance (CSMA/CA)
  - Hidden Terminal
  - QoS guarantee
  - Other Issues
  - Performance Analysis
- Bluetooth

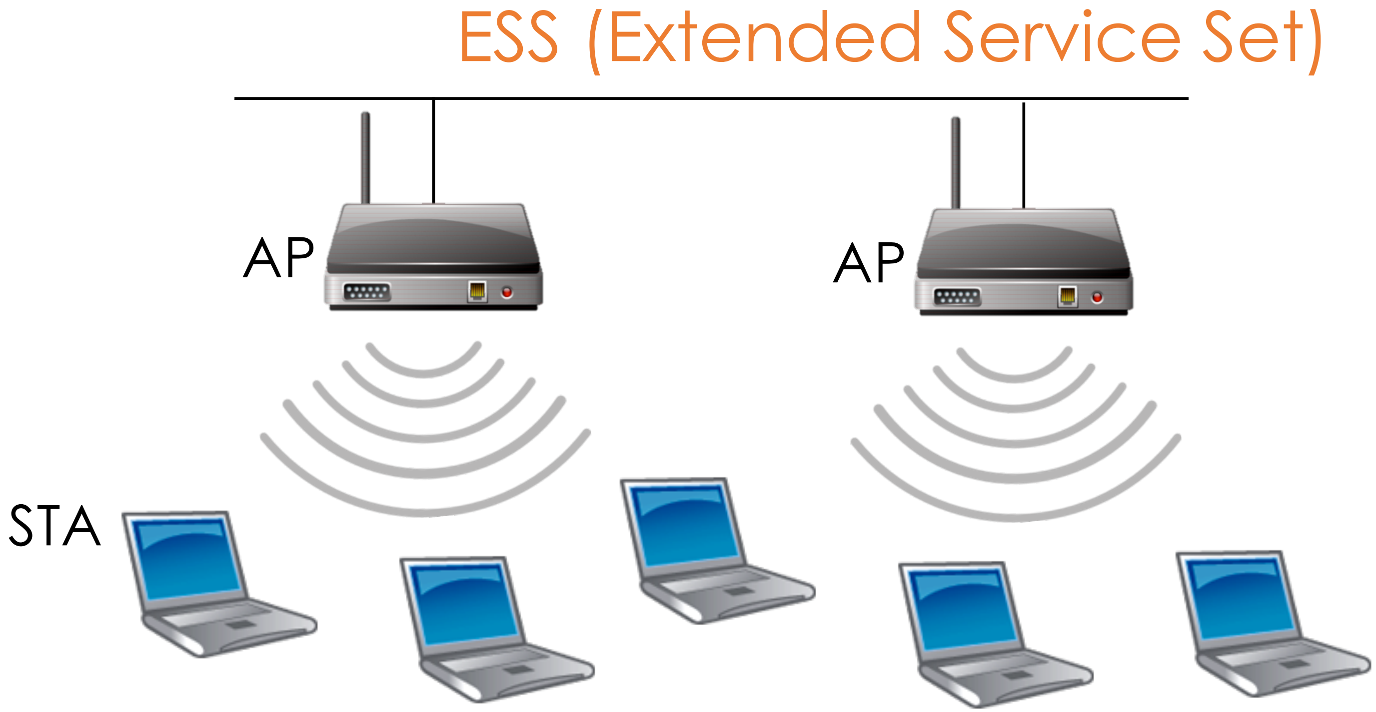
# Basic Service Set (BSS)

- BSS
  - Basic building block
  - Infrastructure mode
- IBSS (independent BSS)
  - Ad-hoc network
- ESS (extended service set)
  - Formed by interconnected BSSs

# Infrastructure Mode

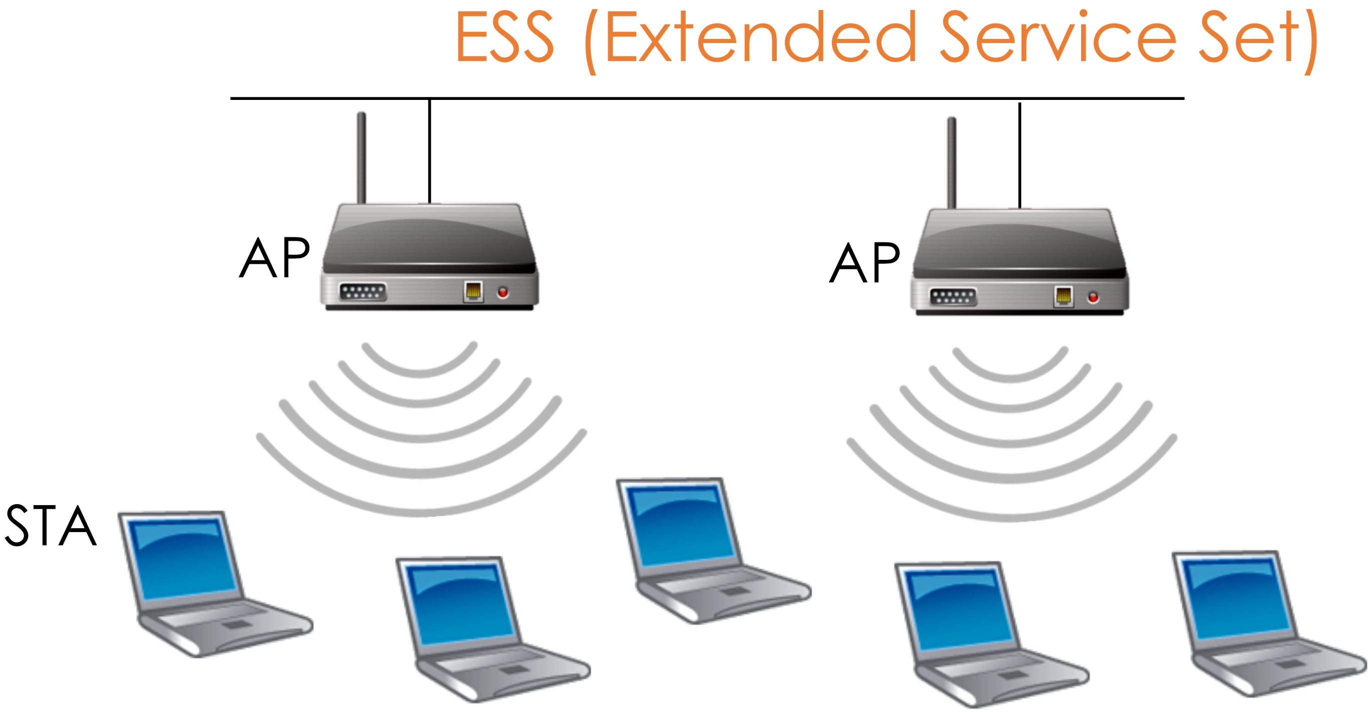

- Each station (STA) associates with a central station Access point (AP)
- An AP and its stations form a basic service set (BSS)
- AP announces beacons periodically

# Infrastructure Mode




- Several BSSs could form an ESS
- A roaming user can move from one BSS to another within the ESS by re-association

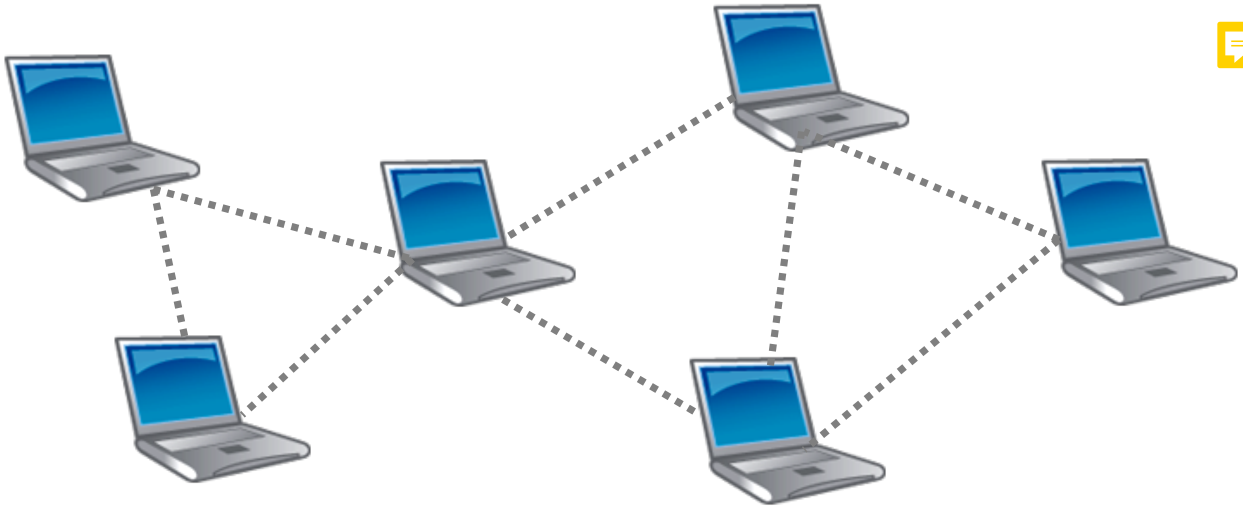
# Infrastructure Mode




- Issues
  - Inter-BSS interference: via proper channel assignment
  - Load balancing: via user management

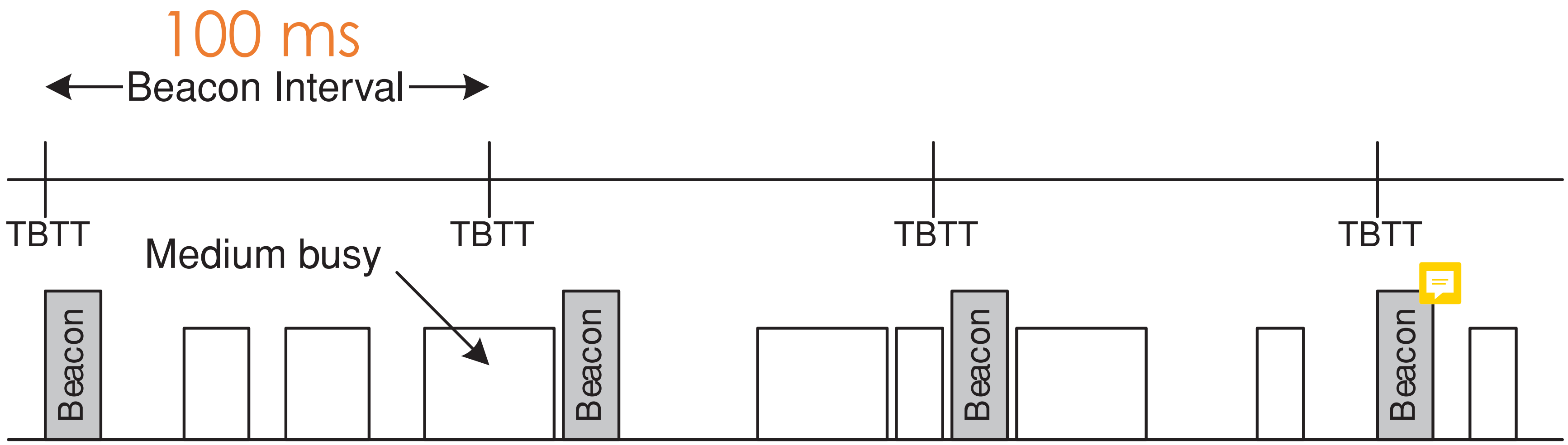
# Ad-Hoc Networks

IBSS (independent BSS)



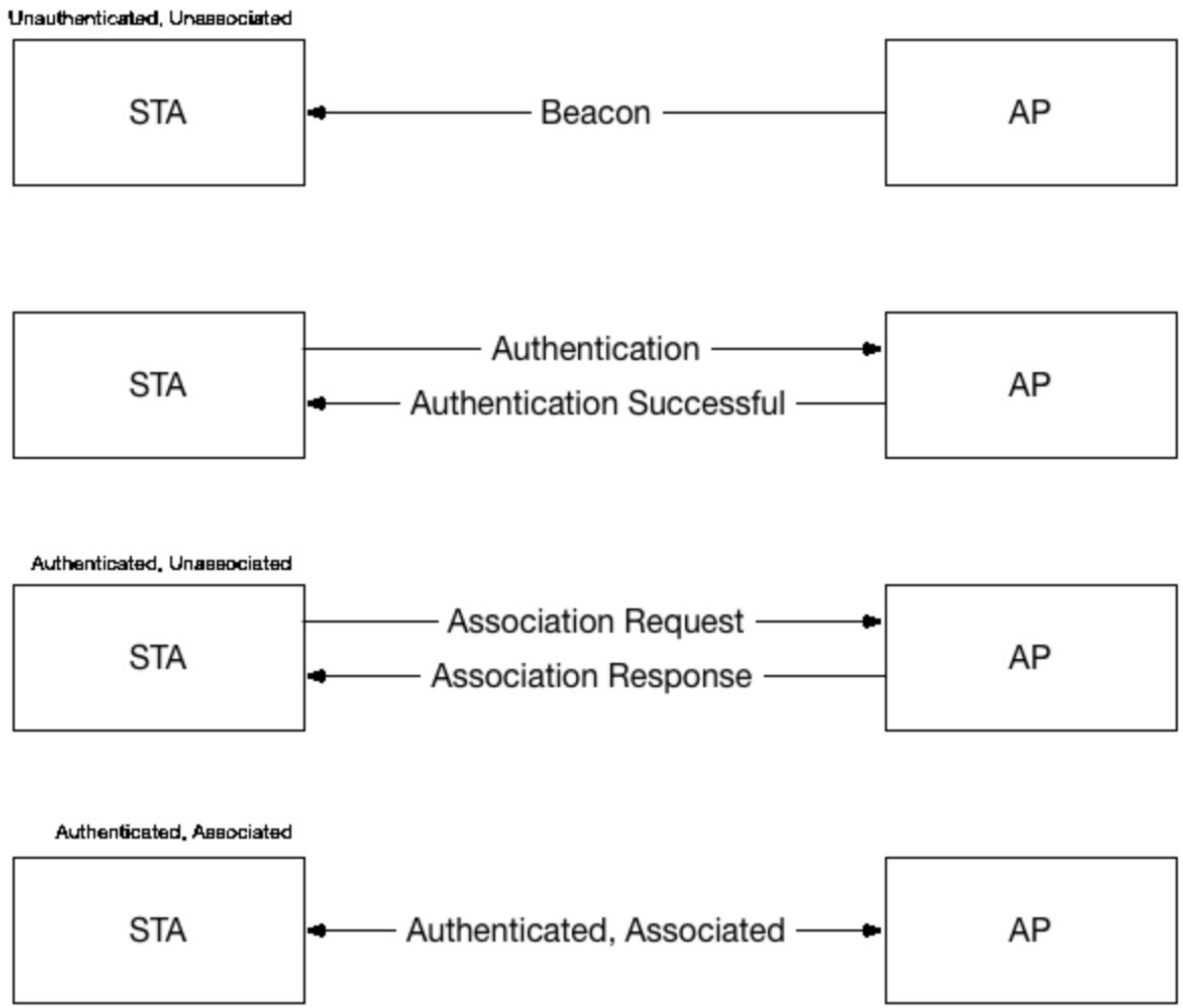
- Clients form a peer-to-peer network without a centralized coordinator
- Clients communicate with each other via multi-hop routing
  - Will introduce ad-hoc routing

# Beacon and WiFi Scanning




- The AP in each BSS broadcasts beacon frames periodically (every 100ms by default)
- Each beacon includes information such as SSID and AP's address
- A STA discovers a BSS by switching channels and scanning to look for beacons

# Athentication  and Association




- Register a broadcast listener
- Request a scan
- Get scan results

# Two Operational Modes

- Distributed coordination function (DCF)
  - Stations contend for transmission opportunities in a distributed way
  - Rely on CSMA/CA
- Point coordination function (PCF)
  - AP sends poll frames to trigger transmissions in a centralized manner
  - Less used

# CSMA/CA

- Carrier sense multiple access with collision avoidance
- Similarity and difference between CSMA/CD and CSMA/CA

same

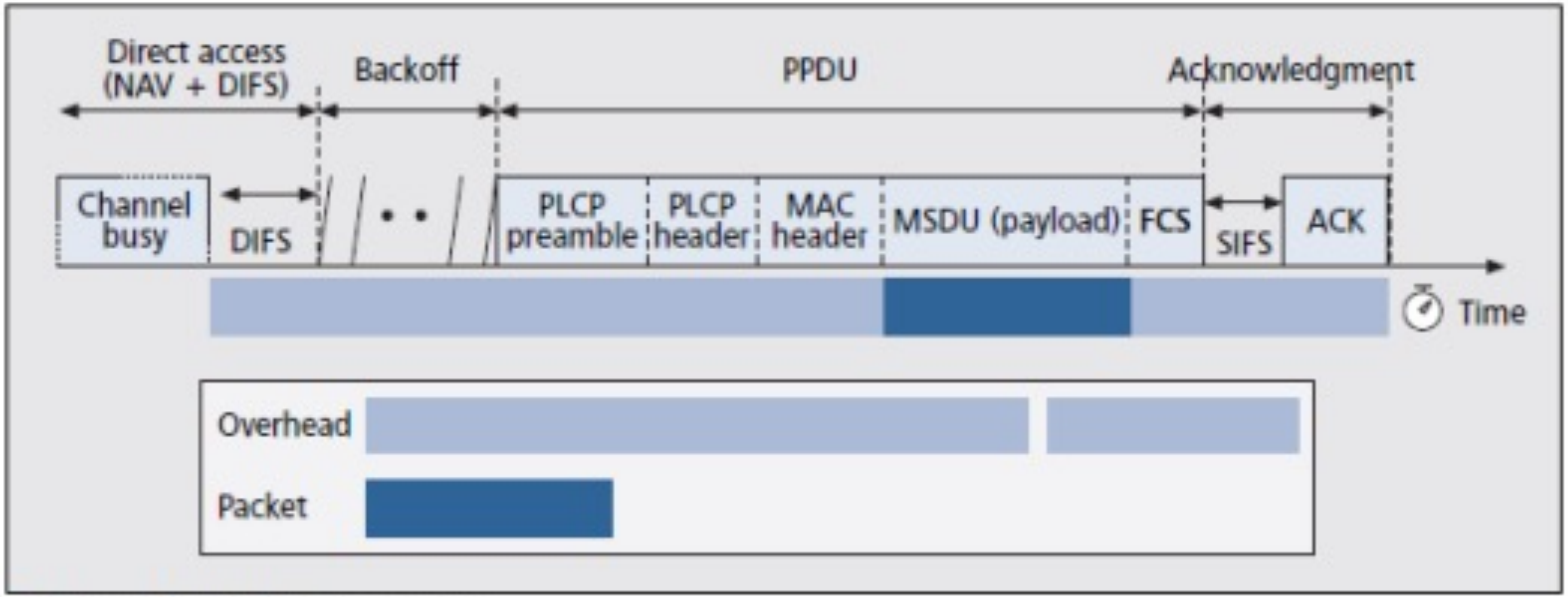
  - Both allow a STA to send if the medium is sensed to be "idle"
  - Both defer transmission if the medium is sensed to be "busy"

diff

  - CD: immediately stop the transmission if a collision is detected
  - CA: apply random backoff to avoid collisions! **Why?**

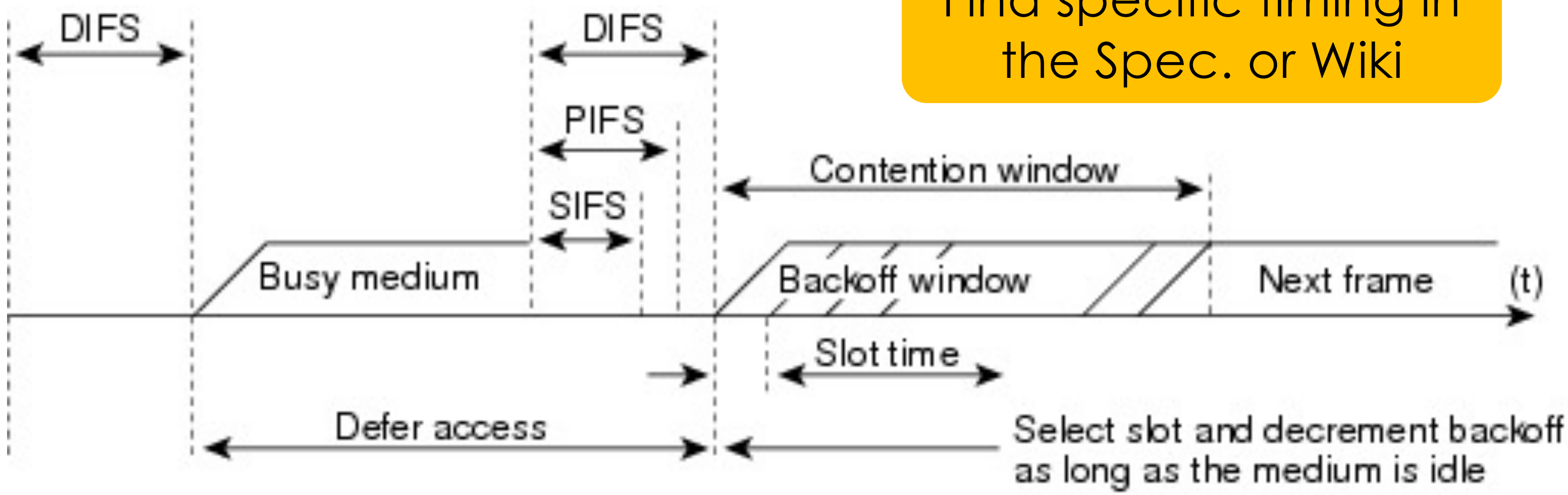
    → a **half-duplex** STA cannot detect collisions during transmission

# DCF




- Start contention after the channel keeps idle for DIFS
- Avoid collisions via random backoff
- AP responds ACK if the frame is delivered correctly (i.e., passing the CRC check) → No NACK
- Retransmit the frame until the retry limit is reached

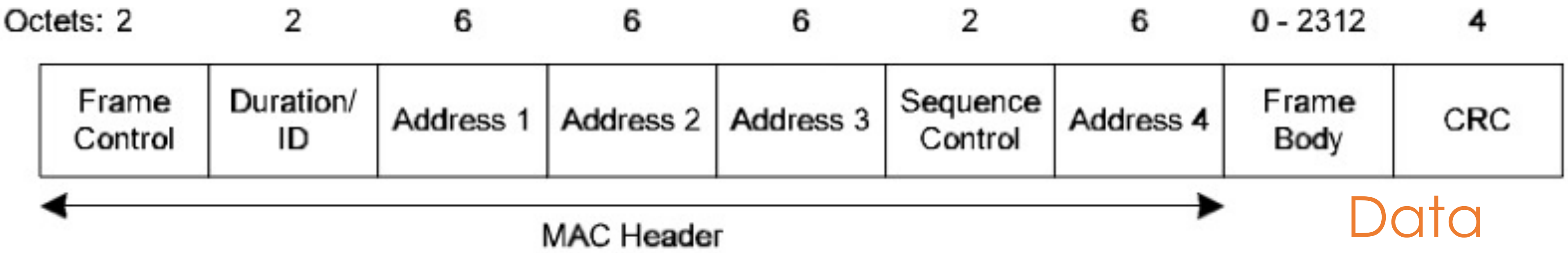
# Prioritized Interframe Spacing



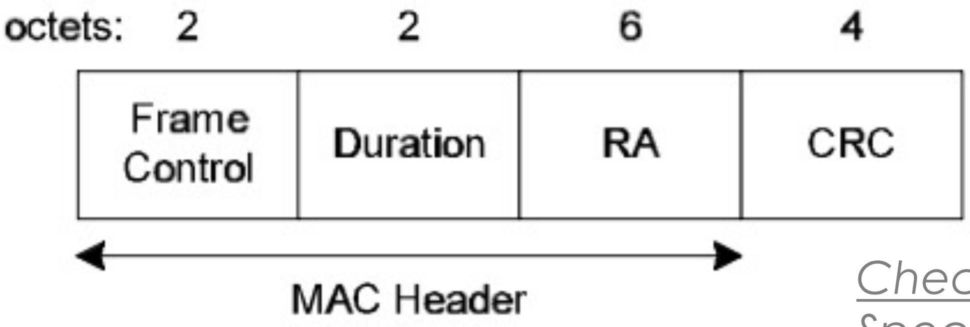

Find specific timing in the Spec. or Wiki

- Latency: SIFS < PIFS < DIFS
  Priority: SIFS > PIFS > DIFS
- SIFS (Short interframe space): control frames, e.g., ACK and CTS
- PIFS (PCF interframe space): CF-Poll
- DIFS (DCF interframe space): data frame

# Frame Format




Data




ACK

Check other frame format in Spec.

- How to estimate protocol overhead without considering backoff
  - $1 - T_{Data} / (T_{DIFS} + T_{PLCP} + T_{MAC} + T_{Data} + T_{SIFS} + T_{ACK})$
  - Control frames are sent at the base rate (lowest bit-rate)

# Overhead vs. Throughput

- Effective throughput

$$\frac{\text{number of successfully delivered bits}}{\text{total occupied time}}$$

- Packet size vs. Effective throughput

?

| header | 1500-byte data | tail |
|---|---|---|

✗

| header | 1-byte data | tail |
|---|---|---|

Effective throughput ~ 0

- Bit-rate vs. Effective throughput

| header | 1500-byte data sent at 24 mb/s | tail |
|---|---|---|

| header | 1500-byte data | tail |
|---|---|---|

Sent at 48 mb/s
(halve the tx time)

Throughput(48) != 2 x Throughput (24)

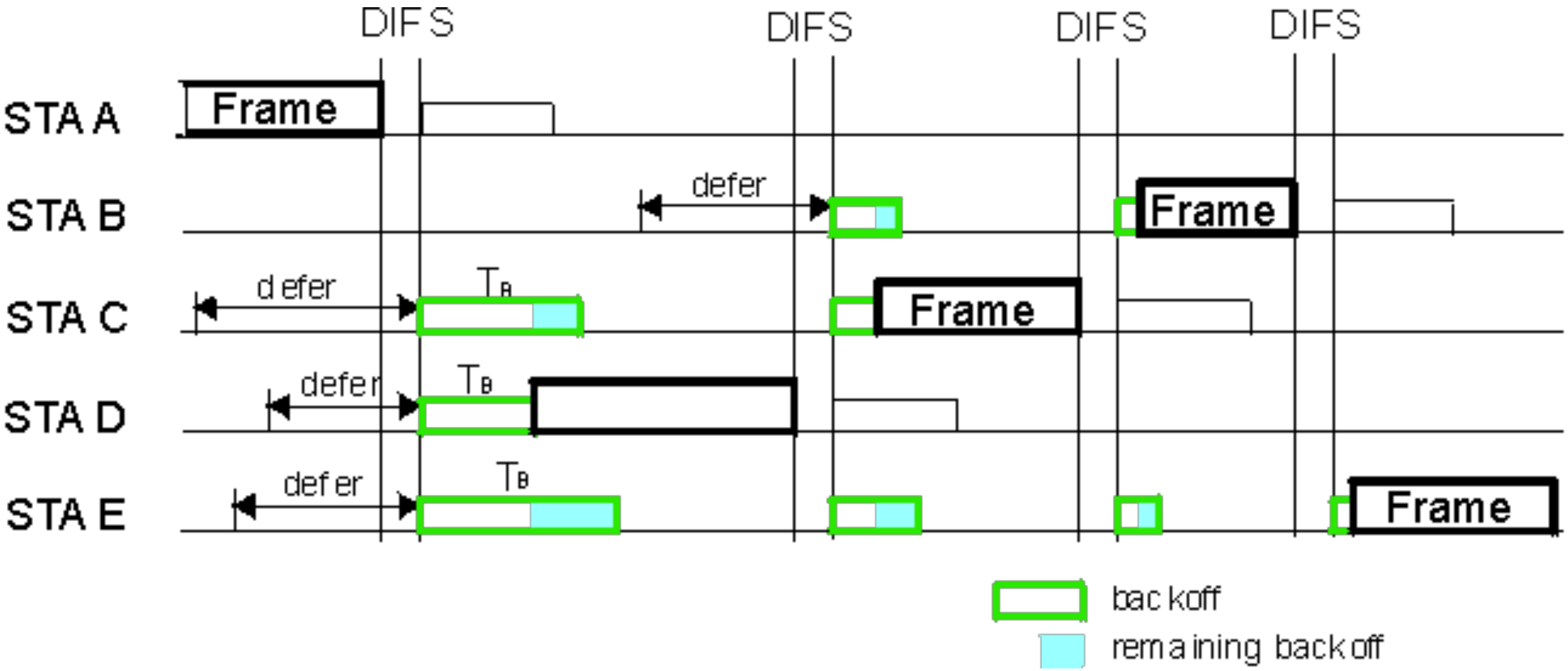
# Fragmentation and Aggregation

- Success probability vs. frame size
  - Large frame reduces overhead, but is less reliable
  - Discard the frame even if only one bit is in error
  - Packet delivery ratio of an N-bit packet: $(1\text{-}BER)^N$
- Fragmentation
  - Break a frame into into small pieces
  - All are of the same size, except for the last one
  - Interference only affects small fragments
- Aggregation
  - Aggregate multiple small frames in order to reduce the overhead
  - Supported in 802.11e and 802.11n

# Agenda

- Basic 802.11 Operation
- Collision Avoidance
- Hidden Terminal
- QoS guarantee
- Other Issues
- Performance Analysis

# Random Backoff




- STAs listen to the channel before transmission after DIFS
- Avoid collision by random backoff

# Exponential Random Backoff

1. Each STA maintains a contention window
   - Initialized to $CW_{min}$ = 32
2. Randomly pick a number, say *k*, between [0,CW-1]
3. Count down from *k* when the channel becomes idle
4. Start transmission when *k* = *0* if the channel is still idle
5. Double CW for every unsuccessful transmission, up to $CW_{max}$ (1024)
6. CW is reset to $CW_{min}$ after every successful transmission

When will collisions occur?

What's the probability a collision occurs?

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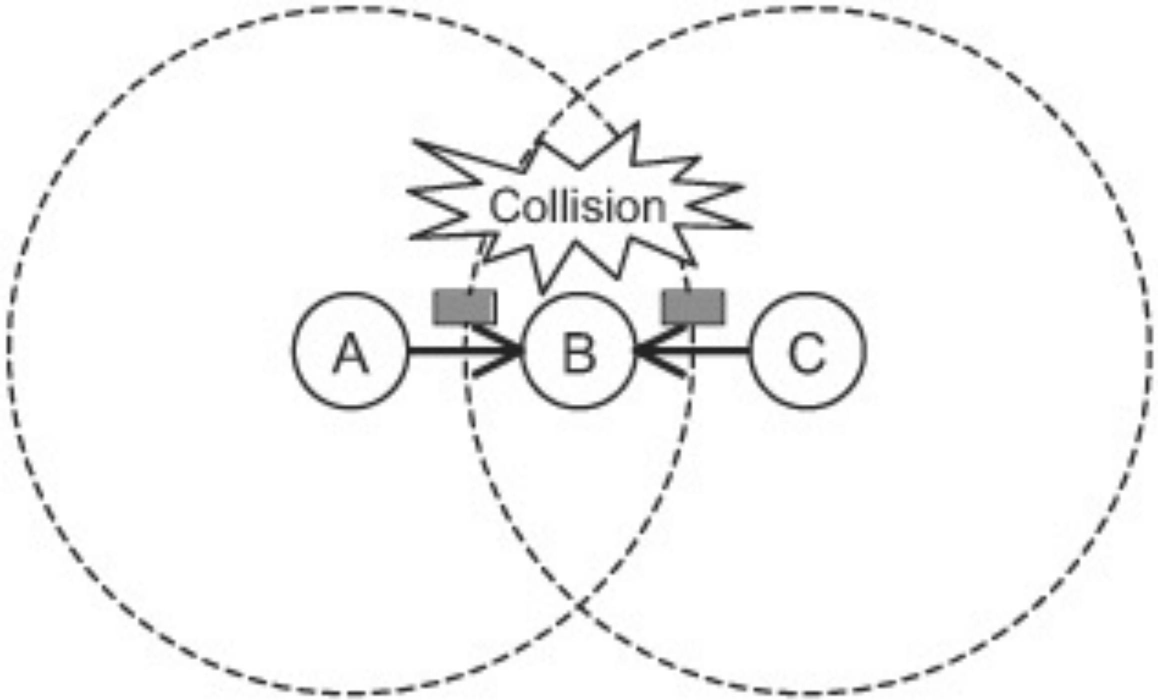
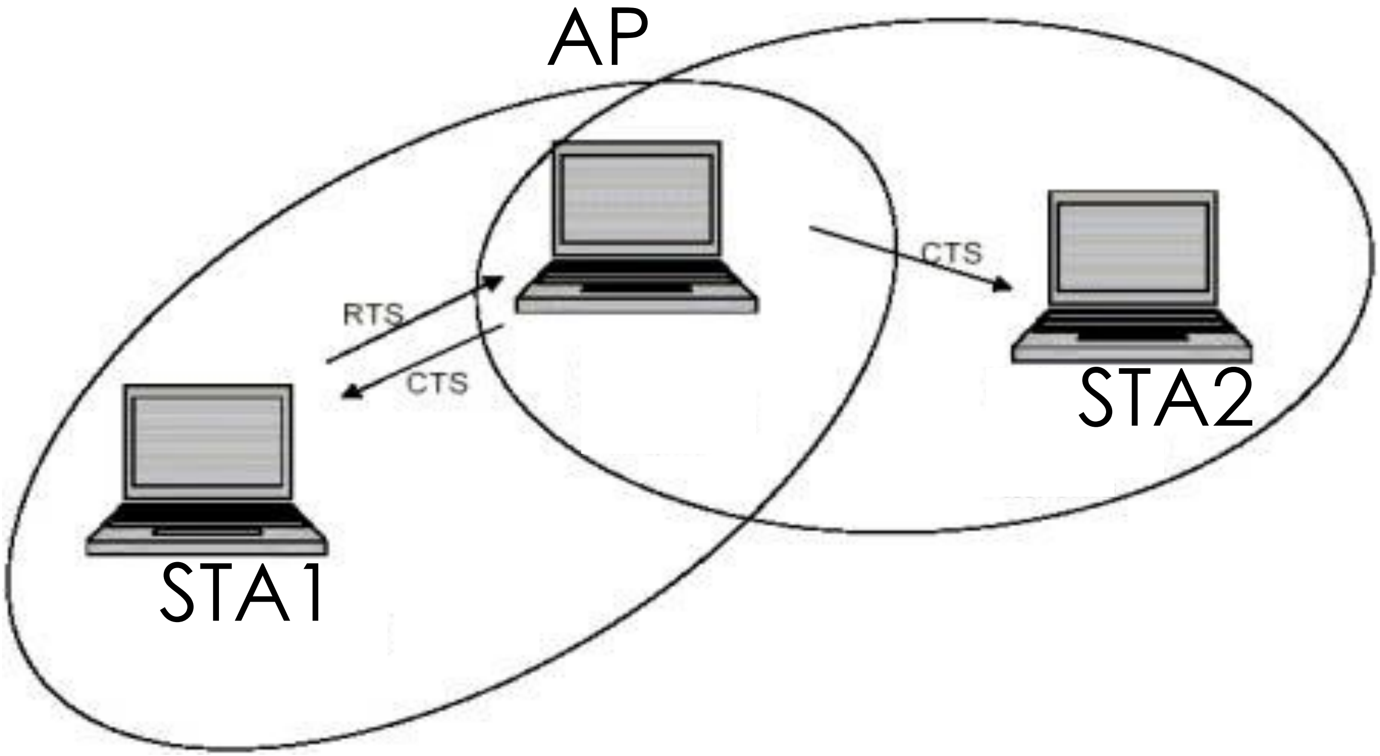
# Hidden Terminal Problem



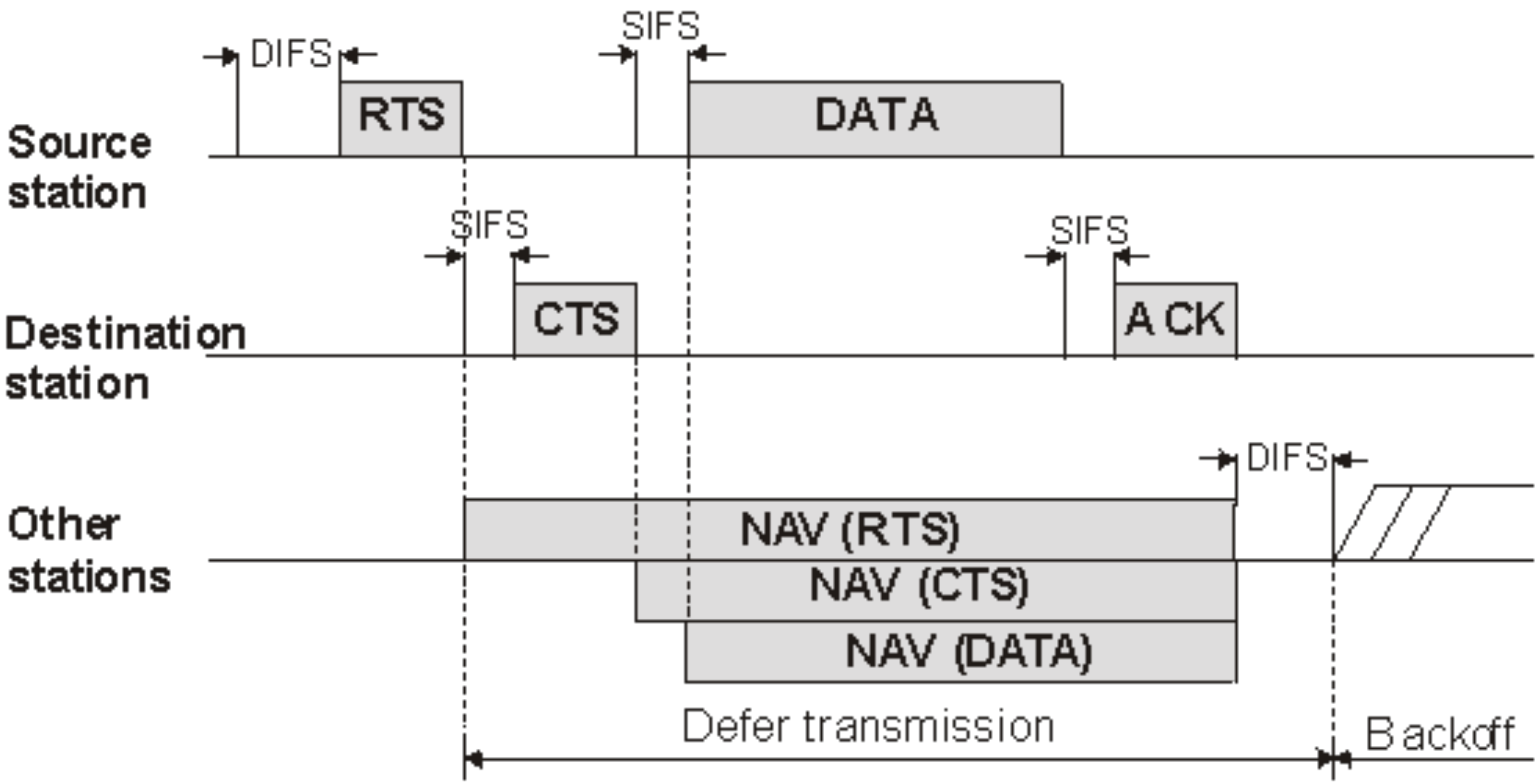

- Two nodes hidden to each other transmit at the same time, leading to collision

# 802.11's Solution: RTS/CTS




- STA1 sends RTS whenever it wins contention
- AP broadcasts CTS
- Other STAs that receive CTS defer their transmissions

# 802.11's Solution: RTS/CTS




NAV (Network allocation vector): STA performs virtual carrier sense for the specified time interval

Usually disabled in practice due to its expensive overhead

# Other Solutions to Hidden Nodes

- Embrace collisions and try to decode collisions
  - ZigZag decoding
  - S. Gollakota and D. Katabi, "ZigZag decoding: combating hidden terminals in wireless networks," ACM SIGCOMM, 2008
- Rateless code
  - Continuously aggregate frames and stop until decoding succeeds
  - A. Gudipati and S. Katti, "Strider: automatic rate adaptation and collision handling," ACM SIGCOMM, 2011

# Agenda

- Basic 802.11 Operation
- Collision Avoidance
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# 802.11 Family

- 802.11a/b/g: conventional DCF
- 802.11e: support quality of service (QoS) enhancements for wireless LANs
- 802.11n: support single-user MIMO
- 802.11ac: support multi-user MIMO
- 802.11ad: define a new physical layer in the 60GHz (mmWave)
- 802.11ay: extension of ad, supporting MU-MIMO
- 802.11ax: successor to 802.11ac, support OFDMA
- 802.11p: for vehicular networks

# 802.11e EDCA MAC

- Enhance distributed channel access (EDCA)
- Support prioritized quality of service (QoS)
- Define four access categories (ACs)

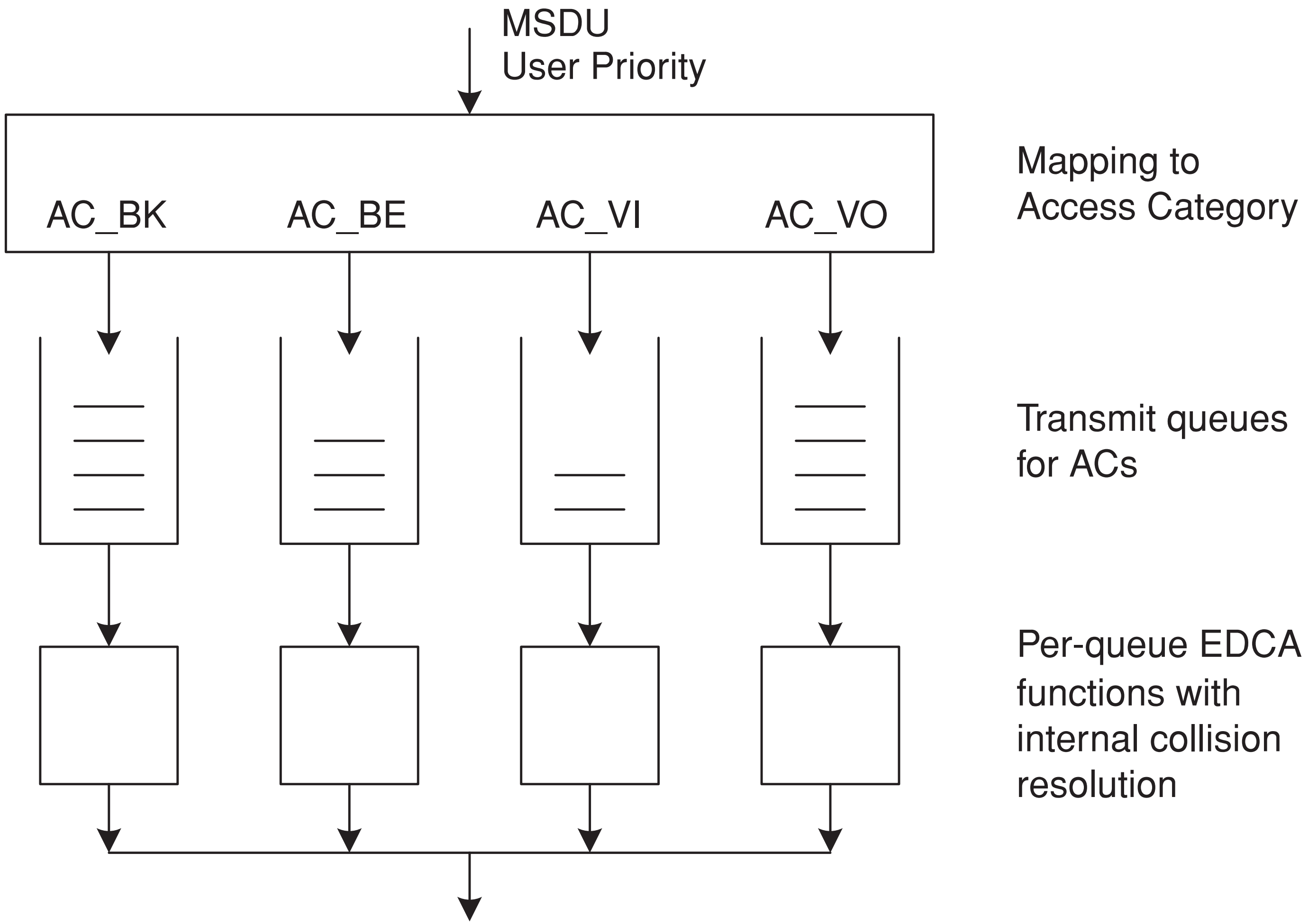
priority

low

| 802.1D User priority | 802.1D Designation | AC | Designation |
|---|---|---|---|
| 1 | BK | AC_BK | Background |
| 2 | – | | |
| 0 | BE | AC_BE | Best effort |
| 3 | EE | | |
| 4 | CL | AC_VI | Video |
| 5 | VI | | |
| 6 | VO | AC_VO | Voice |
| 7 | NC | | |

high

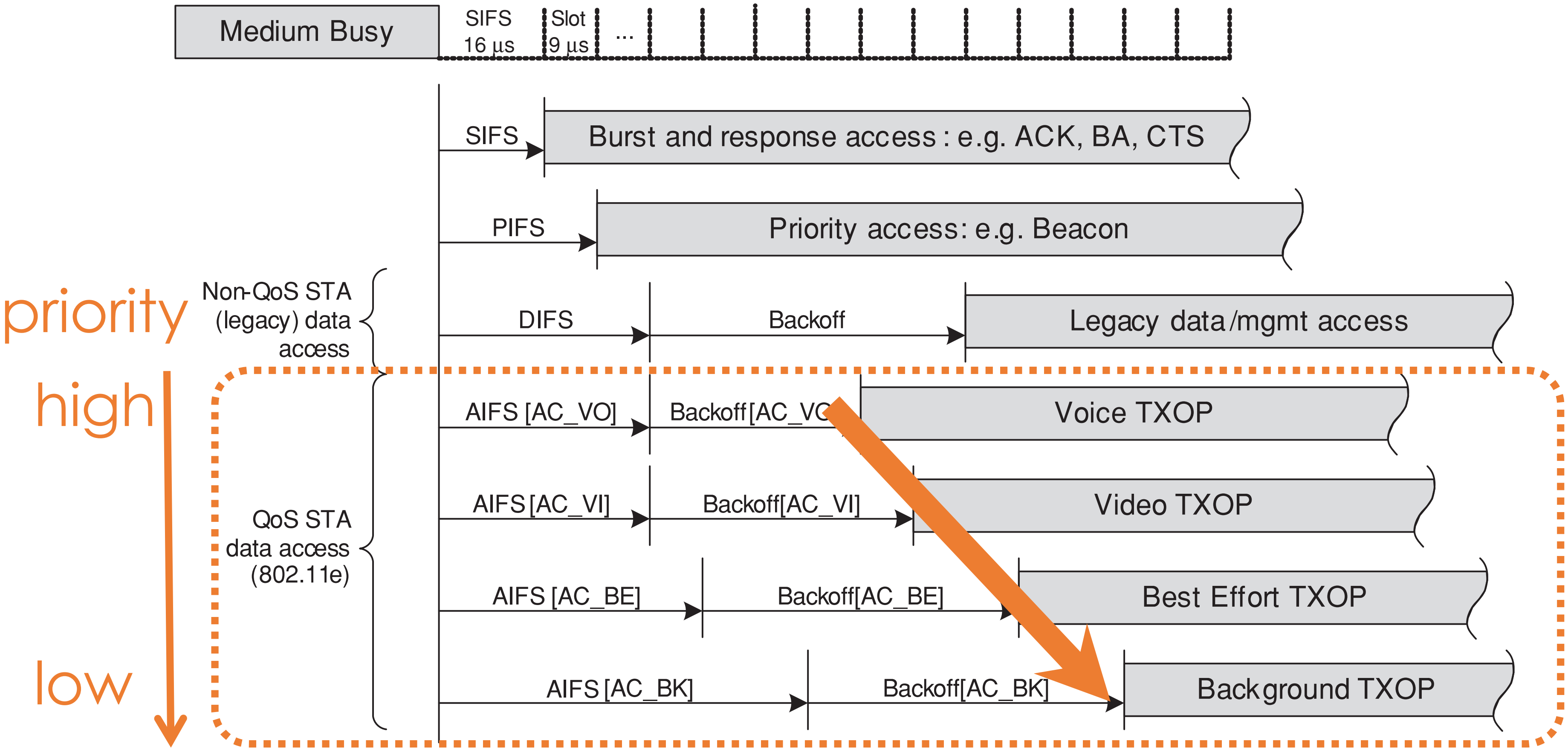
# 802.11e EDCA MAC – Priority Queues




Manage frames using priority queues

# How to Prioritize Frames in 802.11e?

- Again, by controlling the waiting time
  - A higher-priority frame waits for shorter time
  - Frames with the same priority contend as usual



# How to Prioritize Frames in 802.11e?

- Again, by controlling the waiting time
  - A higher-priority frame waits for shorter time
  - Frames with the same priority contend as usual
- AIFS (Arbitration Inter-Frame Spacing)

| AC | CWmin | CWmax | AIFSN | TXOP limit |
|---|---|---|---|---|
| AC_BK | 31 | 1023 | 7 | 0 |
| AC_BE | 31 | 1023 | 3 | 0 |
| AC_VI | 15 | 31 | 2 | 3.008 ms |
| AC_VO | 7 | 15 | 2 | 1.504 ms |
| legacy | 15 | 1023 | 2 | 0 |

probabilistic (Within an AC)

guarantee (between ACs)

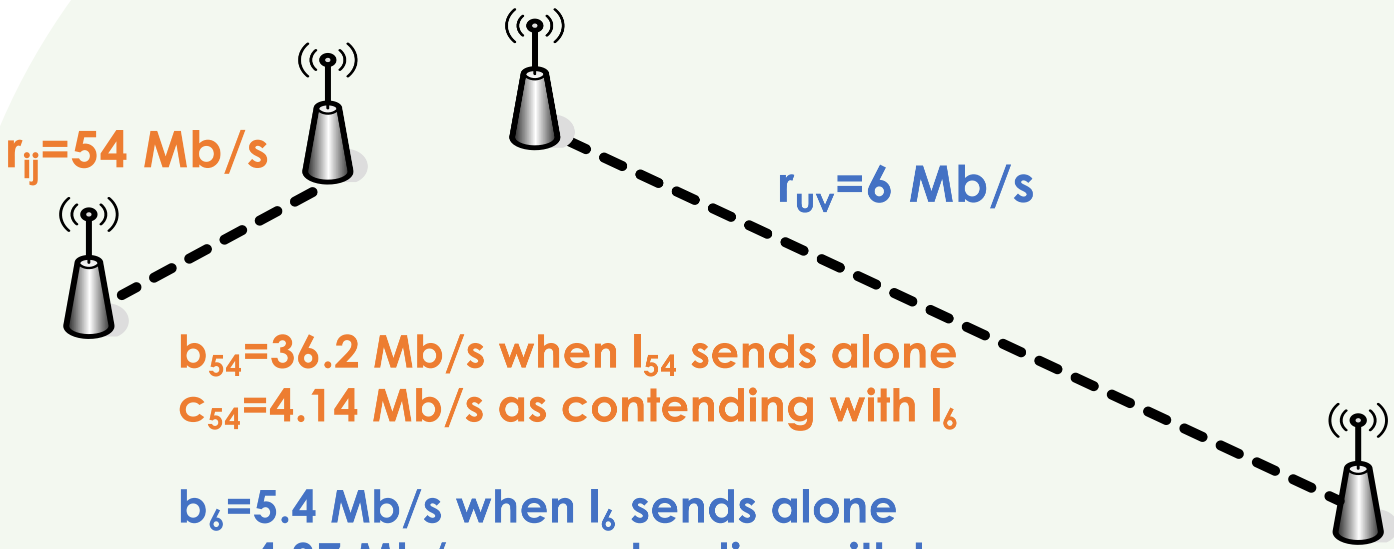
# Agenda

- Basic 802.11 Operation
- Collision Avoidance
- Hidden Terminal
- QoS guarantee
- Other Issue
- Performance Analysis

# Other Issues

- Performance anomaly
  - M. Heusse, et al., "Performance anomaly of 802.11b," IEEE INFOCOM, 2003
- Expensive overhead as the PHY rate increases
  - K. Tan, et al., "Fine-grained channel access in wireless LAN," ACM SIGCOMM, 2011
  - S. Sen, et al., “No time to countdown: migrating backoff to the frequency domain,” ACM MobiCom, 2011
- Unequal band-width and flexible channelization
  - 20MHz in 802.11a/b/g/n/ac, 40MHz in 802.11n/ac, 80MHz and 160Hz in 802.11ac
  - S. Rayanchu, et al., ”FLUID: improving throughputs in enterprise wireless LANs through flexible channelization,“ ACM MOBICOM, 2012

# Performance Anomaly




$b_{54}$=36.2 Mb/s when $l_{54}$ sends alone
$c_{54}$=4.14 Mb/s as contending with $l_6$

$b_6$=5.4 Mb/s when $l_6$ sends alone
$c_6$=4.37 Mb/s as contending with $l_{54}$


Channel is mostly occupied by low-rate links

➔ Everyone gets a similar throughput, regardless of its bit-rate

# Performance Anomaly

- The throughput of a STA sending at a high rate (e.g., 54Mbps) is degraded by that sending at a low rate (e.g., 6Mbps)
- Root causes?
  - 802.11 supports multiple transmission bit-rates, each of which has a different modulation and coding scheme
  - 802.11 ensures **packet fairness**, instead of **time fairness**

**Packet fairness:** each STA has an equal probability to win the contention → the average number of delivered packets for all STAs are roughly the same (802.11)

**Time fairness:** each STA occupies roughly the same proportion of channel time

# Agenda

- Basic 802.11 Operation
- Collision Avoidance
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- Performance Analysis

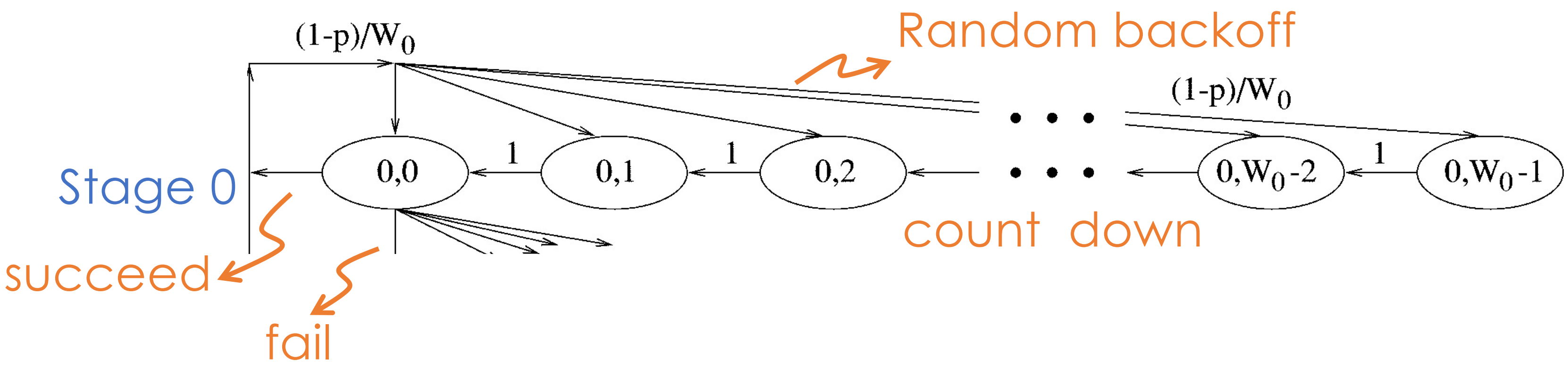
# Performance Analysis for CSMA/CA

G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," Selected Areas in Communications, IEEE Journal on 18, no. 3 (2000): 535-547

- Model to compute the 802.11 DCF throughput
- Assumptions
  - Finite number of stations
  - Ideal channel, i.e., no packet errors and no hidden terminals
  - Consider "saturation throughput", i.e., the maximal load a system can achieve
- Core ideas:
  - At each transmission attempt (either first transmission or retransmissions), each packet collides with constant and independent probability $p$
  - $p$: conditional probability related to contention window $W$ and number of stations $N$

# Performance Analysis for CSMA/CA

Model as a bi-dimensional discrete-time Markov chain $\{s(t), b(t)\}$
$s(t)$: backoff stage at time $t$, $b(t)$: backoff time counter at time $t$



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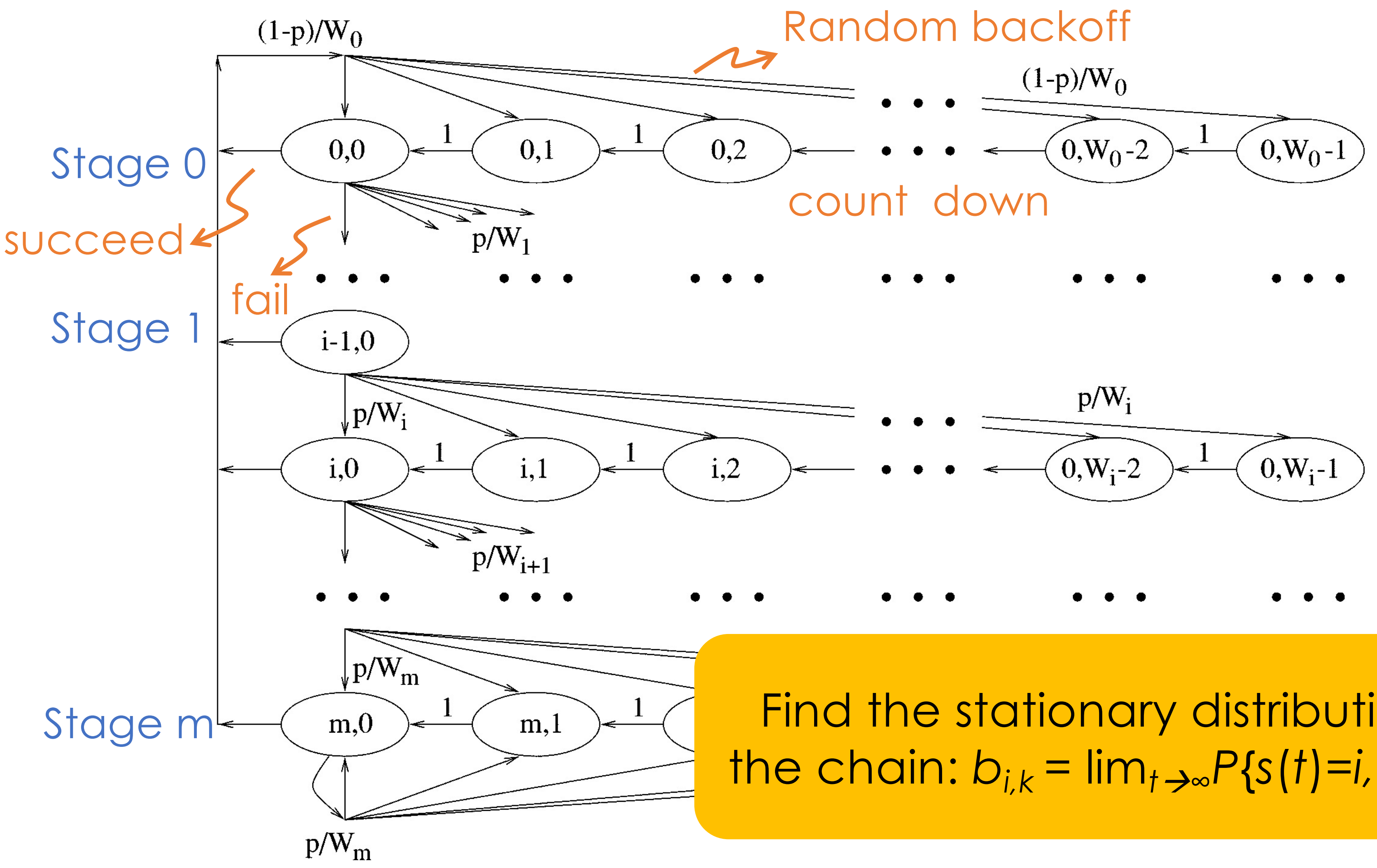



Find the stationary distribution of the chain: $b_{i,k} = \lim_{t\to\infty} P\{s(t)=i, s(t)=k\}$

# Performance Analysis for CSMA/CA

- Find the stationary distribution of the chain

$$b_{i,k} = \lim_{t \to \infty} P\{s(t) = i, s(t) = k\}$$

- The probability that a station transmits in a randomly chosen slot time

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2}{W+1}$$

- The probability that there is at least one transmission

$$P_{tr} = 1 - (1-\tau)^n$$

- The success probability of a transmission

$$P_S = P(\text{exactly one transmission}|\text{at least one transmission})$$

$$= \frac{n\tau(1-\tau)^{(n-1)}}{P_{tr}}$$

# Summary of WiFi

- Nice properties of WiFi
  - Unlicensed band → Free!!
  - Distributed random access and no coordination
  - Ensuring fairness
- Common issues
  - Expensive overhead and lower spectrum efficiency
  - Hard to avoid collisions
  - No QoS guarantee

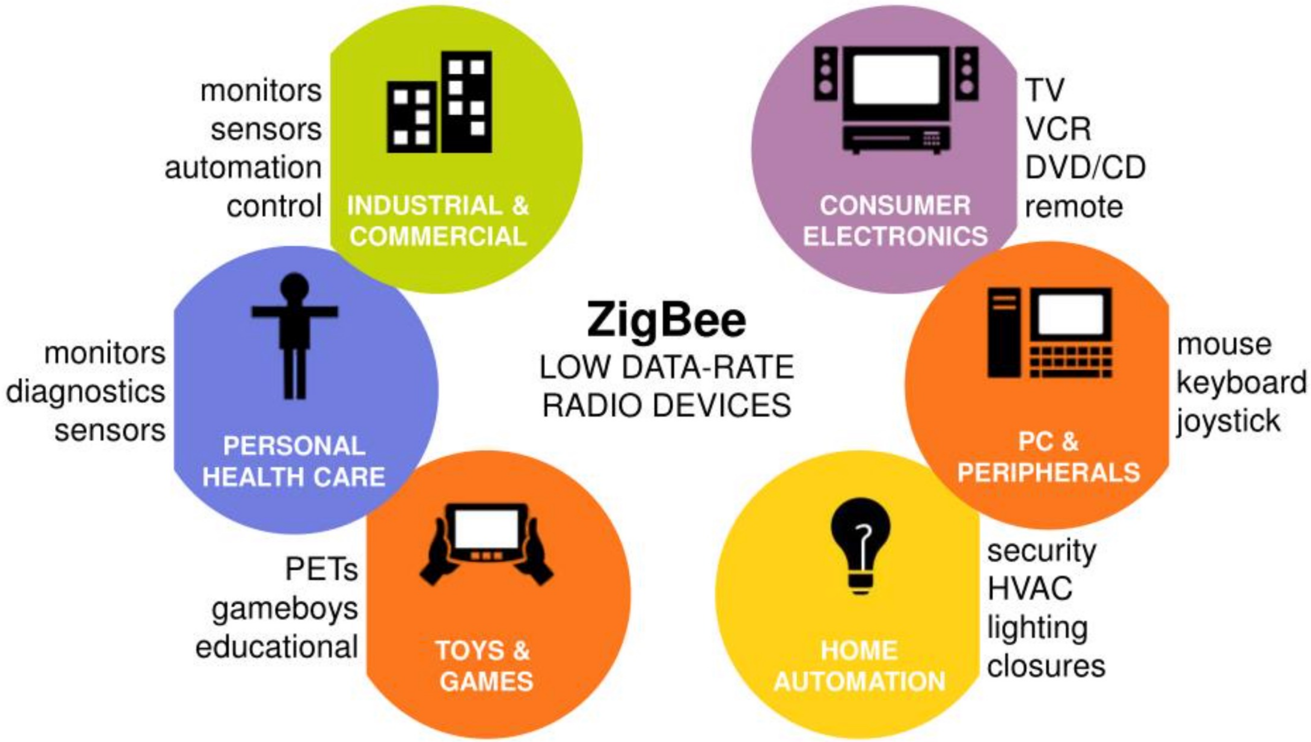
Every protocol balances the trade-off between <u>performance and overhead</u>

# Agenda

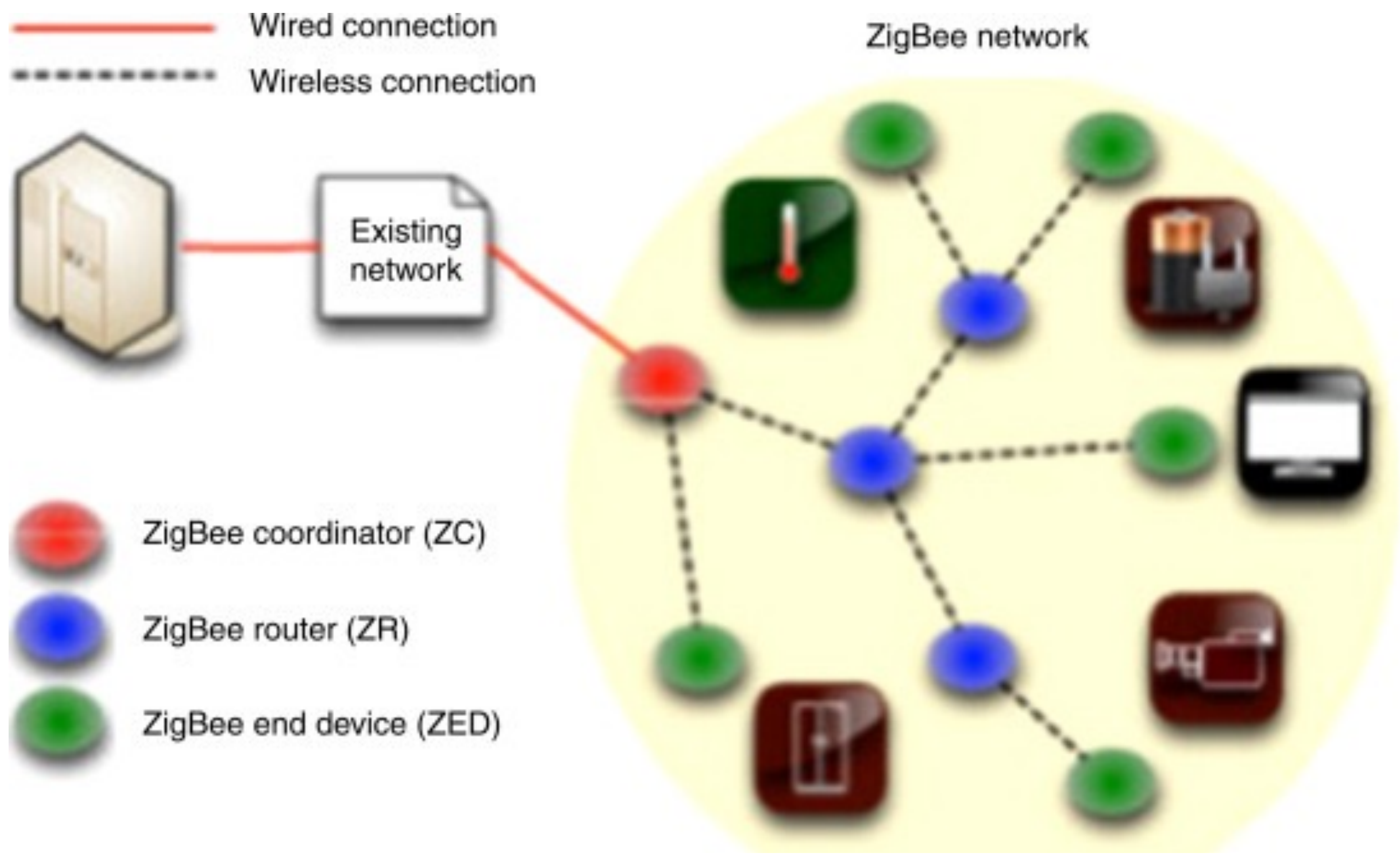
- Medium Access Control
- WiFi
  - Basic 802.11 Operation
  - Collision Avoidance (CSMA/CA)
  - Hidden Terminal
  - QoS guarantee
  - Other Issues
  - Performance Analysis
- **Bluetooth**

# ZigBee

- Designed for Wireless Personal Area Network (WPAN)
  - Short range
  - Low power consumption



# ZigBee Topology



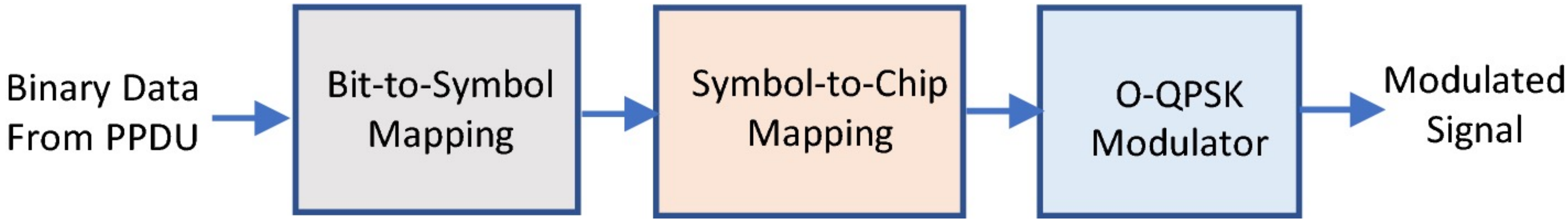

Typically form a star topology with a coordinator and multiple end devices

# 802.15.4

- A standard provides the MAC and PHY layers for ZigBee and 6LoWPAN
  - Short range
  - Little or no infrastructure
  - Small
  - Power-efficient
  - Inexpensive
- Operate over the license free radio bands (2.4GHz)
  - Compete with WiFi

# 802.15.4 PHY

- **DSSS (Direct-sequence spread spectrum)**
  - The message bits are modulated by a psuedorandom bit sequence known as a **spreading sequence**
  - Each spreading-sequence bit is known as a **chip**
  - 16-ary quasi-orthogonal modulation
    - 4 bits → 1 symbol, i.e., 16-bits **pseudo-noise (PN) code**
  - 32 chip sequence
    - 1 PN code → 32 chips

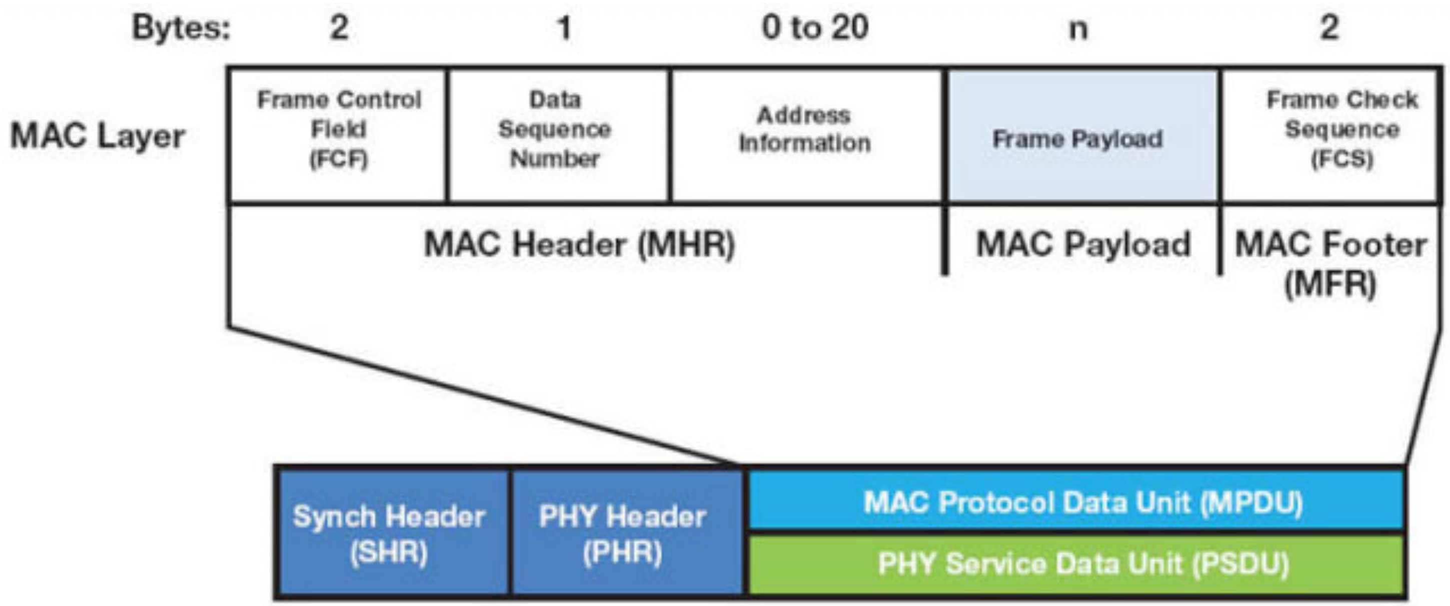



  - Incoming 32-bit chips are compared with one of the 16 PN codes using maximum likelihood (ML) detection

# 802.15.4 MAC

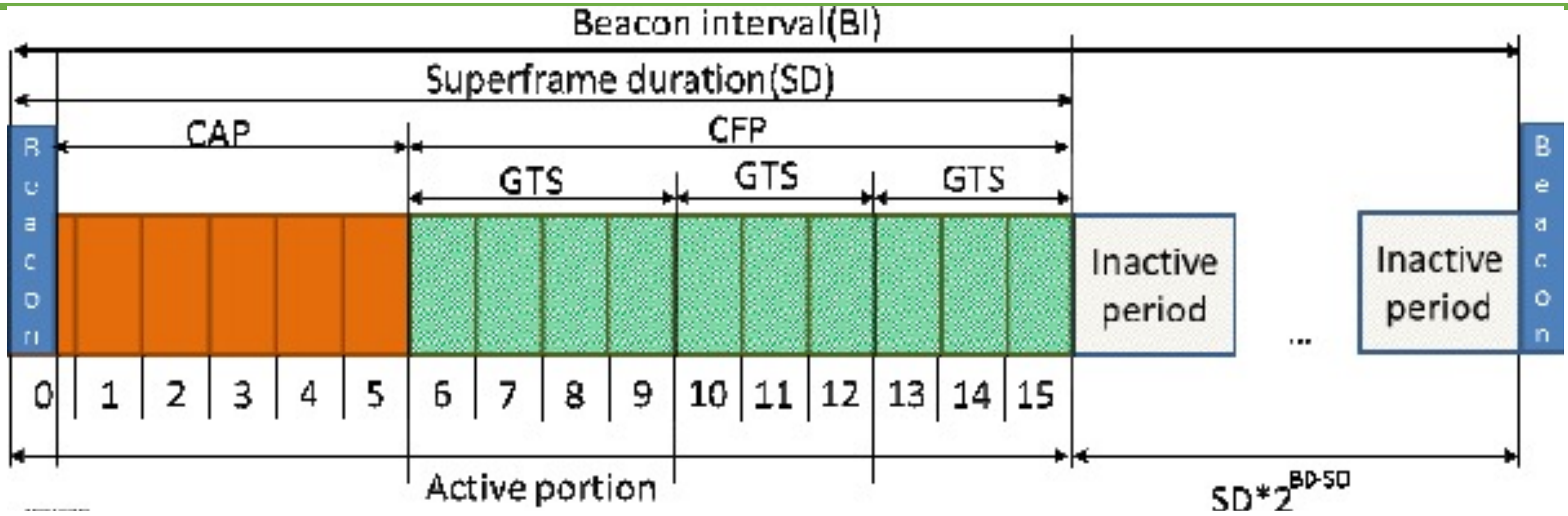
- Low-cost random access
- Synchronization to beacons
- Channel access based on CSMA/CA
- Traffic types
  - **Periodic data**
    - Applications defined rate (e.g., sensors)
  - **Intermittent data**
    - Application stimulus defined rate (e.g., light switch)
  - **Repetitive low latency data**
    - Allocation of time slots (e.g., moust)

# 802.15.4 MAC Frame Format




- 4 types of frame formats
  - Data frame
  - Beacon frame
  - Acknowledge frame
  - MAC command frame

# Access Control




- The coordinator periodically sends beacons
  - Used to synchronize all devices
- Superframe: CSMA + TDMA
  - CAP (contention access period)
    - Access based on CSMA/CA
  - CFP (contention free period)
    - Invitation-based access