Wireless Communication Systems
@CS.NCTU

Lecture 4: MAC Protocols for WLANs

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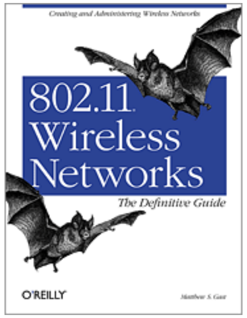
Reference

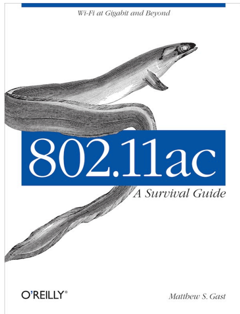
1. A Technical Tutorial on the IEEE 802.11 Protocol
   By Pablo Brenner
   online: http://www.sss-mag.com/pdf/802_11tut.pdf

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

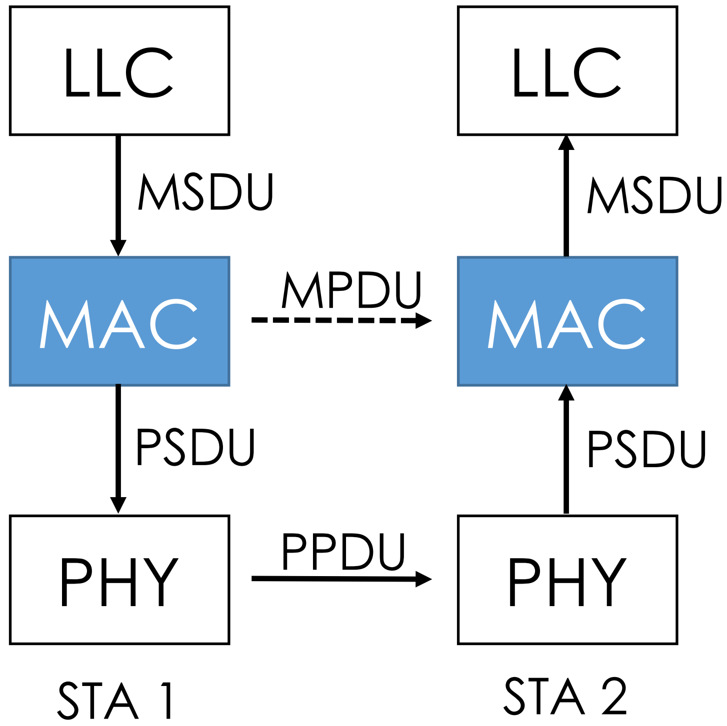
- Basic 802.11 Operation
- Collision Avoidance (CSMA/CA)
- Hidden Terminal
- QoS guarantee
- Other Issues
- Performance Analysis

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

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



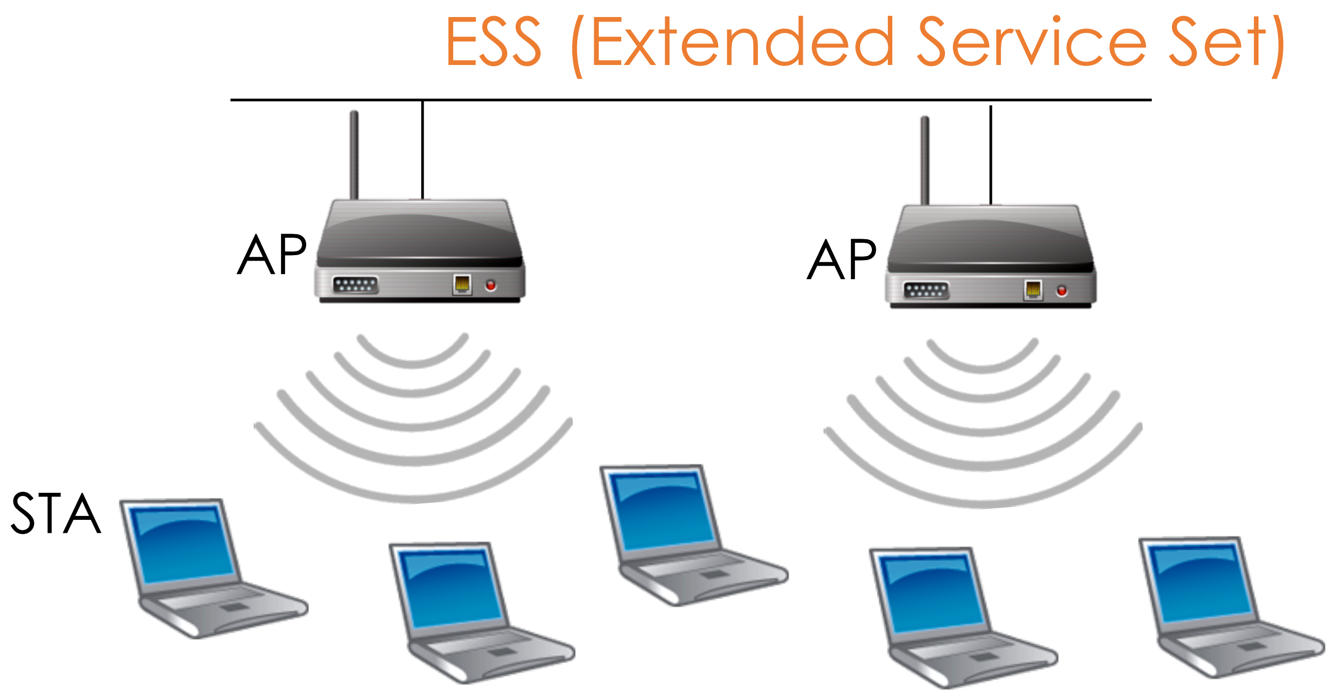
Basic Service Set (BSS)

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

Infrastructure Mode

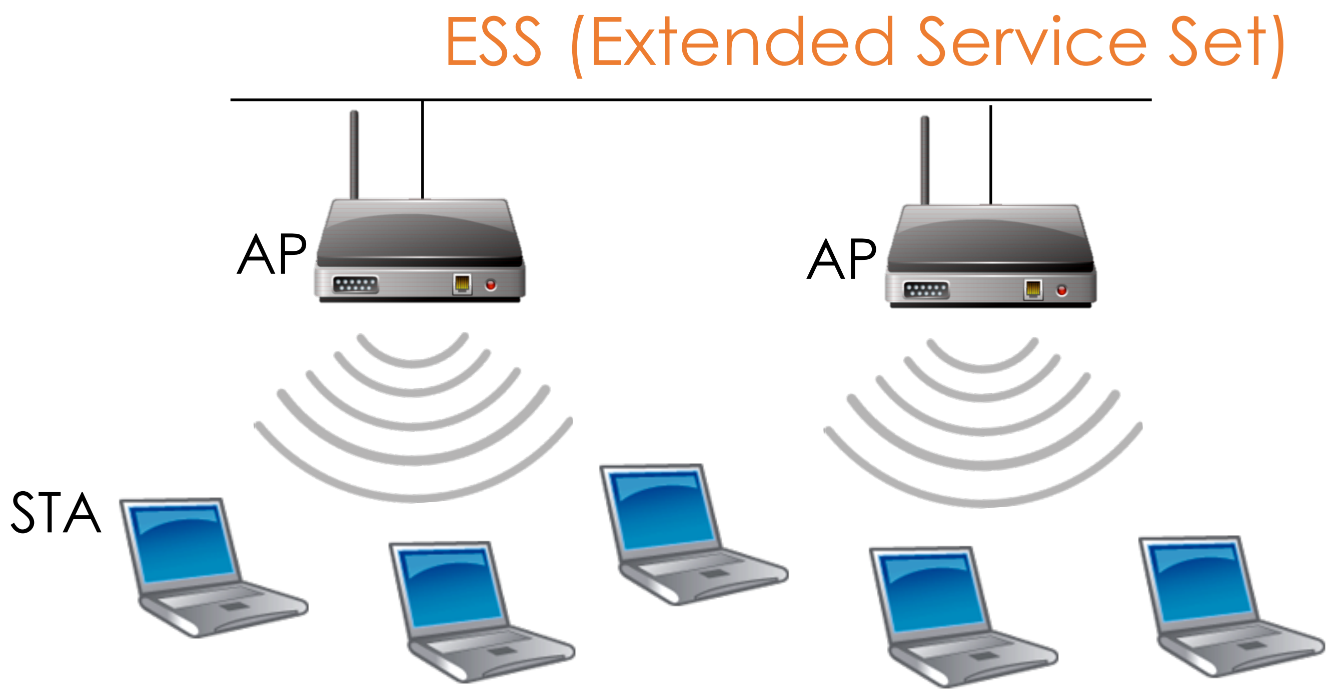
- Each station (STA) associates with a central station Access point (AP)
- An AP and its stations form a basic service set (BSS)
- AP announces beacons periodically

Infrastructure Mode



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

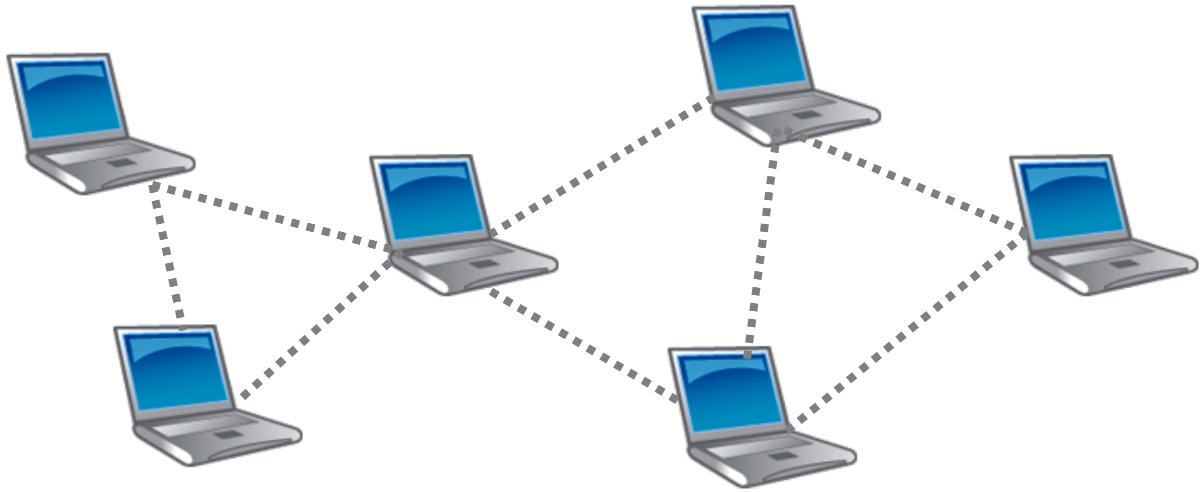
Infrastructure Mode



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

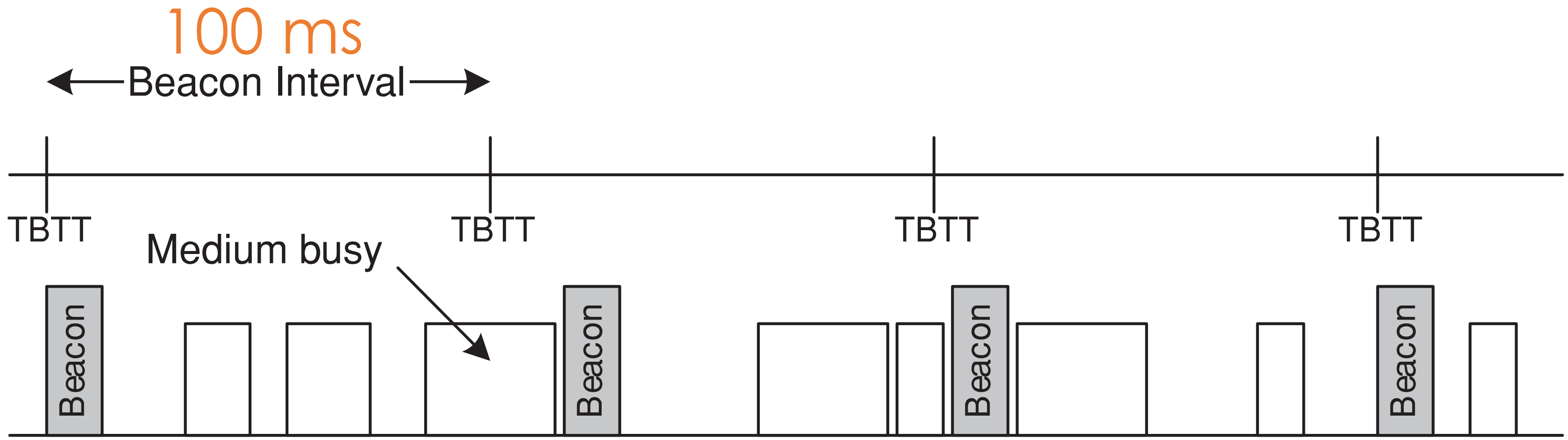
Ad-Hoc Networks

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 Association



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

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

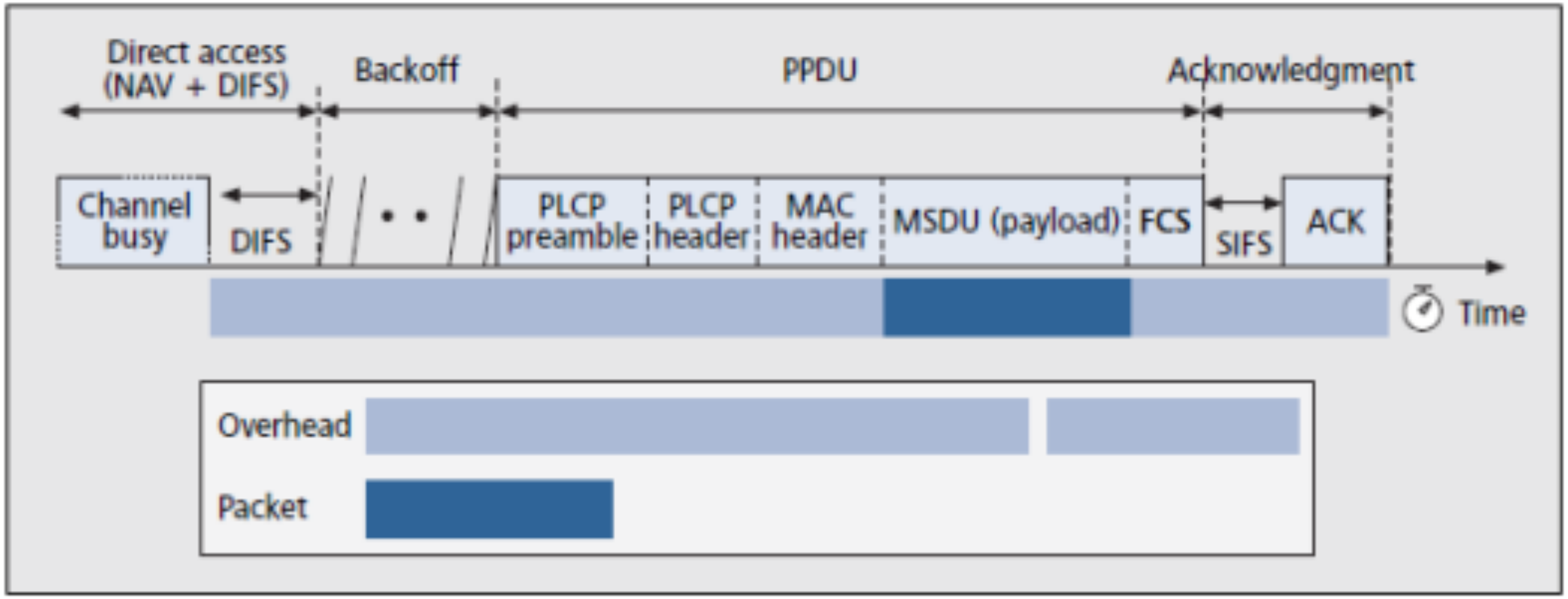
  - Both allow a STA to send if the medium is sensed to be "idle"
  - Both defer transmission if the medium is sensed to be "busy"

diff

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

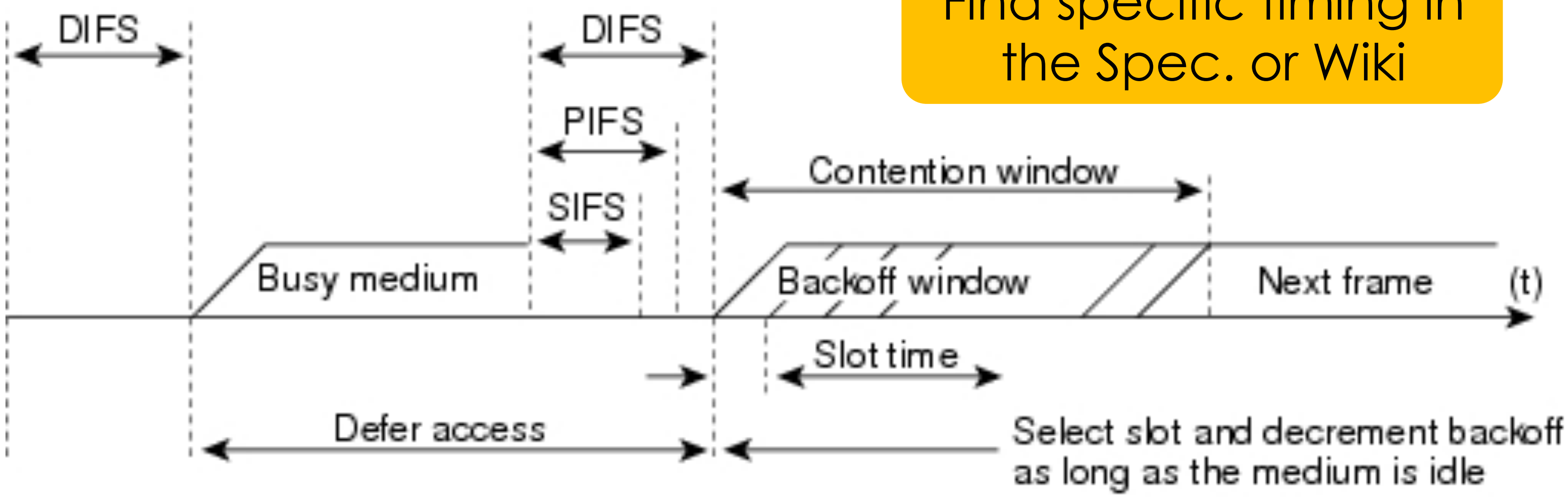
    → a **half-duplex** STA cannot detect collisions during transmission

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

Octets: 2	2	6	6	6	2	6	0 - 2312	4
Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	CRC

MAC Header

Data

octets: 2	2	6	4
Frame Control	Duration	RA	CRC

MAC Header

ACK

Check other frame format in Spec.

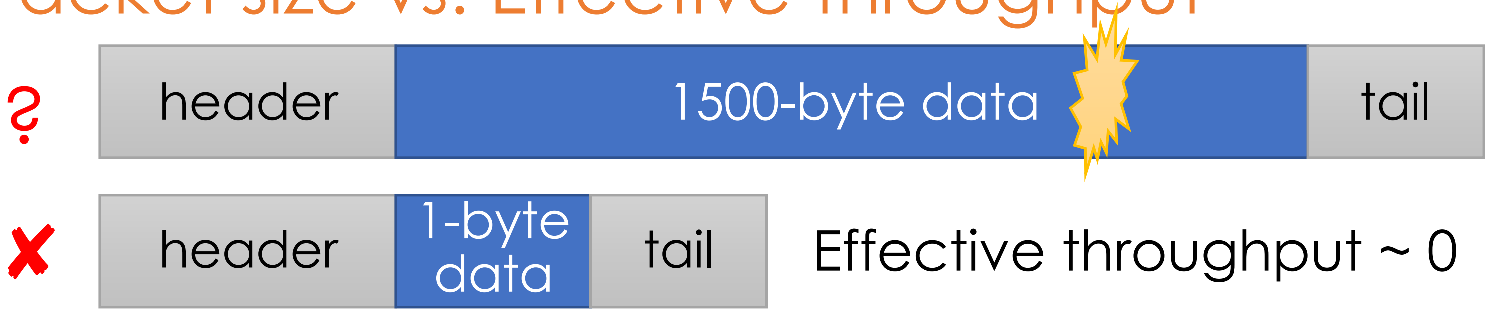
- How to estimate protocol overhead without considering backoff
  - $1 - T_{Data} / (T_{DIFS} + T_{PLCP} + T_{MAC} + T_{Data} + T_{SIFS} + T_{ACK})$
  - Control frames are sent at the base rate (lowest bit-rate)

Overhead vs. Throughput

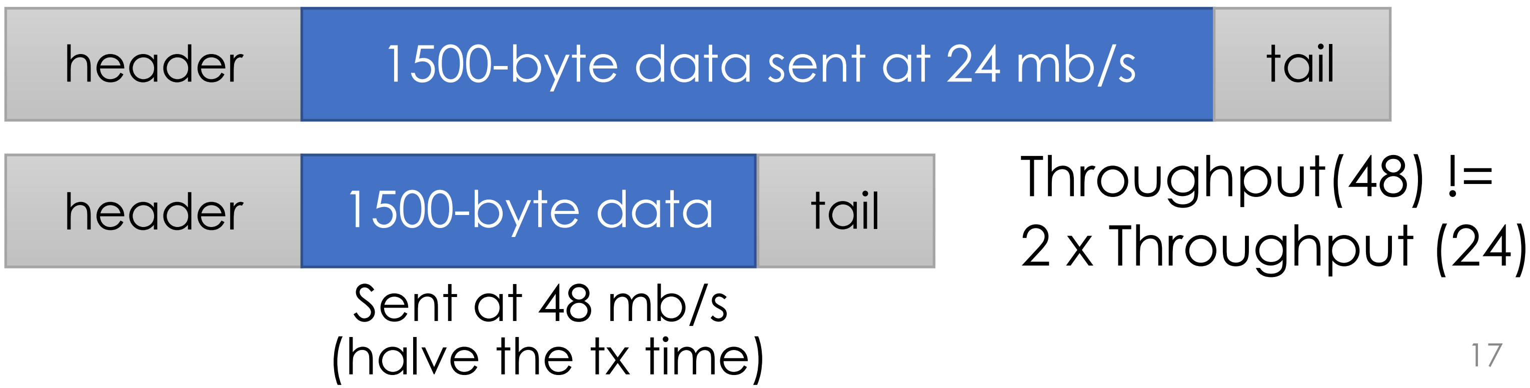
- Effective throughput

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

- Packet size vs. Effective throughput



- Bit-rate vs. Effective throughput



Fragmentation and Aggregation

- Success probability v.s. 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

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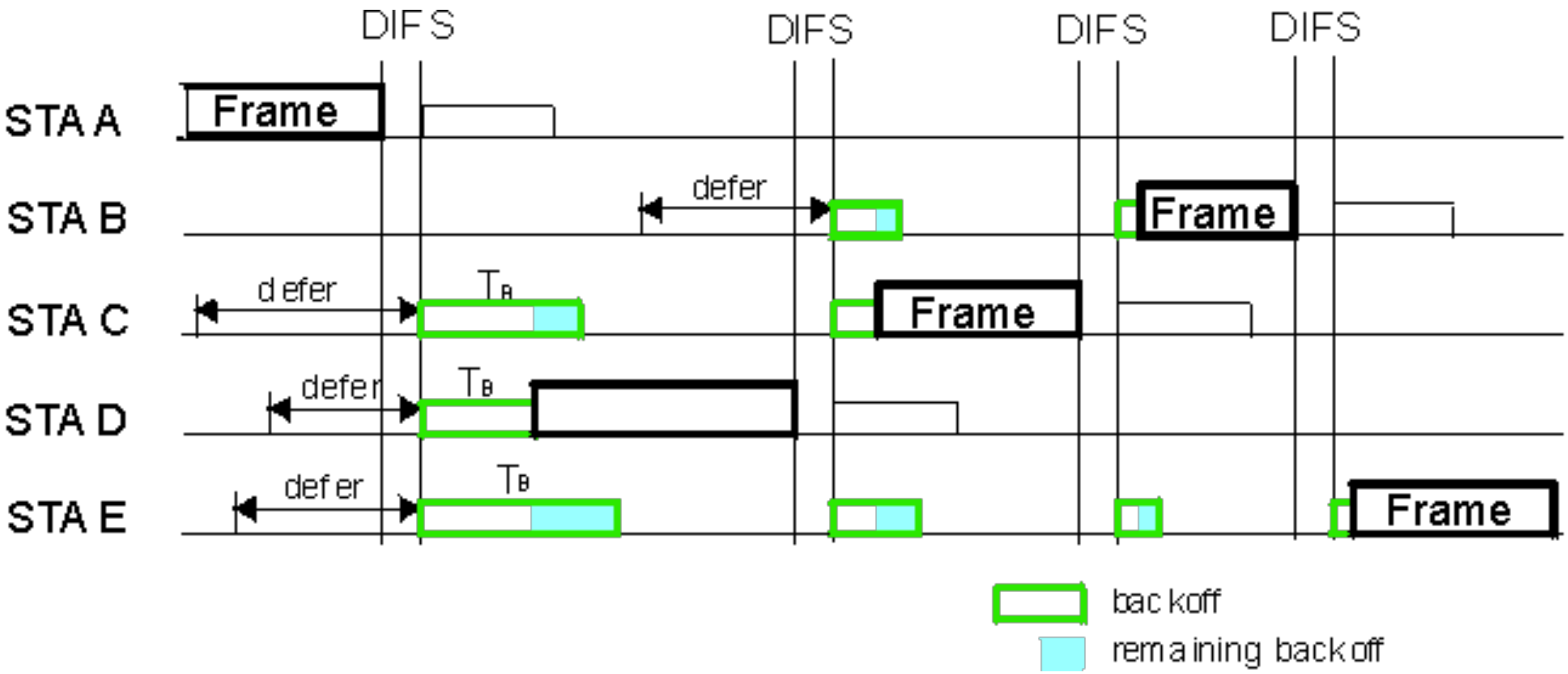
Random Backoff



- 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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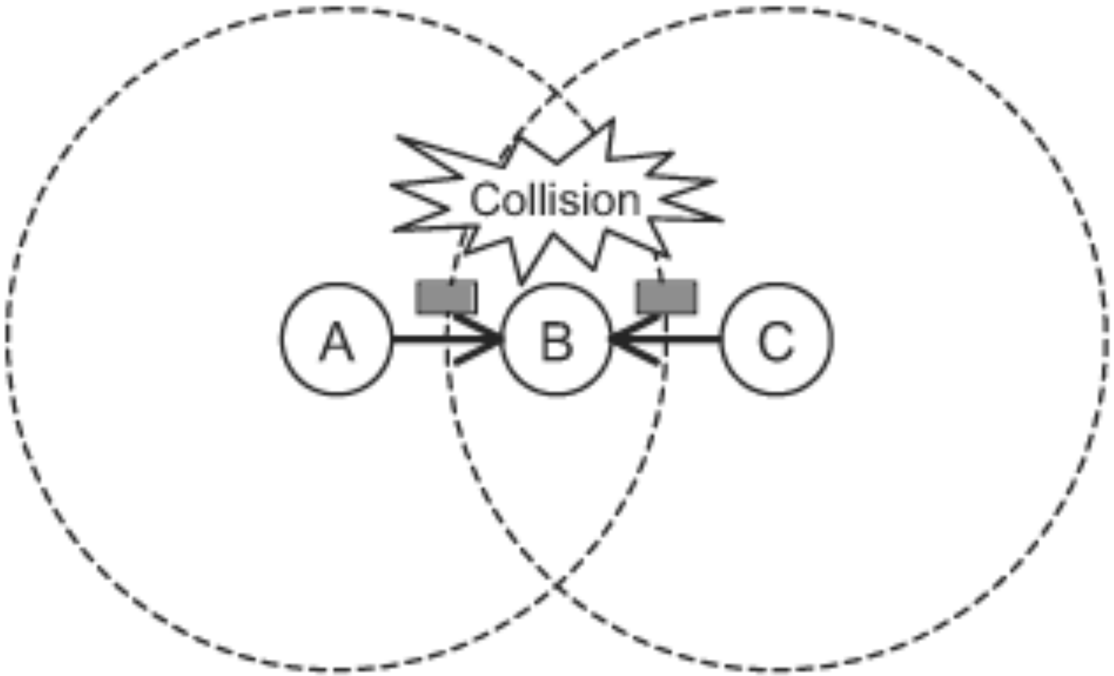
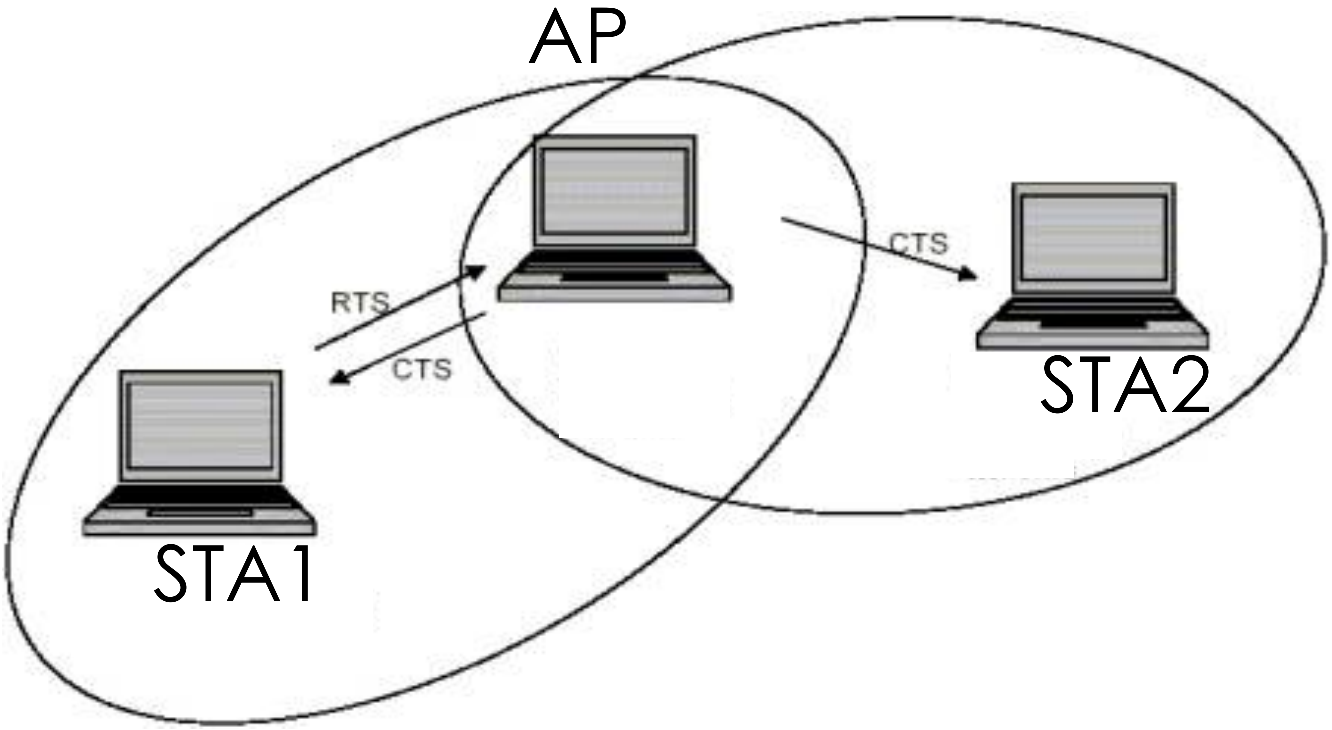
Hidden Terminal Problem



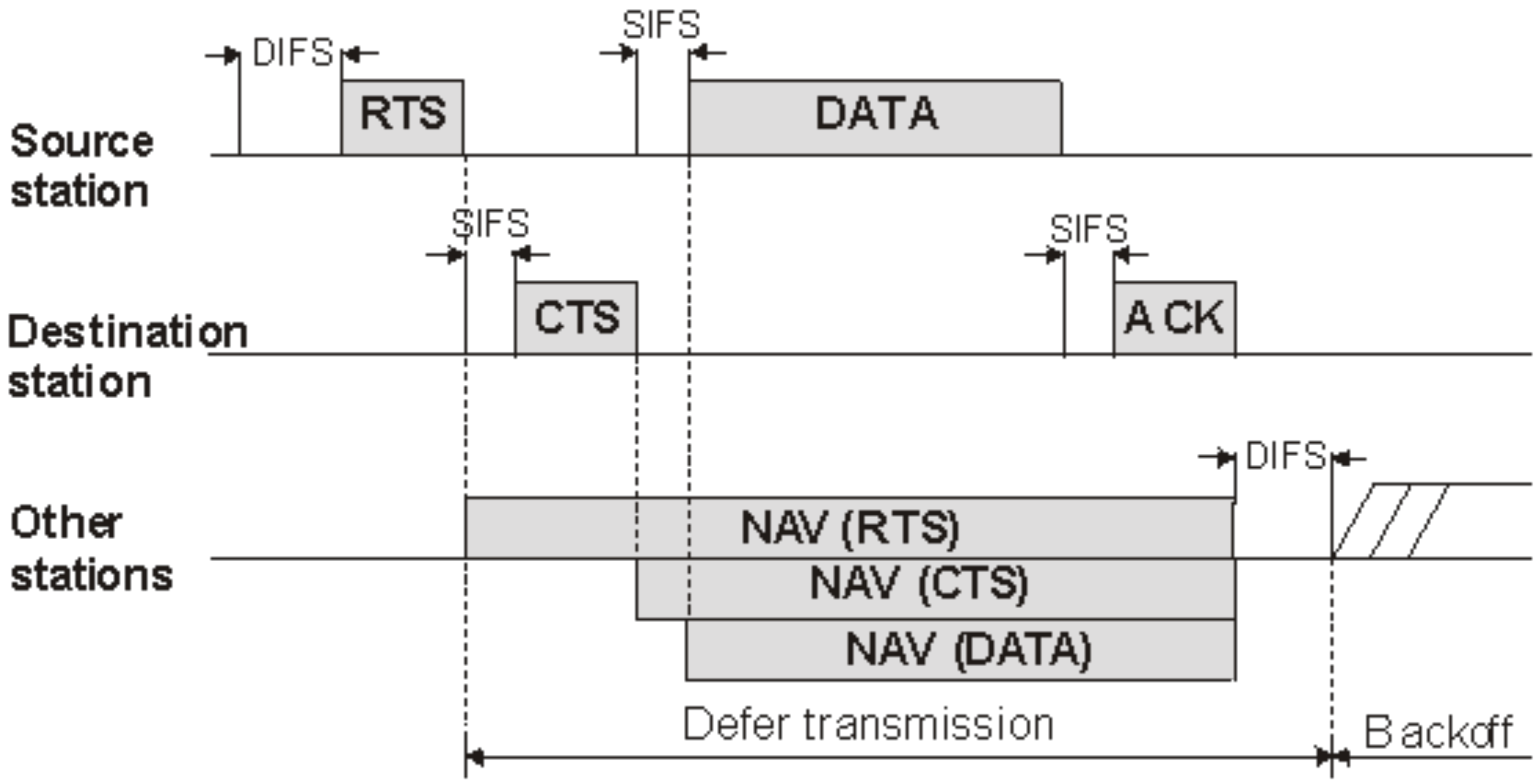
- Two nodes hidden to each other transmit at the same time, leading to collision

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

Recent Solutions to Hidden Terminals

- 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

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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 (lecture 4)
- 802.11ac: support multi-user MIMO (lecture 5)
- 802.11ad: define a new physical layer in the 60GHz (mmWave, last lecture)
- 802.11p: for vehicular networks

802.11e EDCA MAC

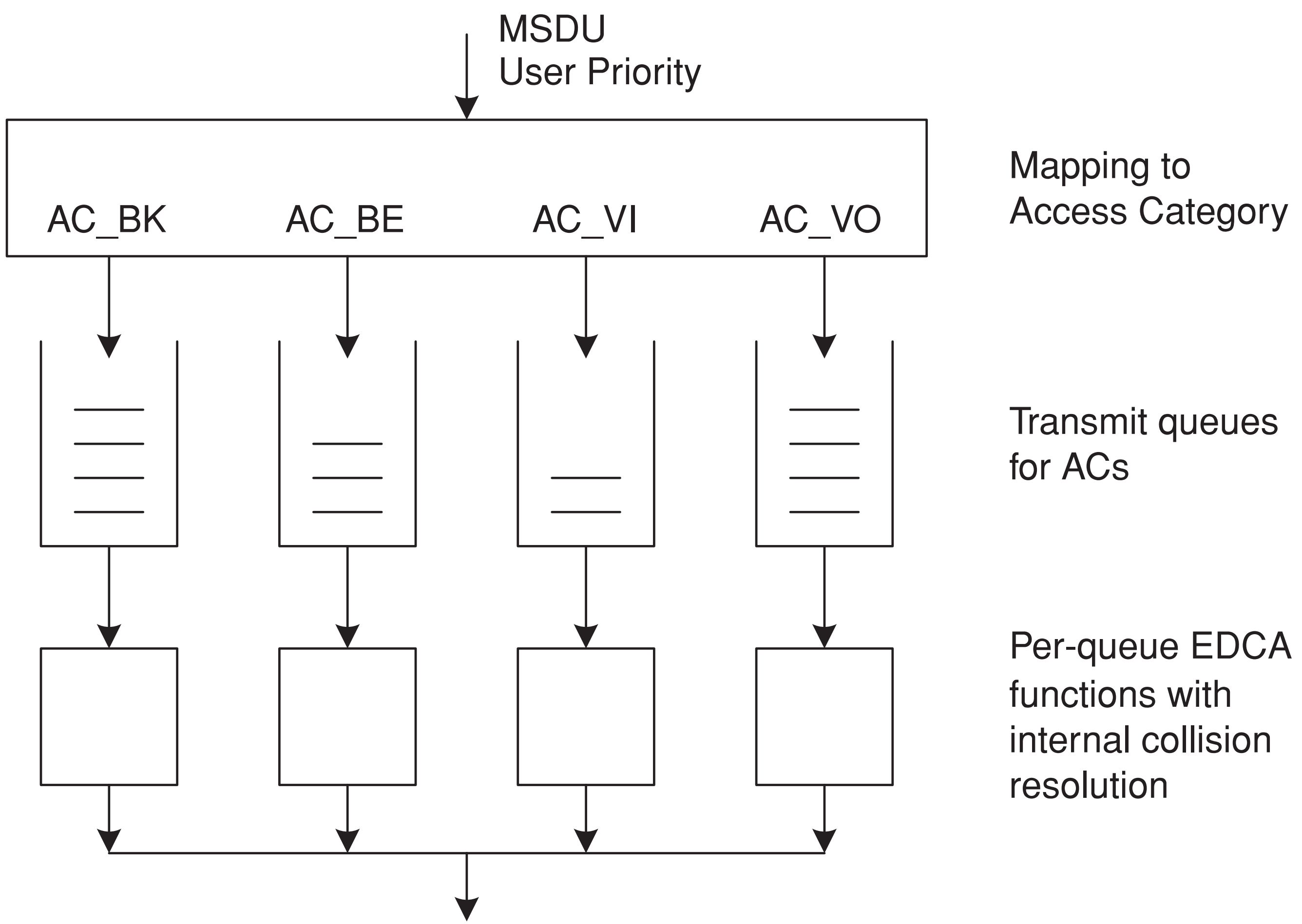
- Enhance distributed channel access (EDCA)
- Support prioritized quality of service (QoS)
- Define four access categories (ACs)

priority

low → high

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		

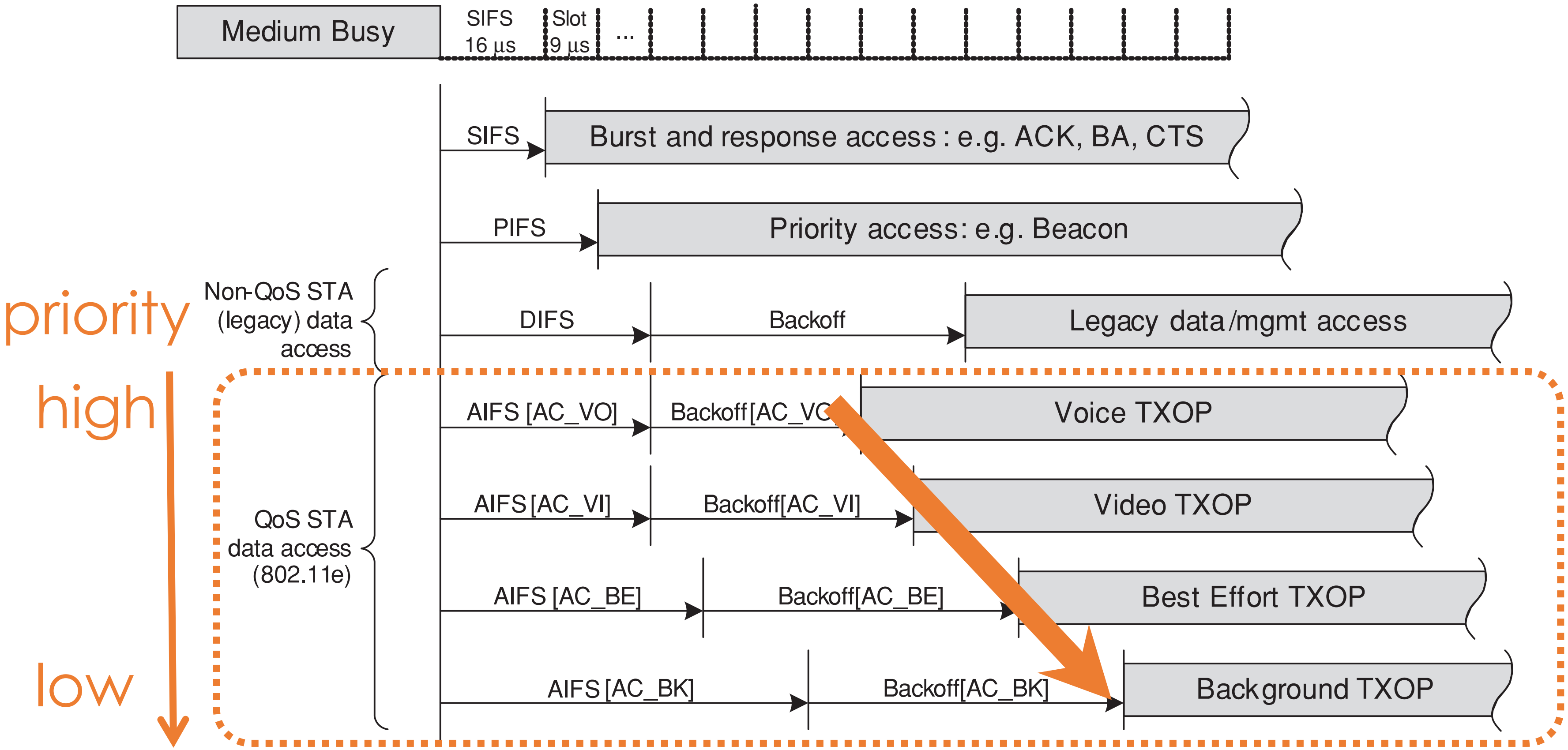
802.11e EDCA MAC – Priority Queues



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
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- 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) — CWmin, CWmax

guarantee (between ACs) — AIFSN

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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

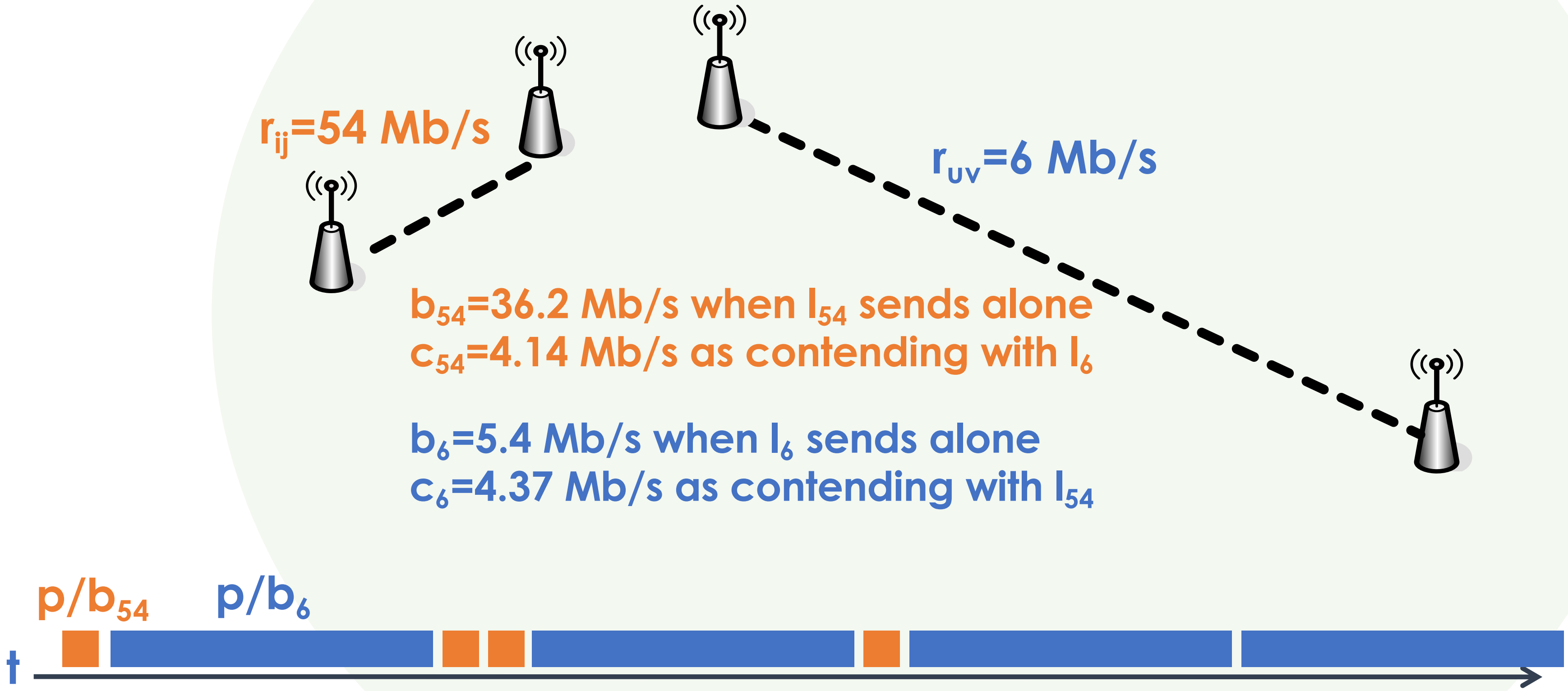
Performance Anomaly

- 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

Performance Anomaly



Channel is mostly occupied by low-rate links

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

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Performance Analysis for CSMA/CA

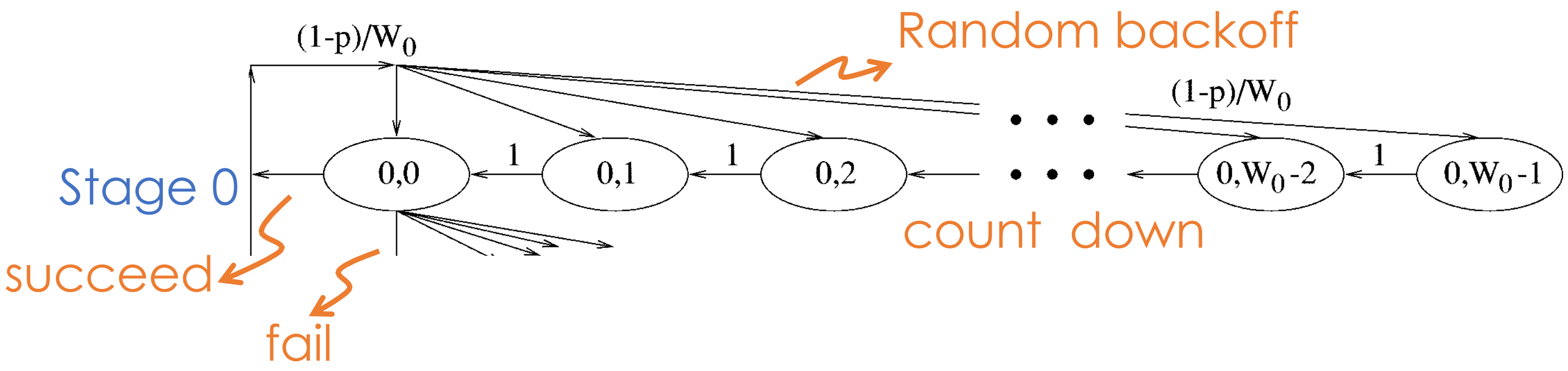
G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," Selected Areas in Communications, IEEE Journal on 18, no. 3 (2000): 535-547

- 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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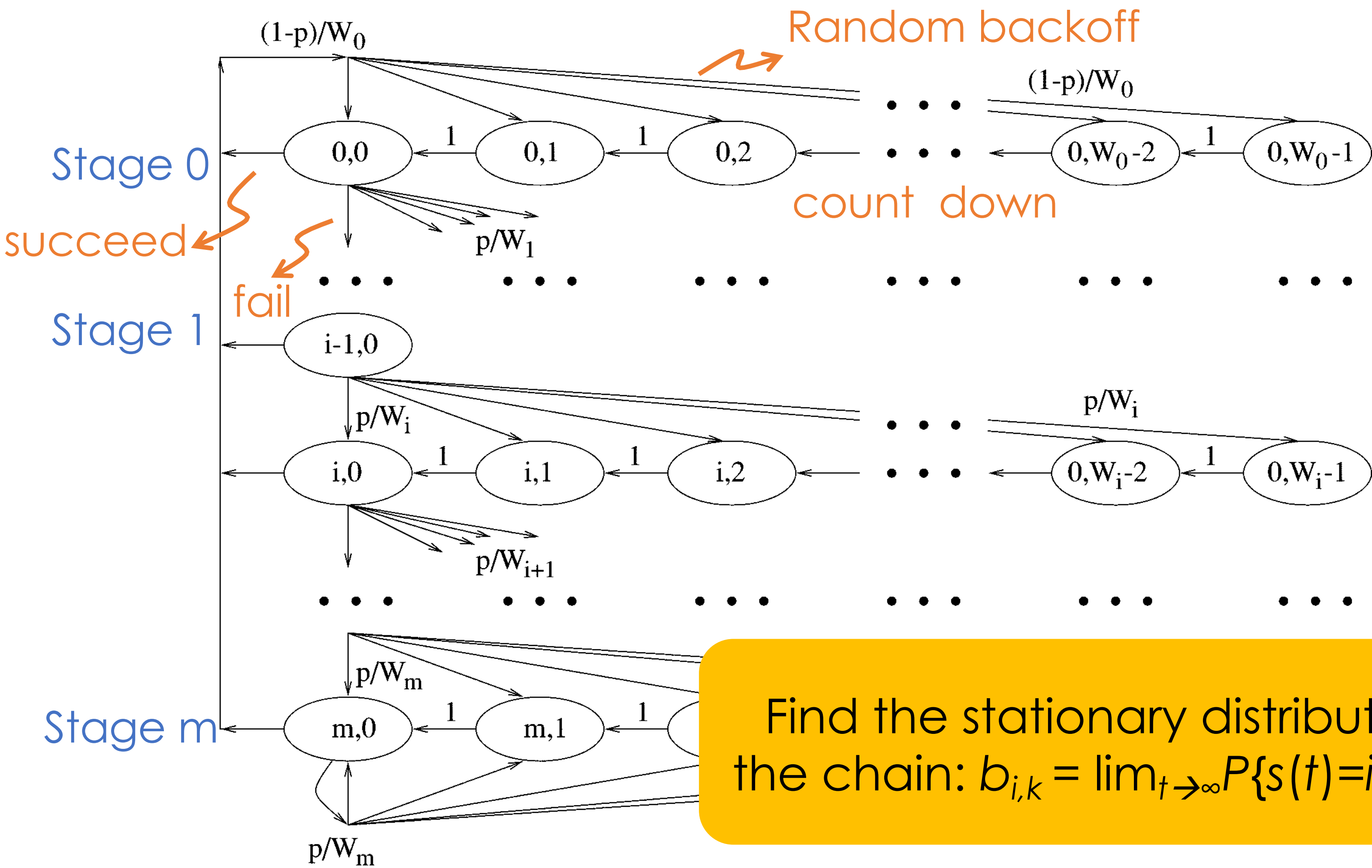

Find the stationary distribution of the chain: $b_{i,k} = \lim_{t \to \infty} P\{s(t)=i, s(t)=k\}$

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

- 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 performance and overhead