Lecture 10

Medium Access in Packet Data Networks

Recap

- Circuit switching
  - Allocate resources for voice calls
    - Use ALOHA followed by channel allocation
  - Voice calls use significant time (several minutes)
    - Quality/data rate is mostly fixed
- Packet Switching
  - Bursty data
  - Should exploit available resources in the best possible way
  - Ethernet/WiFi use all of the channel bandwidth for ONE user device (computer, laptop) for one packet (in time)

Introduction

- What is medium access?
  - Who gets to transmit? How? When?
  - Multiplexing
    - How many stations can share a single link
      - FDMA, TDMA, CDMA in circuit switched voice networks
      - CSMA/CD in Ethernet (simplicity)
  - Duplexing
    - How communication from station A to station B is separated from the communication from station B to station A
    - FDD or TDD
- Impact of architectures
  - Infrastructure – centralized, fixed base station
  - Ad hoc – distributed, peer-to-peer
- Simplicity and overhead

Packet Reservation

- High Level Idea
  - Mobile needs uplink resources
  - Use random access or control signaling to “ask” for resources to send packets
- The “network” (usually BSC, RNC or e-NodeB) assigns the resources on the downlink
  - Lets the mobile know through control signaling
- Implementation varies by technology

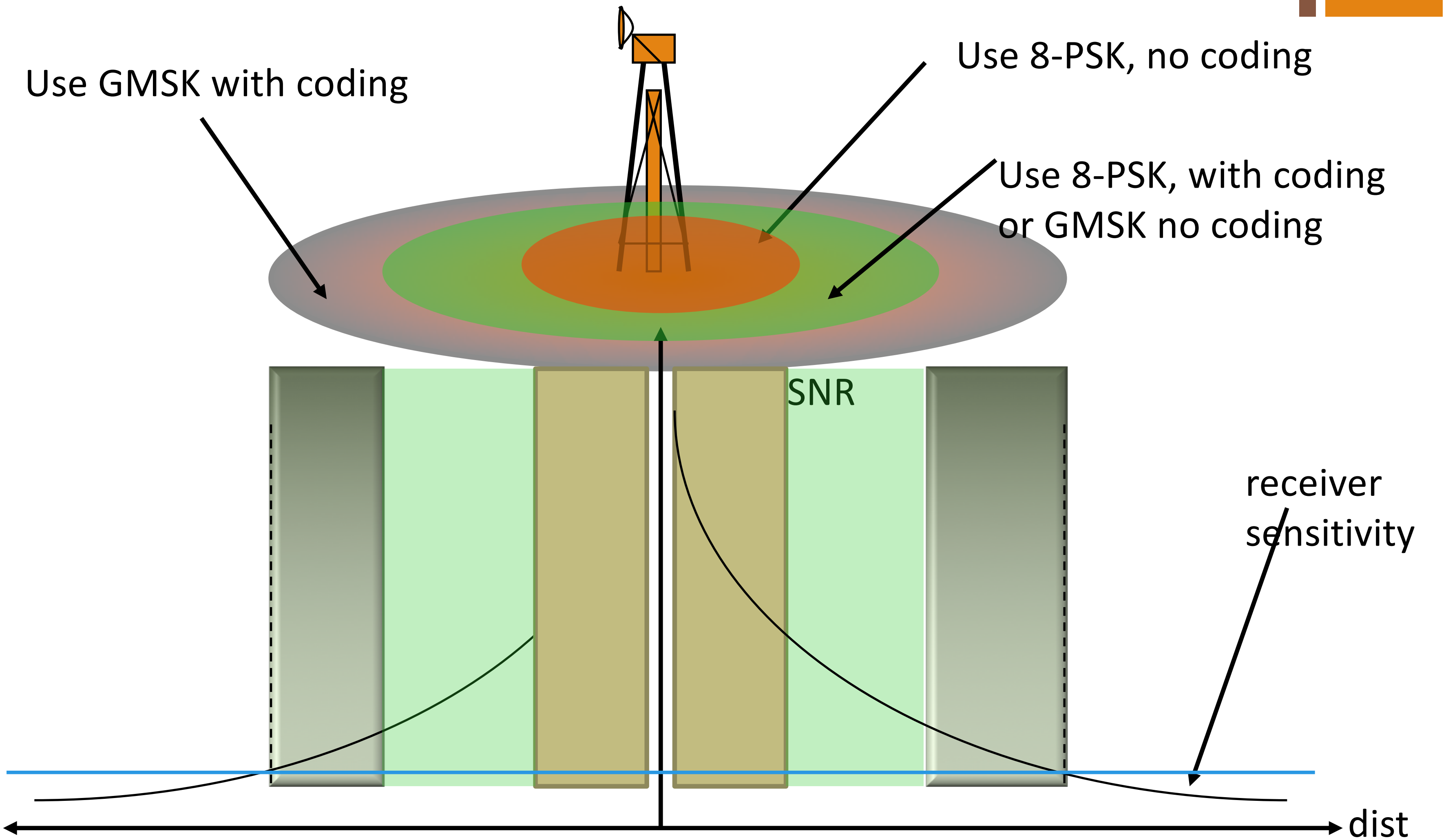
Downlink for packet data traffic

- Scheduling decisions are done by the network
  - Again BSC, RNC/Node-B or e-Node B
- Originally it was similar to round-robin
- Recent changes
  - Use **channel conditions** to improve network throughput
  - Use previously obtained throughput to allocate resources fairly
  - Combine with hybrid ARQ

Using Channel Conditions

- How does the network know about the channel conditions?
    - There is control signaling where a mobile sends measurements
    - Examples are ACK/NACK ratios, RSS measurements, BER, FER
    - Measurement reporting and assignment is part of radio resources management functions (later)
- Fast scheduling
    - Based on QoS, channel conditions, previous throughput, fairness, etc.
- Adaptive multi-rate transmissions

Idea of Multirate Transmission (1)



Use GMSK with coding

Use 8-PSK, no coding

Use 8-PSK, with coding
or GMSK no coding

Idea of Multirate Transmissions (2)

- **Combine channels** where possible
- Example 1: GPRS
  - Reserve more than one time slot for a single user
  - Combine channels in time
- Example 2: IS-95/cdmaOne/HSPA
  - Supplementary channels
  - Combine channels in code
- Example 3: IEEE 802.11n
  - Use two 20 MHz channels instead of one
  - Combine channels in frequency (also in LTE)

Multirate parameters

- Symbol duration = T
- Modulation level = M
- Code rate = r
- Combining “channels”
- What is the “useful” data rate?
- Tradeoffs

Link Adaptation in EDGE

- This is an example of waveform assignment (RRM)
  - Depending on the channel quality, you assign a different modulation/coding scheme to the MS
  - Need to regularly estimate the link quality and signal this information
- The protocols, algorithms and mechanisms to do this fall under RRM
  - Example – incremental redundancy
    - Send information with little coding initially
    - If successful, high bit rates are achieved
    - If unsuccessful, decrease the coding rate till it is successful

Medium Access in HSPA

- Problem
  - ARQ between mobile and RNC incurs delays
  - ACKs/NACKs are at the RLC layer
- Solution
  - Do the scheduling and ARQ between mobile and Node-B
  - ARQ at Layer 1
    - Hybrid ARQ to improve success rate

- Hybrid ARQ
  - Combines erroneous frames with retransmitted frames to achieve **diversity**
- Fast scheduling
  - Instead of signaling from the RNC, a Node-B is allowed to make decisions on the **maximum data rates** that a MS can use to transmit packet data
  - Uses adaptive multi-rate transmission

Similar ideas were adopted in LTE

Link Adaptation in LTE

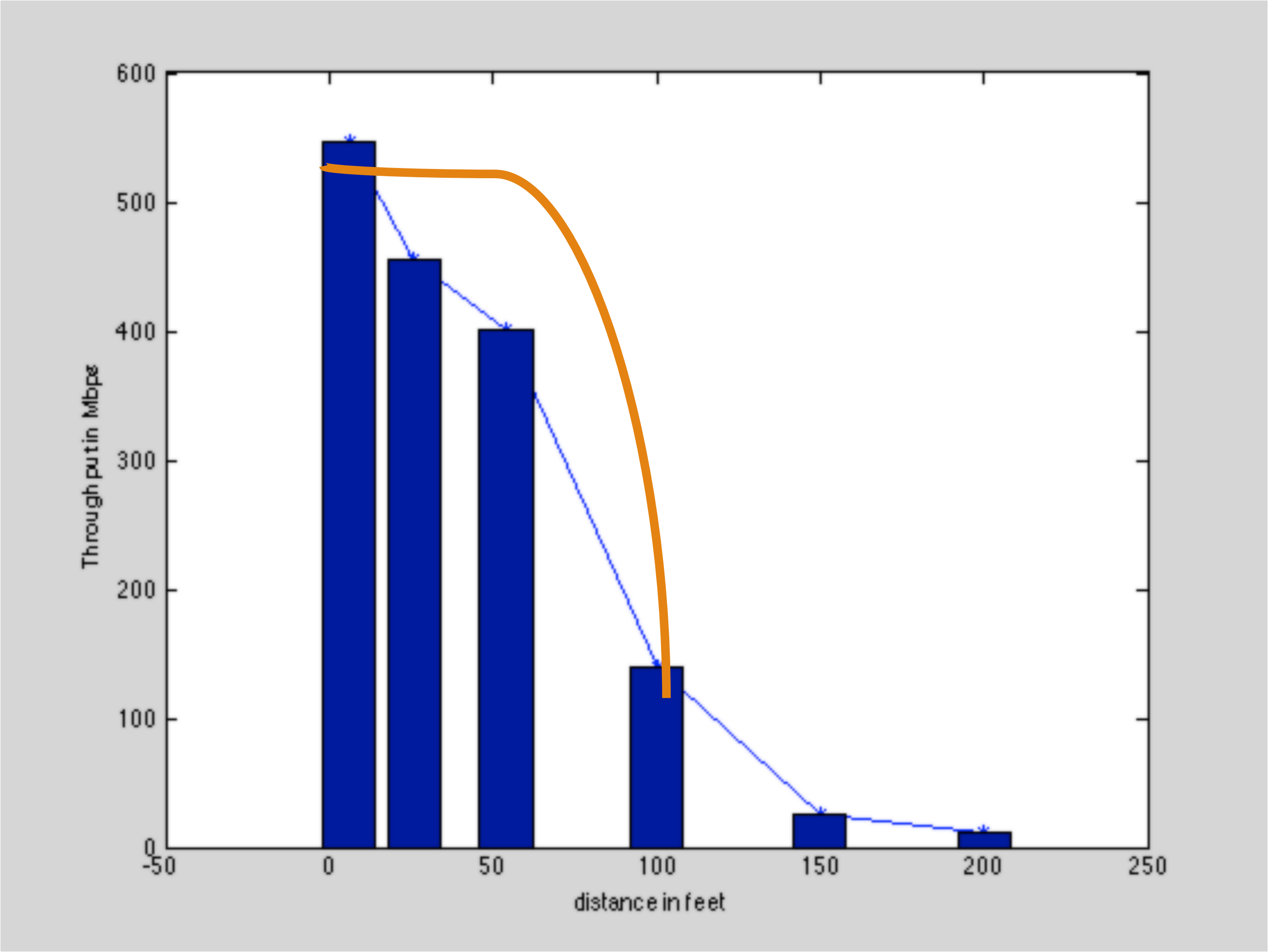
- Uses a “channel quality indicator” or CQI
- Sent by a mobile on an uplink control channel for periodic or aperiodic reporting of CQI
- CQI values can be for
  - Entire system bandwidth
  - Mobile picks a subset of the bandwidth
  - eNode-B picks a subset of the bandwidth

CQI Index	Modulation Scheme	Code Rate
1	QPSK	0.076
4	QPSK	0.3
8	16-QAM	0.48
11	64-QAM	0.55
15	64-QAM	0.93

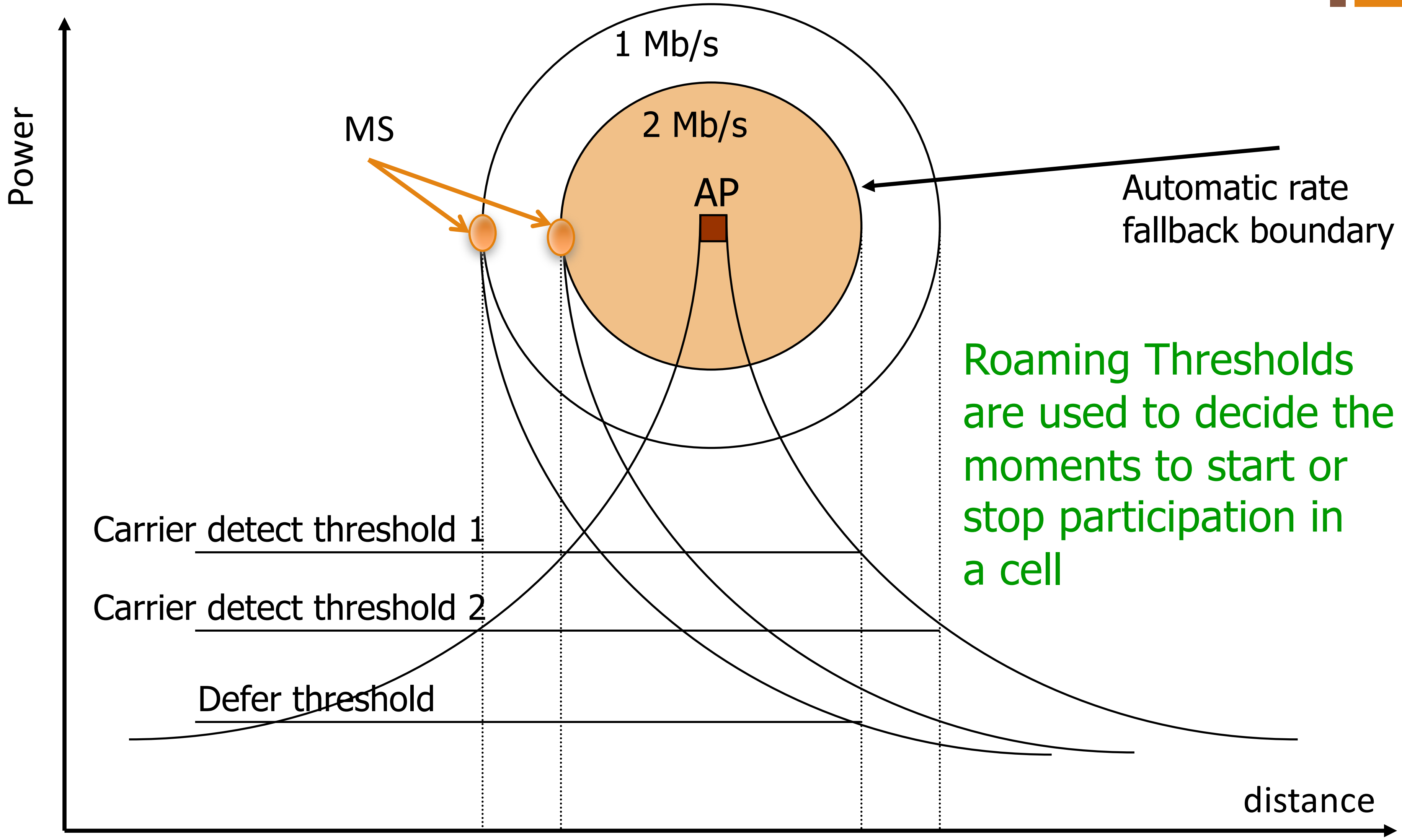
Sample adaptive transmission rates in LTE and their mapping to CQI values

Mobile uses block error rate thresholds to determine the CQI

WiFi Fact or Fiction Article



Power Thresholds in WLANs: Example



Roaming Thresholds are used to decide the moments to start or stop participation in a cell

802.11a,g

- OFDM: Each sub-carrier uses same modulation
- There are 48 sub-carriers for data and 4 used as pilots

Data rate	Modulation	FEC Coding Rate	Data bits per channel symbol
6 Mbps	BPSK	1/2	24
9 Mbps	BPSK	3/4	36
12 Mbps	QPSK	1/2	48
18 Mbps	QPSK	3/4	72
24 Mbps	16QAM	1/2	96
36 Mbps	16QAM	3/4	144
48 Mbps	64QAM	2/3	192
54 Mbps	64QAM	3/4	216

OFDM Symbol in 802.11a/g

- One OFDM symbol (consisting of the sum of the symbols on all carriers) lasts for 4 microseconds
- Symbol carries anywhere between 48 and 288 coded bits.
- Example:
  - At 54 Mbps, the OFDM symbol has 216 bits
    - Data rate = $216/(4 \times 10^{-6}) = 54$ Mbps
  - With a code rate of 3/4, the number of coded bits/symbol will be $4 \times 216/3 = 288$
    - 6 bits × 48 sub-carriers= 288 bits

See http://en.wikipedia.org/wiki/IEEE_802.11n-2009 for 802.11n

802.11n

- Approved a few years back- works in 2.4 and 5 GHz bands
  - 4 to 5 times the data rates of 802.11a,g → 200-300Mbps
- Main Changes
  - Physical layer uses Multiple Input Multiple Output (MIMO) OFDM
    - Has multiple antennas at each end of the channel – provides spatial diversity
    - OFDM part about the same as 802.11a,g – uses 64QAM with 5/6 FEC rate
  - Channel Bonding
    - Combines 2 of the 20MHz 802.11a,g channels to achieve higher data rates
  - Packet Aggregation
    - Reduce overhead by aggregating multiple packets from a single application/user into a common frame

Carrier Sensing

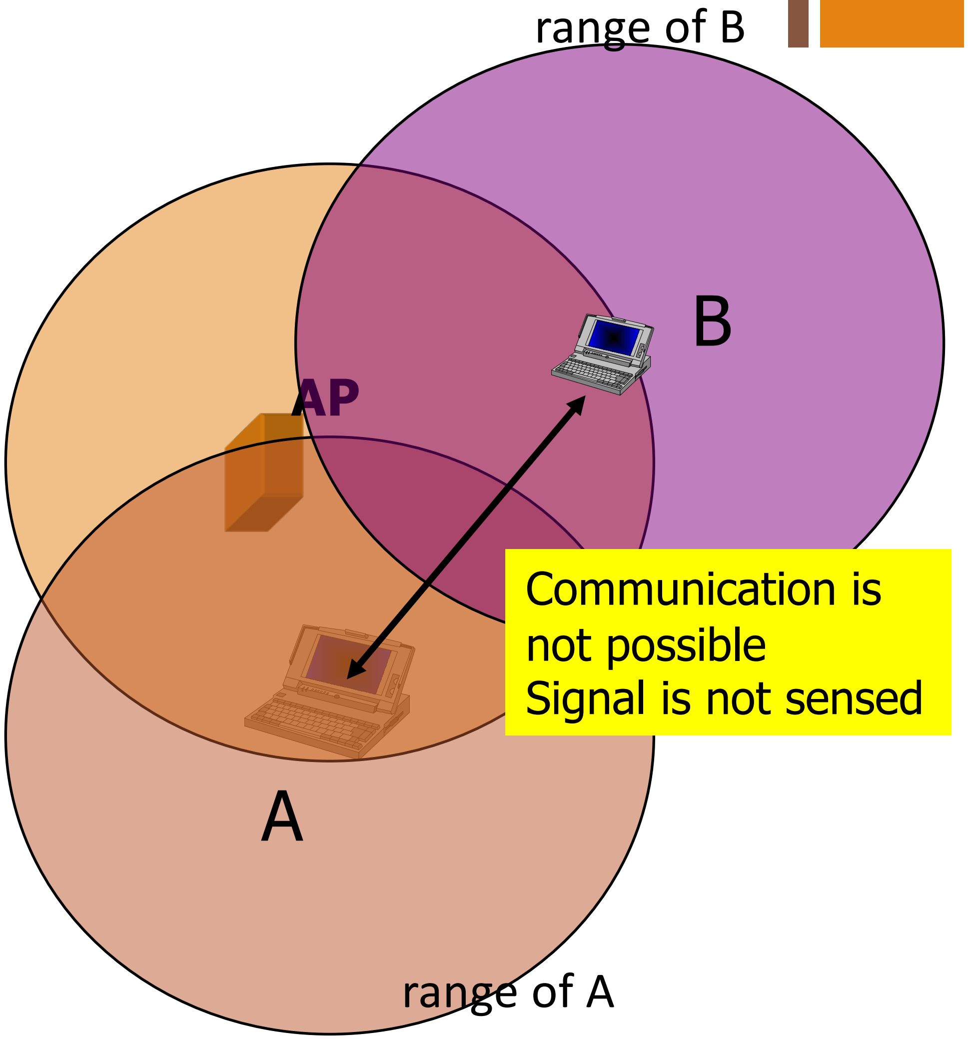
- Carrier sensing
  - It is an improvement of ALOHA (no carrier sensing in ALOHA)
  - Depending on the protocol a variety of CSMA protocols exist
    - Non-persistent
    - *p*-persistent
    - Binary exponential back-off
  - Collision detection Vs Collision avoidance
- Most random access protocols are based on some form of carrier sensing!

Problems with carrier sensing

- The signal strength is a function of distance and location
  - Path loss and shadow fading
  - Not all terminals at the same distance from a transmitter can “hear” the transmitter and vice versa
- The hidden node problem
- The exposed node problem
- Capture

The Hidden Terminal Problem

- A MS that is within the range of the destination but out of range of a transmitter
- MS A transmits to the AP
- MS B cannot sense the signal
    - MS B may also transmit resulting in collisions
    - MS B is called a "hidden terminal" with respect to MS A



Communication is not possible
Signal is not sensed

Mechanisms for overcoming collisions due to hidden terminals

- Busy-tone multiple access (BTMA)
  - Out of band signaling scheme
  - Any node that hears a transmission will transmit a busy tone in an out of band channel
- Control handshaking
  - Use a three-way handshake like RS-232
  - Terminal A sends a short request-to-send (RTS) packet to the AP
  - The AP sends a short clear-to-send (CTS) packet that is received by Terminal A AND Terminal B
  - Terminal B defers to terminal A

Exposed Terminal Problem

- Reverse of hidden terminals
- The exposed terminal is in the range of the transmitter but outside the range of the destination
- Terminals may unnecessarily backoff
  - Low utilization of bandwidth
- Solutions
  - Proper frequency planning
  - Intelligent thresholds for carrier sensing

Capture

- Capture
  - A receiver can “cleanly” receive a signal from one of many simultaneous transmissions

- Suppose MS-A, MS-B and MS-3 all simultaneously transmit to an AP with the same transmit power
  - MS-A is the closest and its signal is received with a larger strength obscuring the transmissions from MS-B and MS-C
  - The AP is said to have “captured” the signal from MS-A
  - Common in FM or FSK transmissions but not a big problem in other systems

- Capture improves the throughput

- Capture results in unfair sharing of bandwidth
  - Need protocols to ensure fairness

Problems with Collision Detection

- Collision detection is easier at baseband than at RF frequencies
  - Receive and transmit frequencies are the same
    - There is a significant leakage of the transmitted signal onto the receiver antenna – “self interference”
    - Transmitting and receiving at the same time is very hard
  - Receive and transmit frequencies are different
    - Circuitry cost and power consumption become prohibitive for collision detection by a MS
  - Transmissions from ground level can be detected at a tower but not at the ground level
  - Collision results in a significant shift in voltage that is detected – fades could obscure this shift

Collision avoidance mechanisms

- Waiting times before transmission
  - If the MS finds the channel idle, it still waits for a fixed amount of time before transmitting
- Random backoff upon detecting a busy channel
  - Randomness reduces the chance of two MSs transmitting at the same time
- Contention resolution mechanisms
  - Use windows where a MS asserts itself or yields to other MS based on several different protocols
  - Randomly addressed polling (uses CDMA)
- Idle sensing at the BS/AP
  - If the uplink and downlink transmissions are separated in frequency, the busy nature of the uplink is communicated to the MSs by the BS/AP

The IEEE 802.11 MAC Layer

- IEEE 802.11 is based on Carrier Sense Multiple Access with Collision Avoidance: CSMA/CA
- Mandatory access mechanism is “asynchronous” based on CSMA/CA and is provided by what is called the Distributed Coordination Function (DCF)
- Optional access mechanism for “time bounded” service is based on polling and is provided by what is called a Point Coordination Function (PCF)

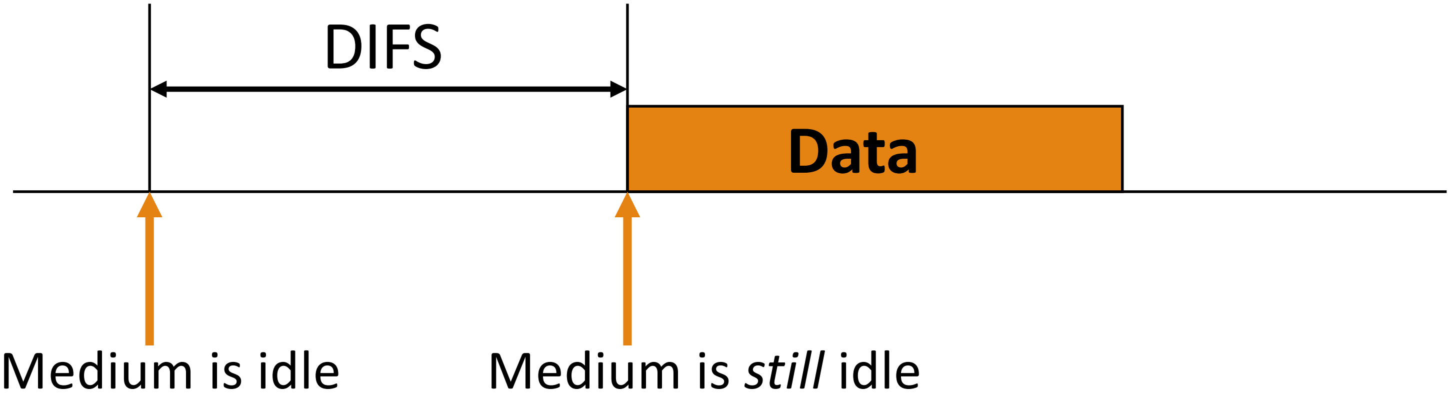
Physical and Virtual Carrier Sensing

- The physical layer performs a “real” sensing of the air interface to determine if a medium is busy or idle
    - Analyzes detected packets
    - Detects carrier otherwise by RSS

- The MAC layer performs a “virtual” carrier sensing
    - The “length” field is used to set a network allocation vector (NAV)
    - The NAV indicates the amount of time that must elapse before the medium can be expected to be free again
    - The channel will be sampled only after this time elapses (why?)

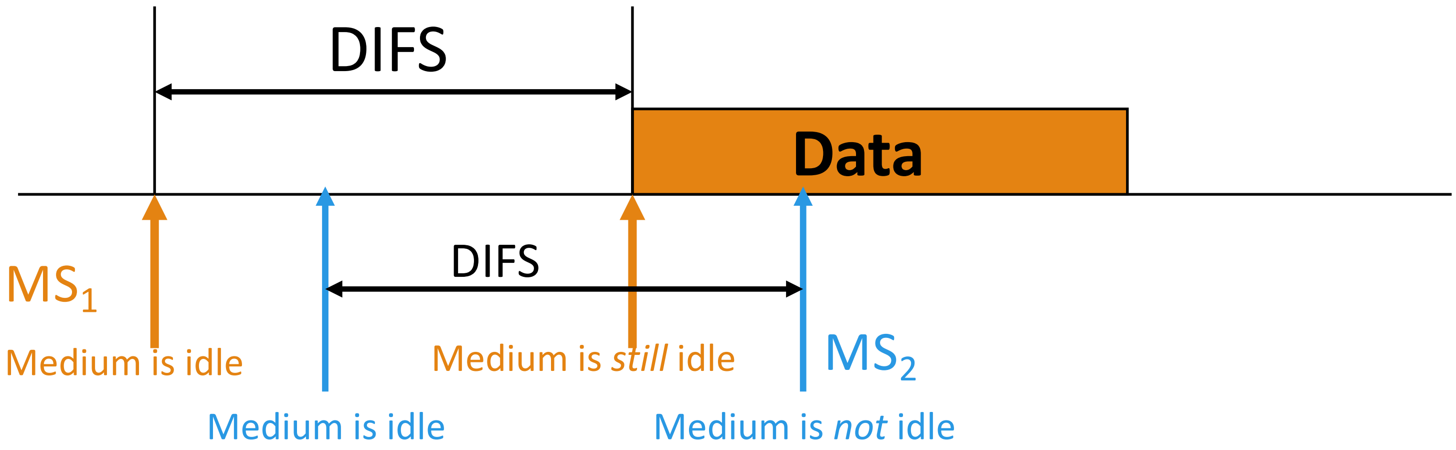
- The channel is marked busy if either of the physical or virtual carrier sensing mechanisms indicate that the medium is busy

Idle Channel



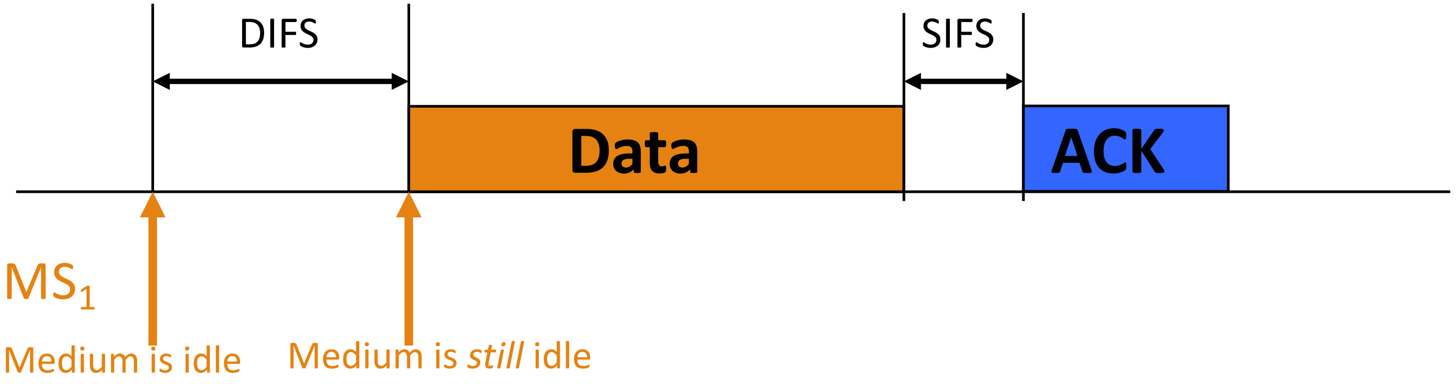
- If the medium is idle, every MS has to wait for a period DIFS (DCF inter-frame spacing) to send DATA
- After waiting for DIFS, if the medium is still idle, the MS can transmit its data frame

How does it help?



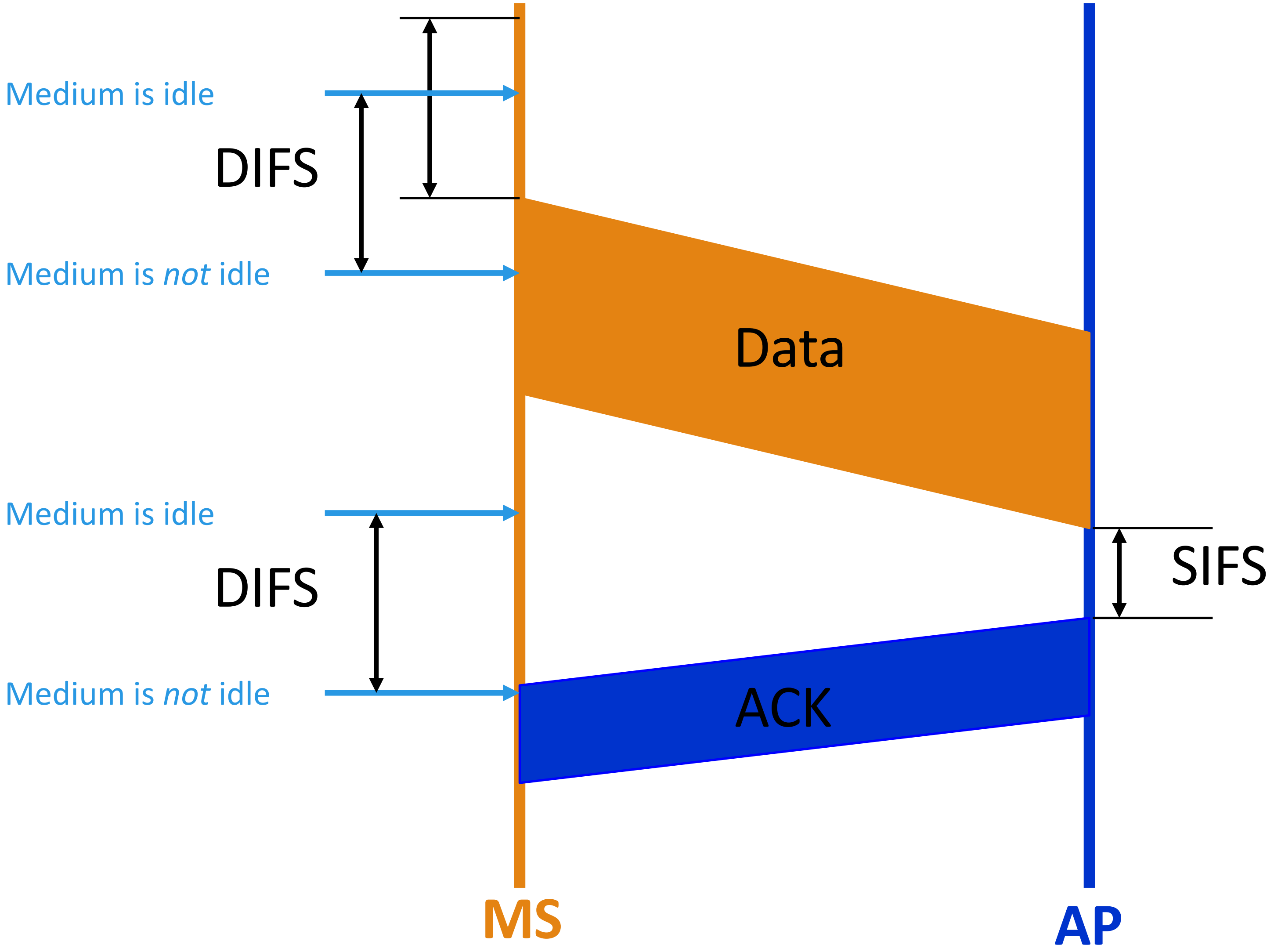
- If a second MS senses the medium to be idle after the first MS, it will find the medium to be busy after DIFS
- It will not transmit => collision is avoided

Acknowledgements

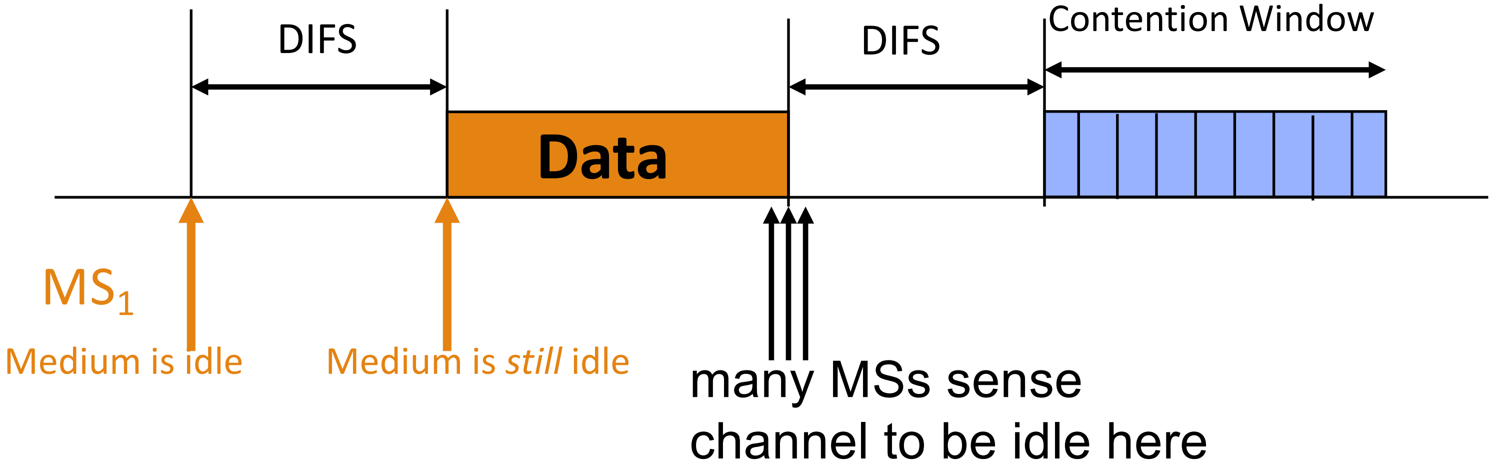


- A short inter-frame spacing (SIFS) is used
  - SIFS is the absolute minimum duration that any MS should wait before transmitting anything
- It is used ONLY for acknowledgements (which will be sent by a receiving MS or AP alone)
- ACKs receive highest priority!
- ACKs will almost always be sent on time

Data Transmission and ACKs

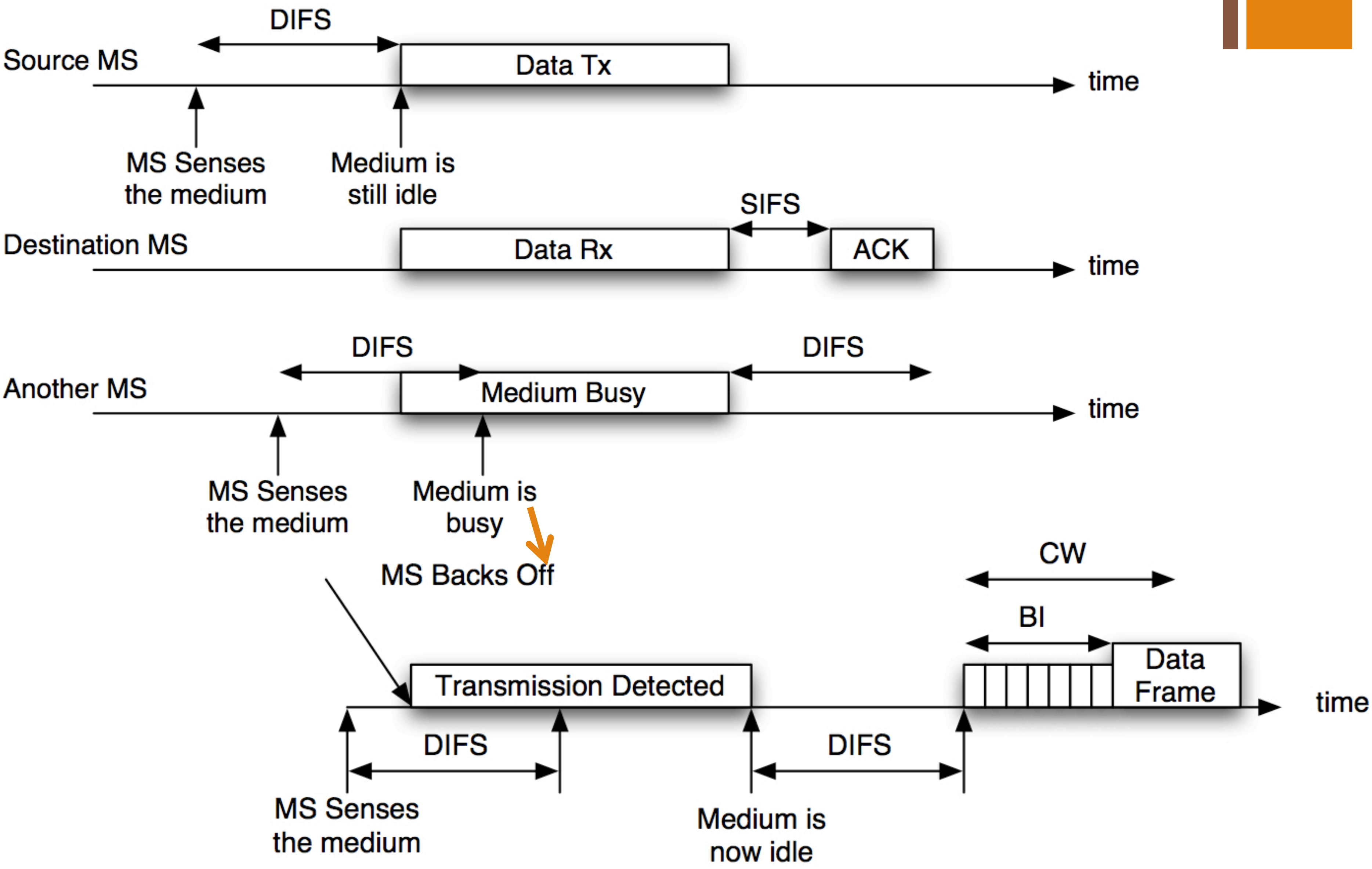


Busy Channel



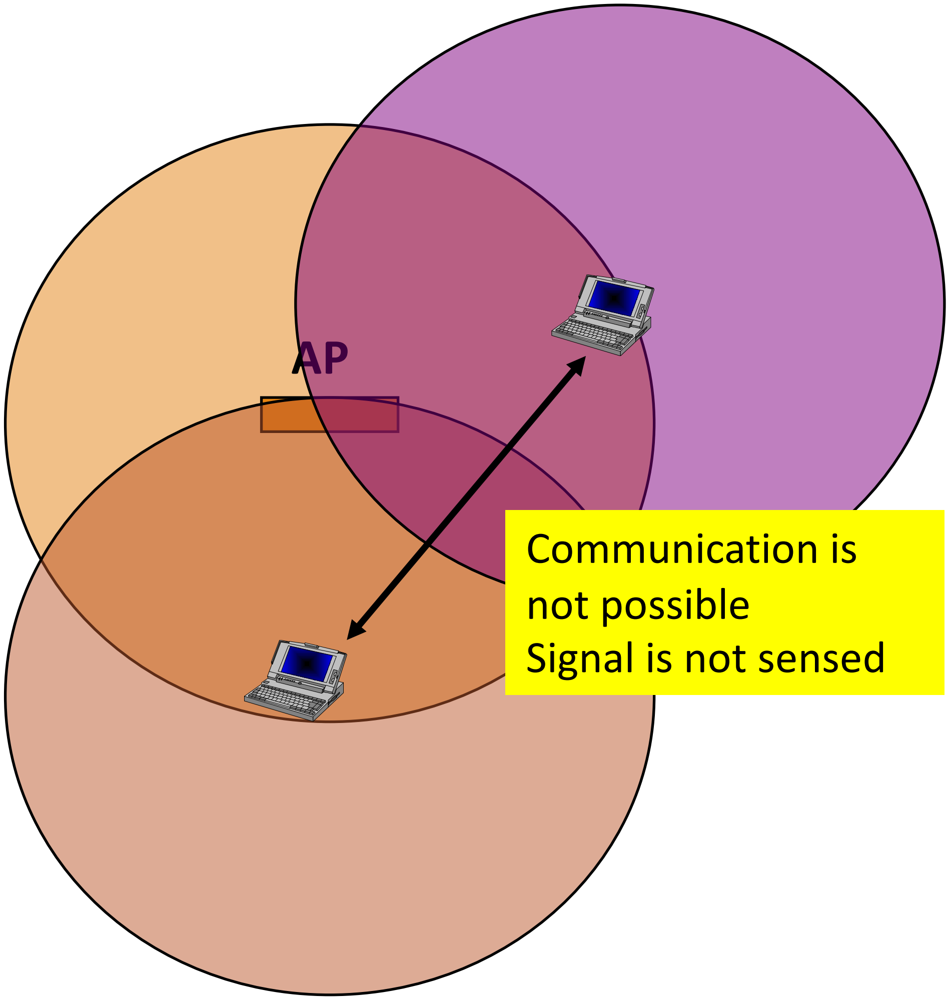
- Each MS has to still wait for a period of DIFS
- Each MS chooses a random time of back-off within a contention window
- Each MS decrements the back-off. Once the back-off value becomes zero, if the medium is idle, the MS can transmit
- The MS with the smallest back-off time will get to transmit
- All other MSs freeze their back-off timers that are "decremented" and start decrementing the timer in the next contention window from that point

Summary


DIFS
Source MS
Data Tx
time
MS Senses the medium
Medium is still idle
SIFS
Destination MS
Data Rx
ACK
time
DIFS
DIFS
Another MS
Medium Busy
time
MS Senses the medium
Medium is busy
MS Backs Off
CW
BI
Transmission Detected
Data Frame
time
DIFS
DIFS
MS Senses the medium
Medium is now idle

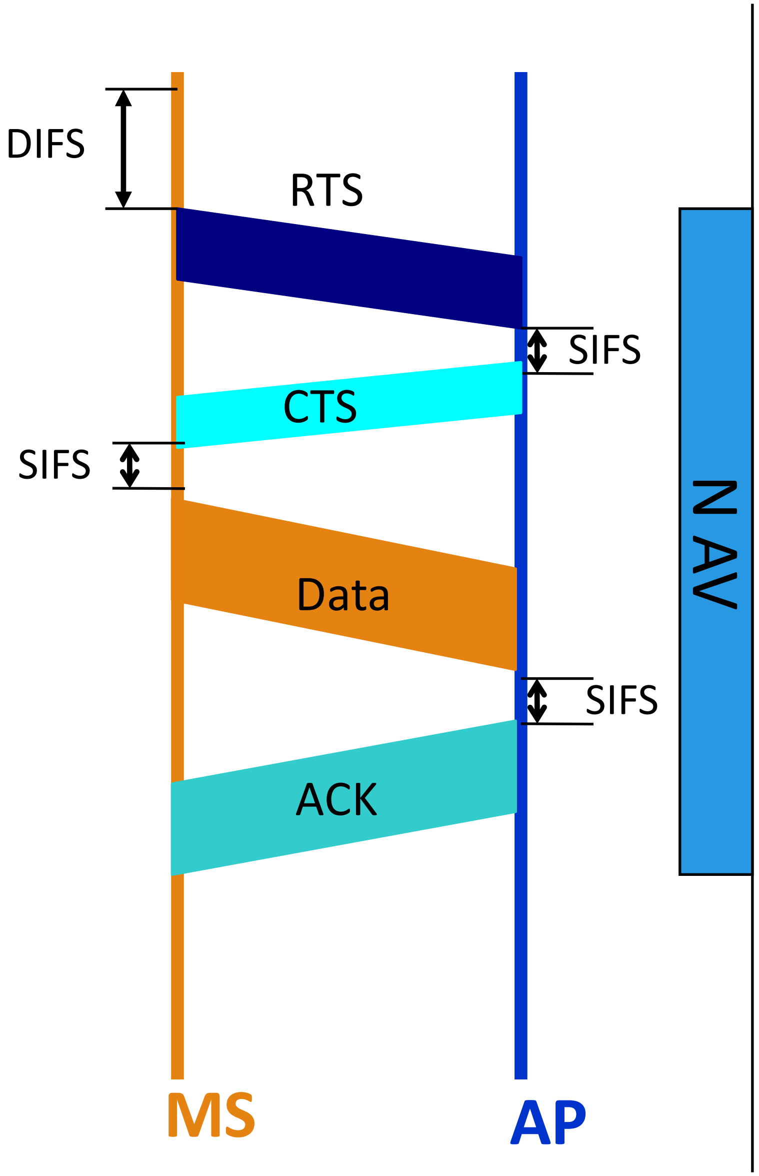
When do collisions occur?

- MSs have the same value of the back-off timer
- MSs are not able to hear each other because of the “hidden terminal” effect
- MSs are not able to hear each other because of fading
- Solution: RTS/CTS
  - Also avoids excessive collision time due to long packets



Communication is not possible
Signal is not sensed

RTS/CTS Mechanism



- RTS-Request to Send (20 bytes)
- CTS-Clear to Send (14 bytes)
- They can be used only prior to transmitting data
- After successful contention for the channel, a MS can send an RTS to the AP
- It gets a CTS in reply after SIFS
- CTS is received by all MSs in the BSS
- They defer to the addressed MS while it transfers data
- If there is a collision, no CTS is received and there is contention again

Large Frames

- Large frames that need fragmentation are transmitted sequentially without new contention
- The channel is automatically reserved till the entire frame is transmitted
- The sequence of events is:
  - Wait for DIFS & CW; Get access to channel OR use RTS/CTS
  - Send first fragment; include number of fragments in the field
    - All other MSs update their NAV based on the number of fragments
    - ACK is received after SIFS
    - The next fragment is transmitted after SIFS
  - If no ACK is received, a fresh contention period is started
- RTS/CTS, if used, is employed only for the first fragment

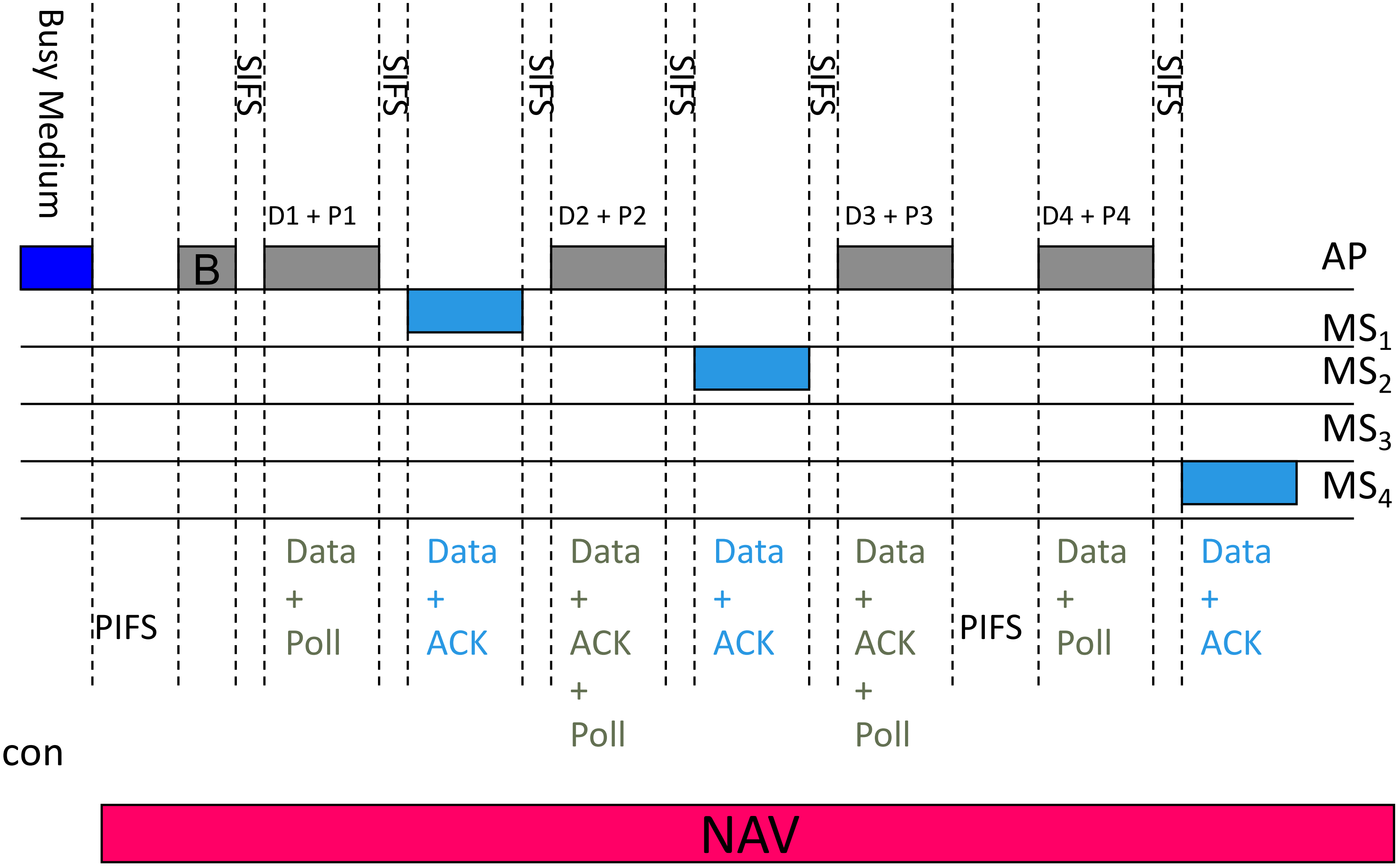
Taking turns protocols

- Token ring or bus
  - Infeasible for wireless networks
    - Errors and self configuration
  - Not widely studied except for IR systems
- Polling
  - A centralized authority polls each MS for data and the MS can respond to the poll if it has anything to transmit
  - If the MS has nothing to transmit or it is inactive, the polling scheme consumes bandwidth unnecessarily
- Can guarantee delays and throughput unlike random access schemes
- Example systems
  - PCF in IEEE 802.11
  - Bluetooth

Point Coordination Function (PCF) in IEEE 802.11

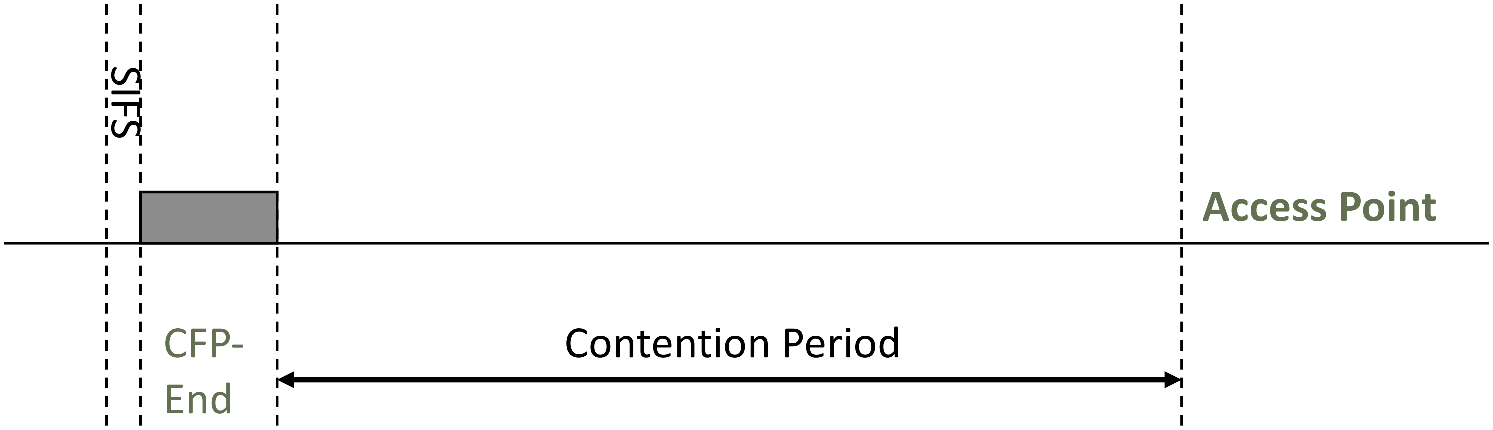
- Optional capability to provide “time-bounded” services
- It sits on top of DCF and needs DCF in order to successfully operate
- A point coordinator (the AP)
    - Maintains a list of MSs that should be polled
    - Polls each station and enables them to transmit without contention
    - Ad hoc networks cannot use this function (why?)
- Time (a superframe) is divided into two parts
    - Contention Free Period (CFP)
    - Contention Period (CP)
- A MS must be CFP-aware to access the CFP
- Replies to polling can occur after SIFS

PCF Continued



B = Beacon

PCF Continued



- The CFP is dynamically variable
- A MS can transmit to another MS within the CFP
  - In such a case, an ACK from the receiver is given priority over the next polling message
- The AP could transmit data to a non CF-aware MS
  - In such a case, once again, an ACK from the receiver is given priority

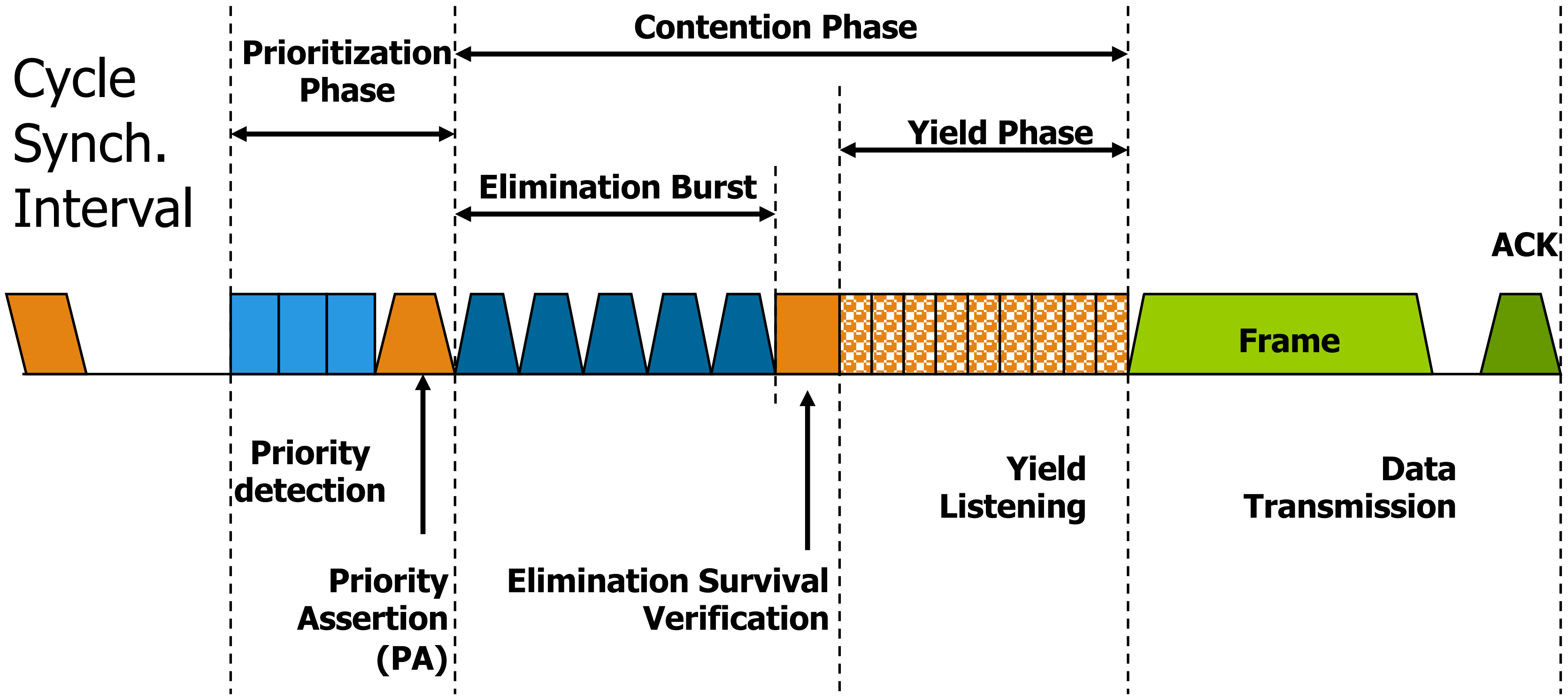
The HIPERLAN/1 MAC Protocol

- It is based on carrier sensing, but of a type unlike IEEE 802.3 or IEEE 802.11
- It is called EY-NPMA: Elimination Yield Non-preemptive Priority Multiple Access
- The idea is to make the probability of a “single” transmission at the end of the contention cycle as close to 1 as possible.

The MAC Protocol Continued

- If a MS senses a medium to be free for at least 1700 bit durations, immediate transmission is allowed
  - Each data frame MUST be acknowledged by an ACK
- Otherwise, the MS goes through two phases once the medium becomes idle:
  - Prioritization
  - Contention
    - Elimination
    - Yield

Channel Access Cycle in HIPERLAN



Prioritization

- Determine the highest priority of a data to be sent by competing MSs
- Allow only those stations with high priority frames to contend for the channel
- Data packets have several types of priorities
- A node with priority p will listen to p-1 time slots (usually 1 to 5 slots of 256 bits each)
  - If the medium is idle after the (p-1)-st slot, the MS will send a burst of 256 bits asserting its priority
  - If the medium becomes busy with a burst any time before, the MS will defer to the next transmission cycle
- Many MSs may have the same priority, but the ones with low priority are eliminated from contention

+ Contention (Elimination)

- Slots of size 256 bits are defined
- Randomly, MSs select the number of slots for which they will send a burst continously
- The maximum number of slots is 12
- The probability of the burst being “n” slots is (p is usually 0.5)
  - $p^n (1-p)$ for $n < 12$
  - p^n for $n = 12$
- After sending a burst, a MS listens to the channel for 256 bit durations (elimination survival verification interval)
- If it hears a burst in this period, it eliminates itself

+

Contention (Yield)

- The remaining MSs have a random yield period
- Each MS will “listen” to the channel for the duration of its yield period which is geometrically distributed
  - Prob (listening to n slots) = $0.9^n\ 0.1$ for $n < 14$ and 0.9^{14} for $n=14$
- If a MS senses the channel to be idle for the entire yield period, it has survived <whew!!>
- It will start transmitting data and will automatically eliminate other MSs that are listening to the channel

Summary

- If simplicity demands a decentralized medium access protocol, CSMA or any of its variants is preferred
- CSMA in wireless networks leads to the hidden terminal, exposed terminal and sometimes the capture problem
- Collision detection in wireless networks is extremely difficult
- Systems that use CSMA are
  - CDPD
  - IEEE 802.11
  - HIPERLAN/1