# Wireless networks & IEEE 802.11

Mobile and Cyber Physical Systems

# Overview

Wireless networks basics

Wireless networks architectures

IEEE 802.11 (Wi-Fi) a/b/g/n/…

# Why Wireless Networks?

1. Cables in computers to:
   - communicate
   - provide power
2. Cyber-physical systems embed computers in (any kind of) physical objects
   - Cyber-physical systems integrate sensing, computation, control and networking into physical objects and infrastructure, connecting them to the Internet and to each other.
   - can’t wire everything…

Hence:

- wireless to replace cables in communications…
- … & batteries to replace cables in power supply

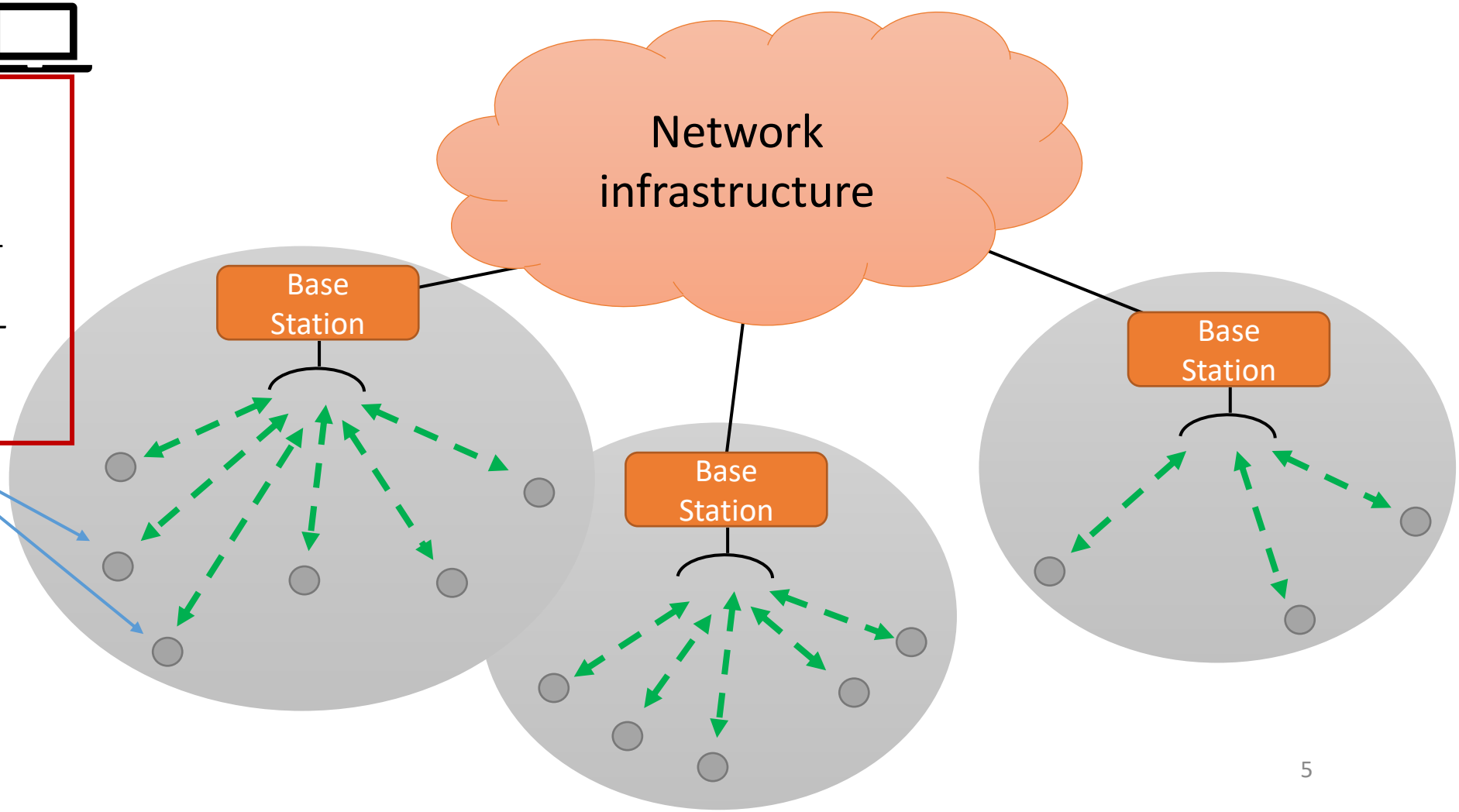
# Wireless Networks

- Networks of **hosts** connected by **wireless links**
- Hosts: end-system devices that run applications
  - often mobile, but not necessarily
  - battery-powered (typically)
  - e.g. smartphone, tablet, sensor, home appliance, vehicle, etc…
- Two modes of operations:
  - **Infrastructure**
    - with base station(s) or
    - with wired access points
  - **ad hoc networking**
    - no centralized coordinators

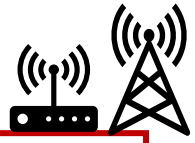
# Elements of a Wireless network (I)

## Wireless hosts

- LAPTOPS, SMARTPHONES
- RUN APPLICATIONS
- MAY BE STATIONARY (NON-MOBILE) OR MOBILE
- WIRELESS DOES *NOT ALWAYS* MEAN MOBILITY

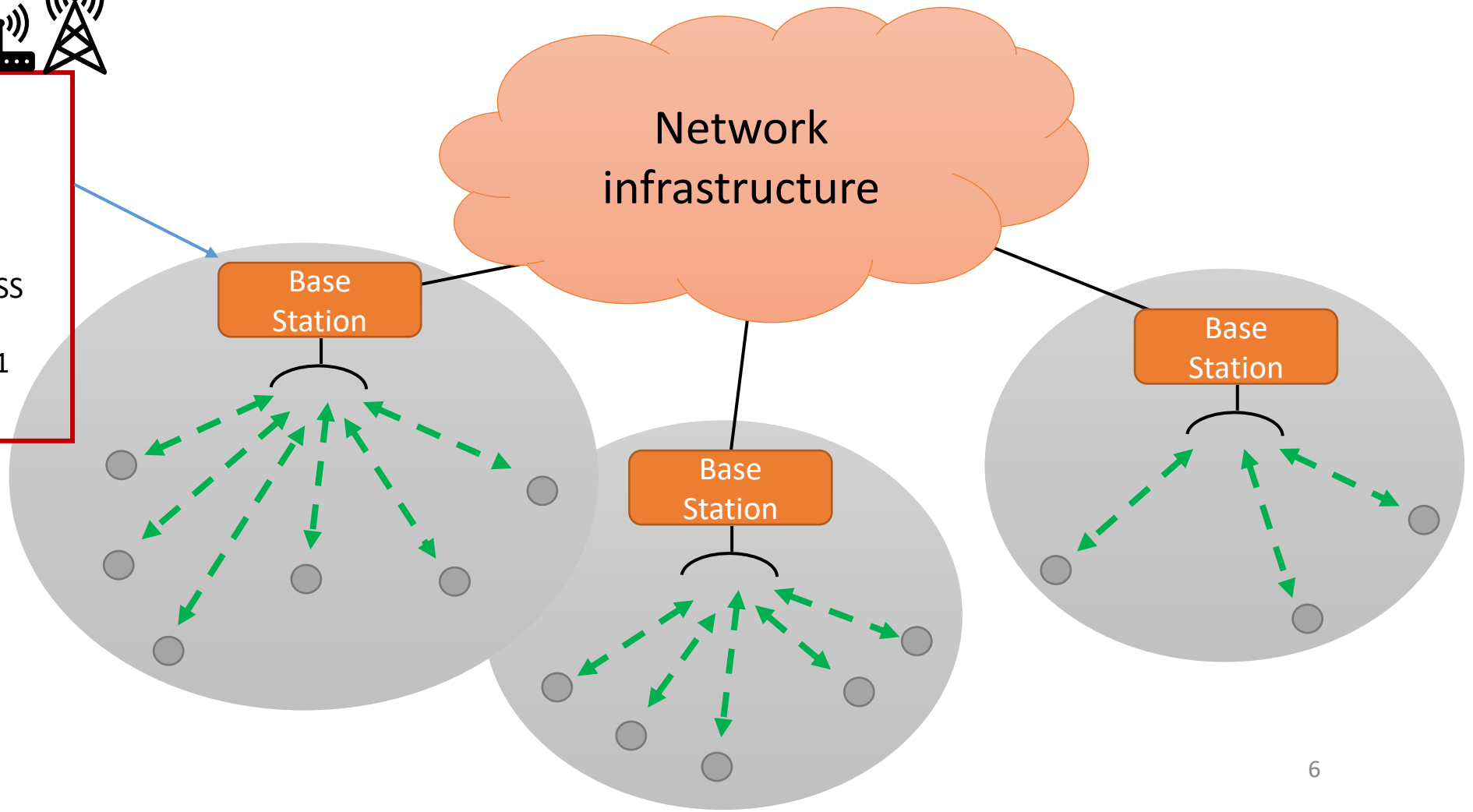


# Elements of a Wireless network (II)



## Base station

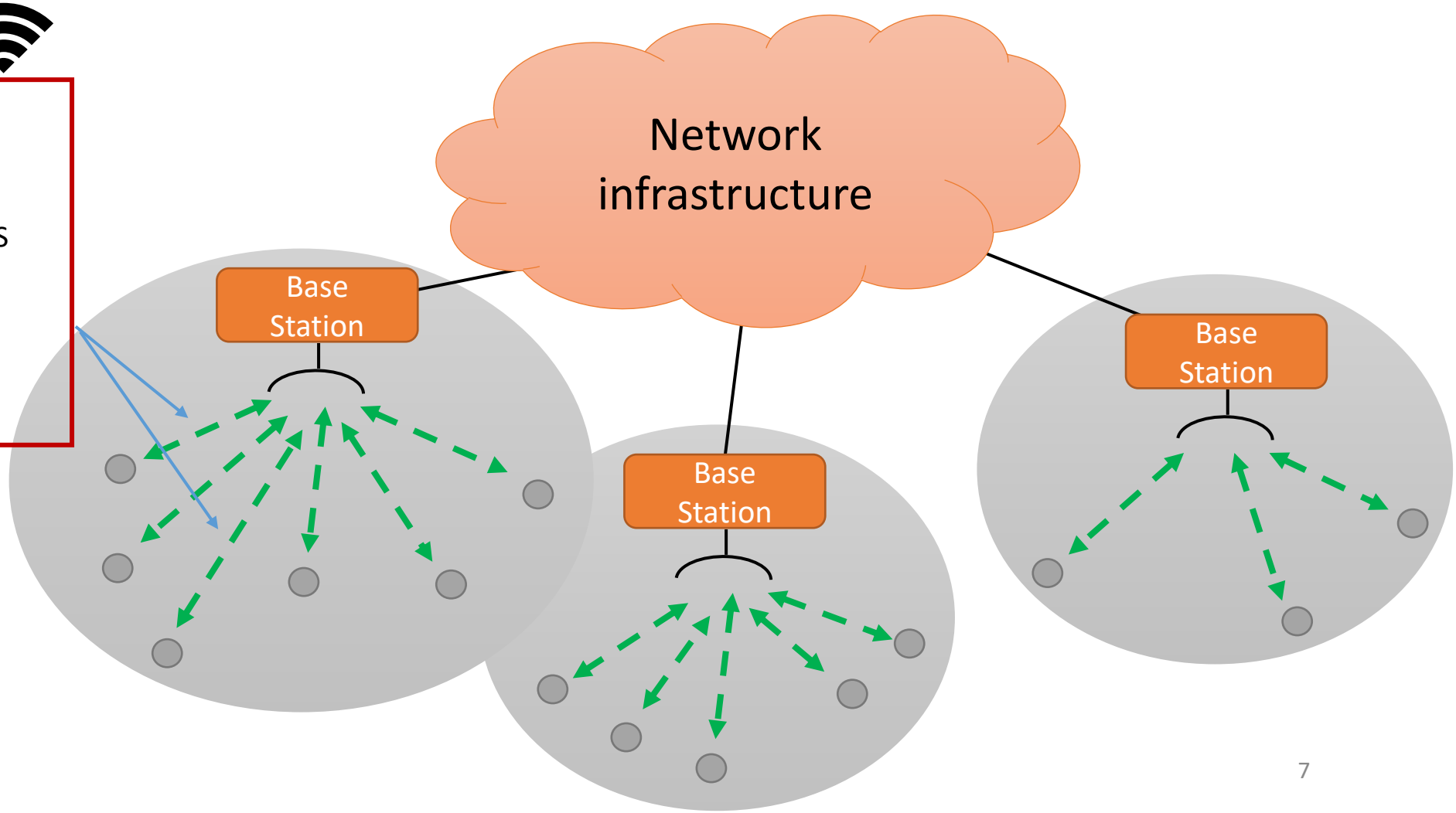
- TYPICALLY CONNECTED TO A WIRED NETWORK
- RELAY - RESPONSIBLE FOR SENDING PACKETS BETWEEN WIRED NETWORK AND WIRELESS HOST(S) IN ITS "AREA"
- E.G., CELL TOWERS, IEEE 802.11 ACCESS POINTS



# Elements of a Wireless network (III)

## Wireless links

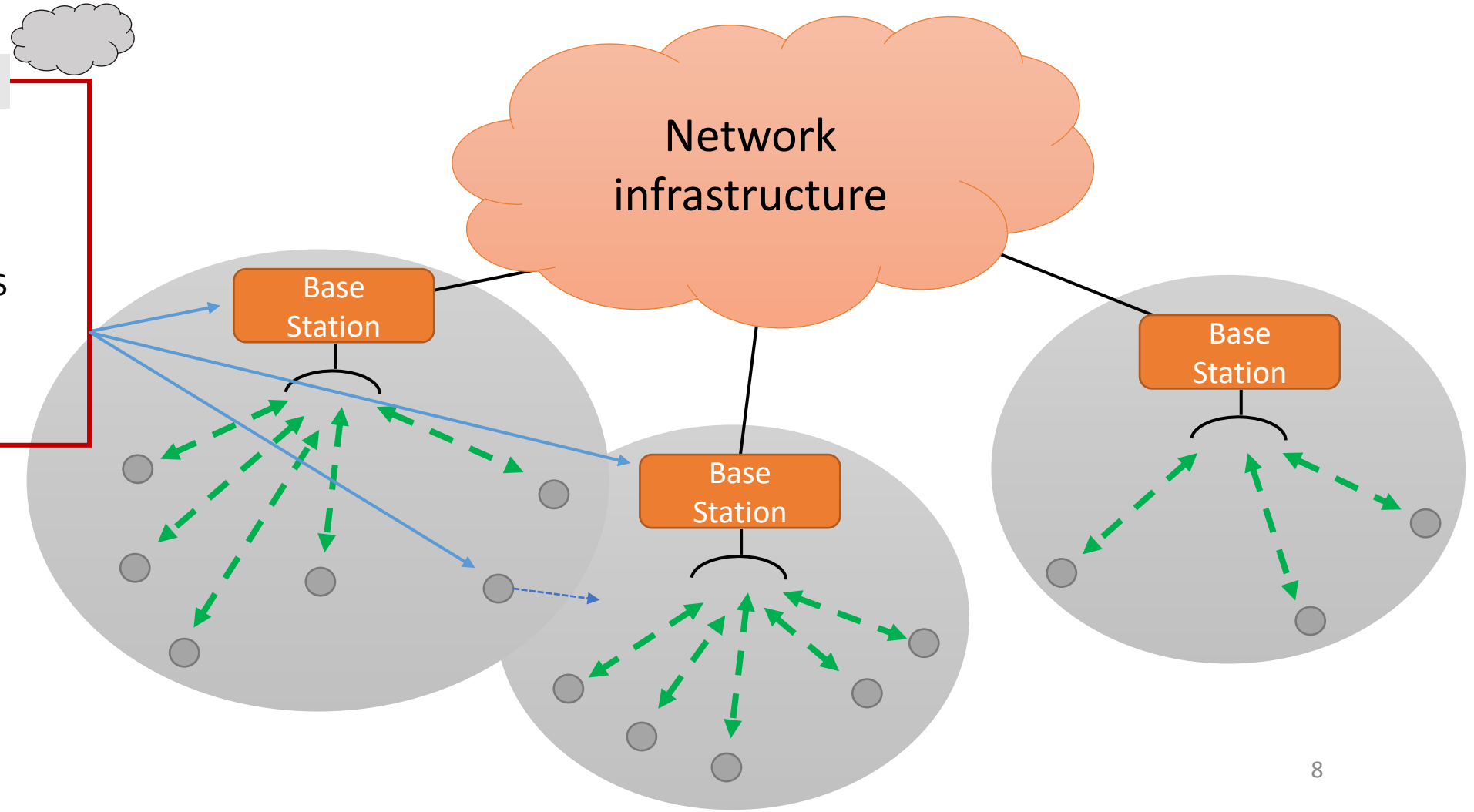
- CONNECT MOBILE(S) TO BASE STATION
- ALSO USED AS BACKBONE LINKS
- MULTIPLE ACCESS PROTOCOL COORDINATES LINK ACCESS
- VARIOUS DATA RATES, TRANSMISSION RANGE,…



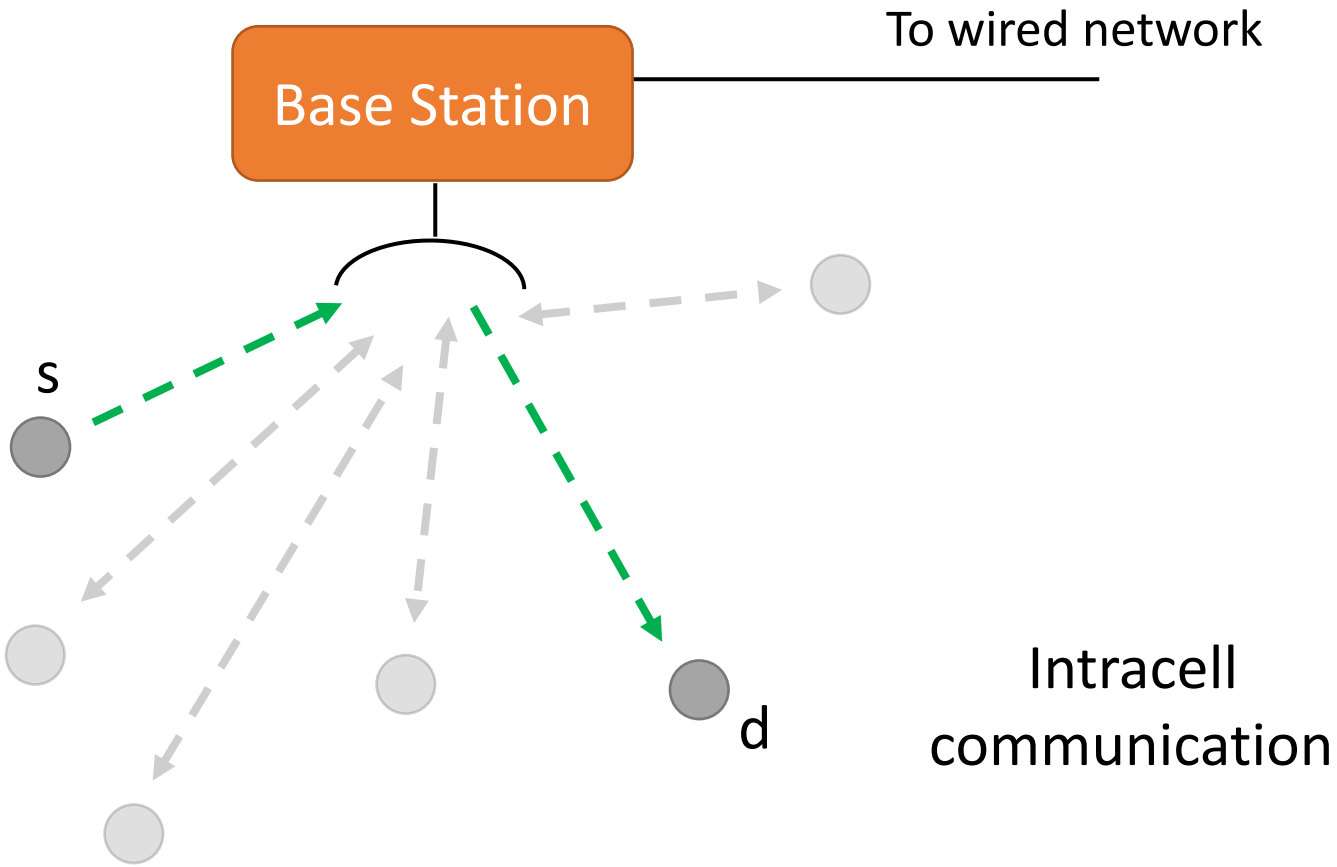
# Elements of a Wireless network (IV)

## Infrastructure mode

- BASE STATION CONNECTS MOBILES INTO WIRED NETWORK
- HANDOFF: MOBILE CHANGES BASE STATION PROVIDING CONNECTION INTO WIRED NETWORK

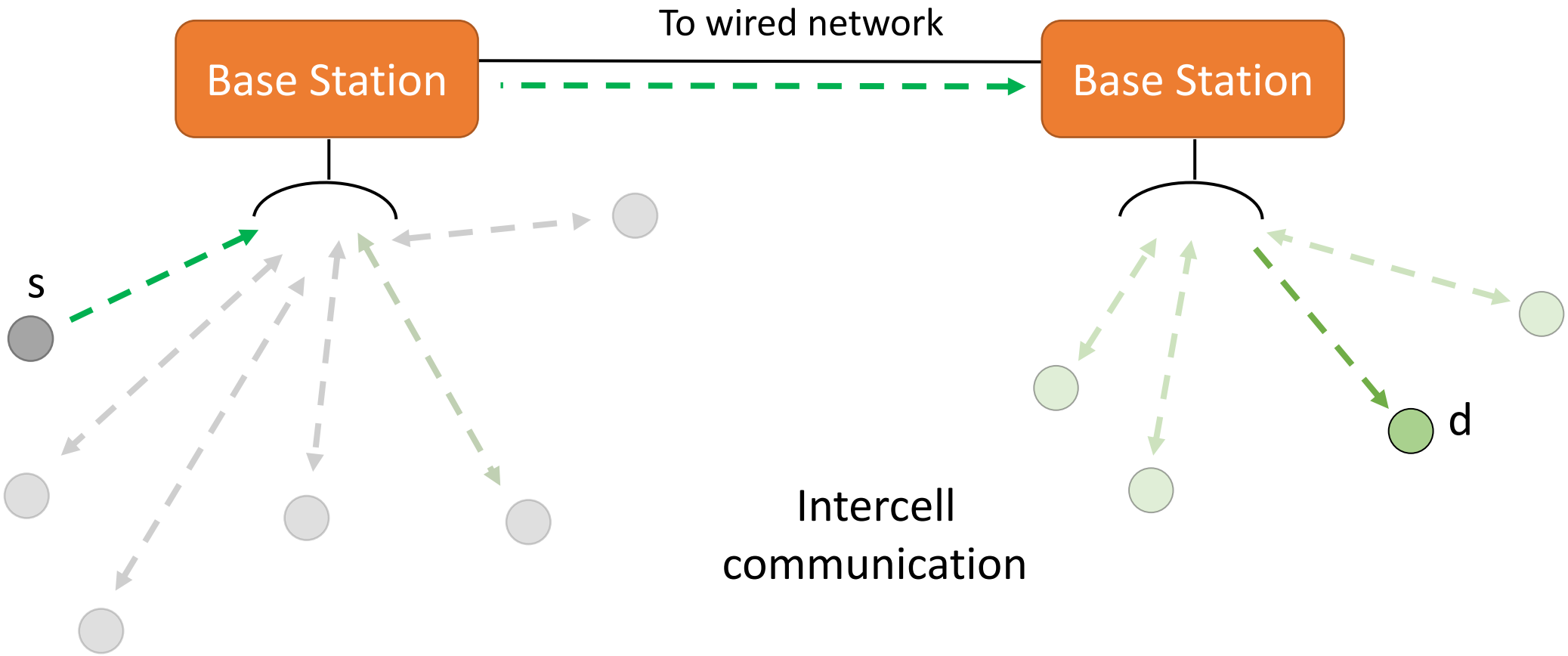


# Elements of a Wireless network (V)

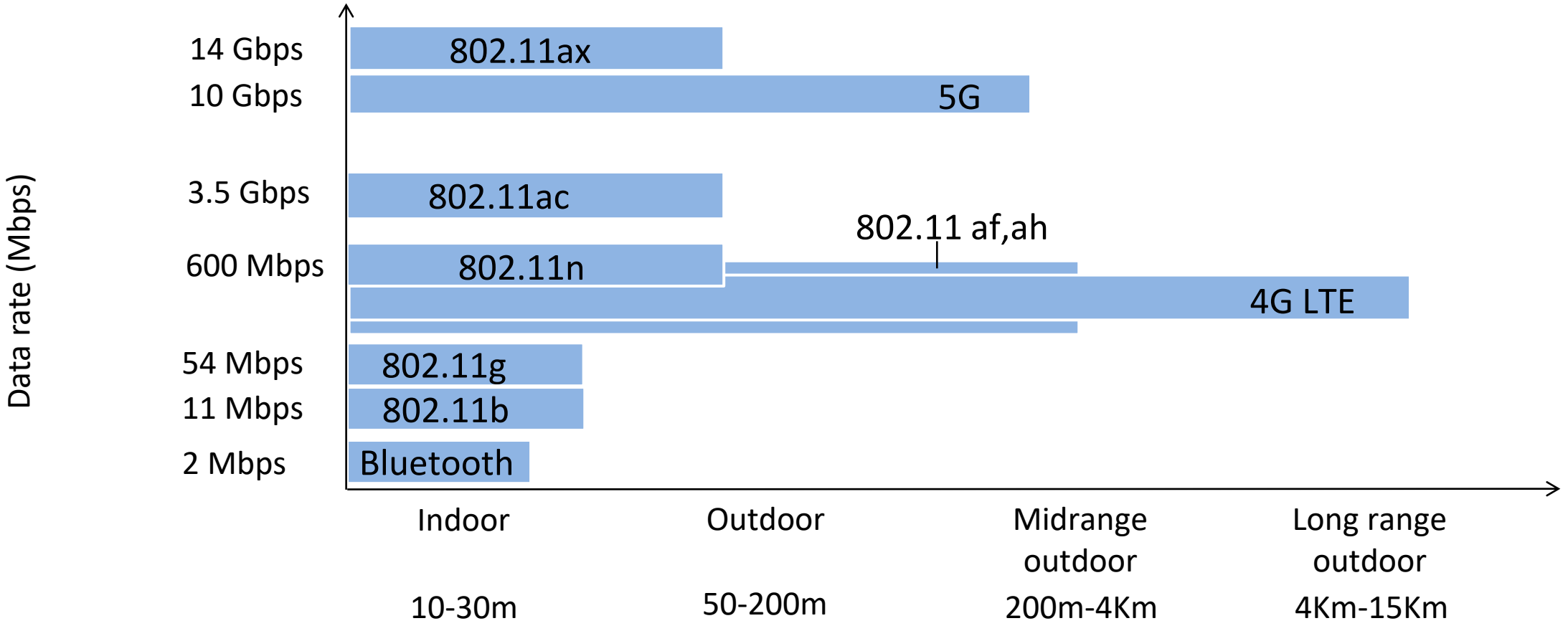



Intracell communication

# Elements of a Wireless network (VI)



# Characteristics of selected wireless links



# Wireless network taxonomy

| | Single hop | Multiple hops |
|---|---|---|
| infrastructure (e.g., APs) | host connects to base station (WiFi, WiMAX, cellular 3G,4G,5G) which connects to larger Internet | host may have to relay through several wireless nodes to connect to larger Internet: MESH networks |
| no infrastructure | no base station, not necessarily connection to larger Internet (e.g. Bluetooth) | no base station, no connection to larger Internet. May have to relay on other nodes to reach a given wireless node (ZigBee, ad hoc, VANET) |

# Wireless Links Characteristics (I)

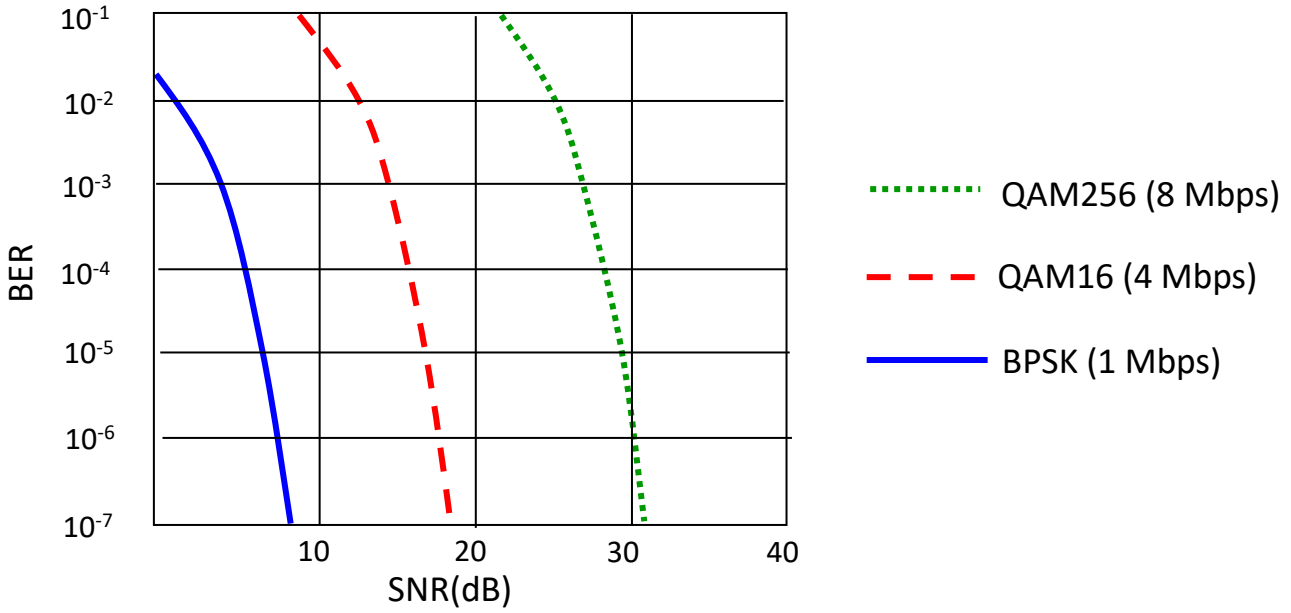
important differences from wired link ….

- decreased signal strength: radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other wireless devices (e.g., mobile phones). Engines, appliances (microwave ovens…),… may interfere as well
- multipath propagation: radio signal reflects off objects or ground, arriving at destination at slightly different times

…. make communication across wireless links much more "difficult" (even a point to point)

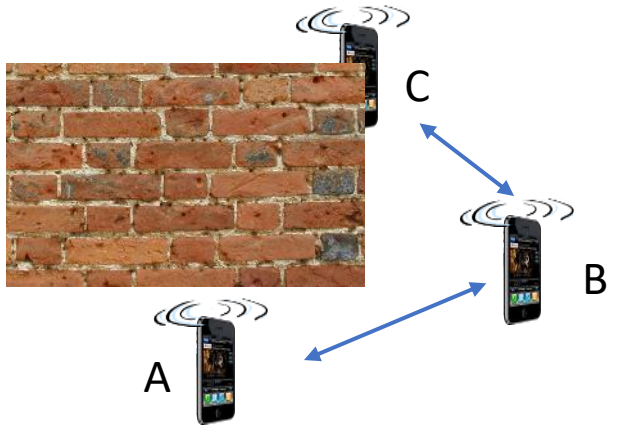
# Wireless Links Characteristics (II)

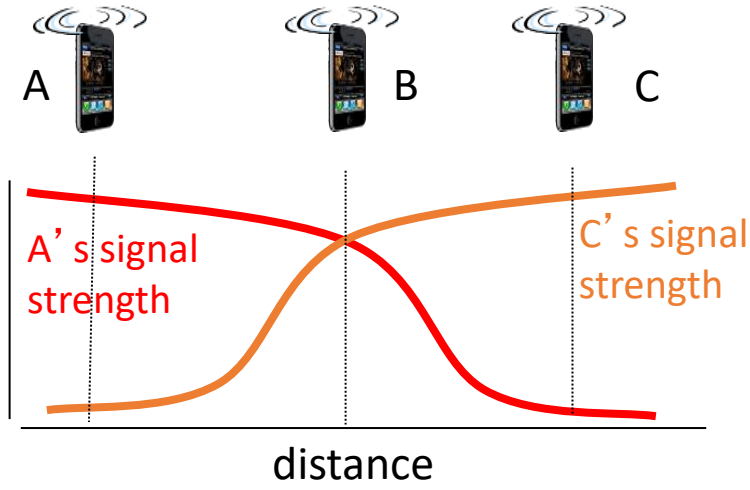
- **SNR: signal-to-noise ratio**
  - larger SNR – easier to extract signal from noise (a “good thing”)
  - SNR in dB = 20*log(signal/noise)
- SNR versus BER tradeoffs
  - bit error rate (BER): probability that a transmitted bit is received in error at the receiver
  - given physical layer: increase power -> increase SNR->decrease BER
  - given SNR: choose physical layer that meets BER requirement, giving highest throughput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



# Wireless Links Characteristics (III)

Signal attenuation or obstacles limit transmission ranges




- B, A hear each other
- B, C hear each other
- A, C can not hear each other

# Wireless networks challenges

Limited knowledge

- a terminal cannot hear all the others
- hidden/exposed terminal problems

Mobility/Failure of terminals

- terminals move in the range of different BS
- terminals move away from each other

Limited terminals

- battery life, memory, processing and transmission range

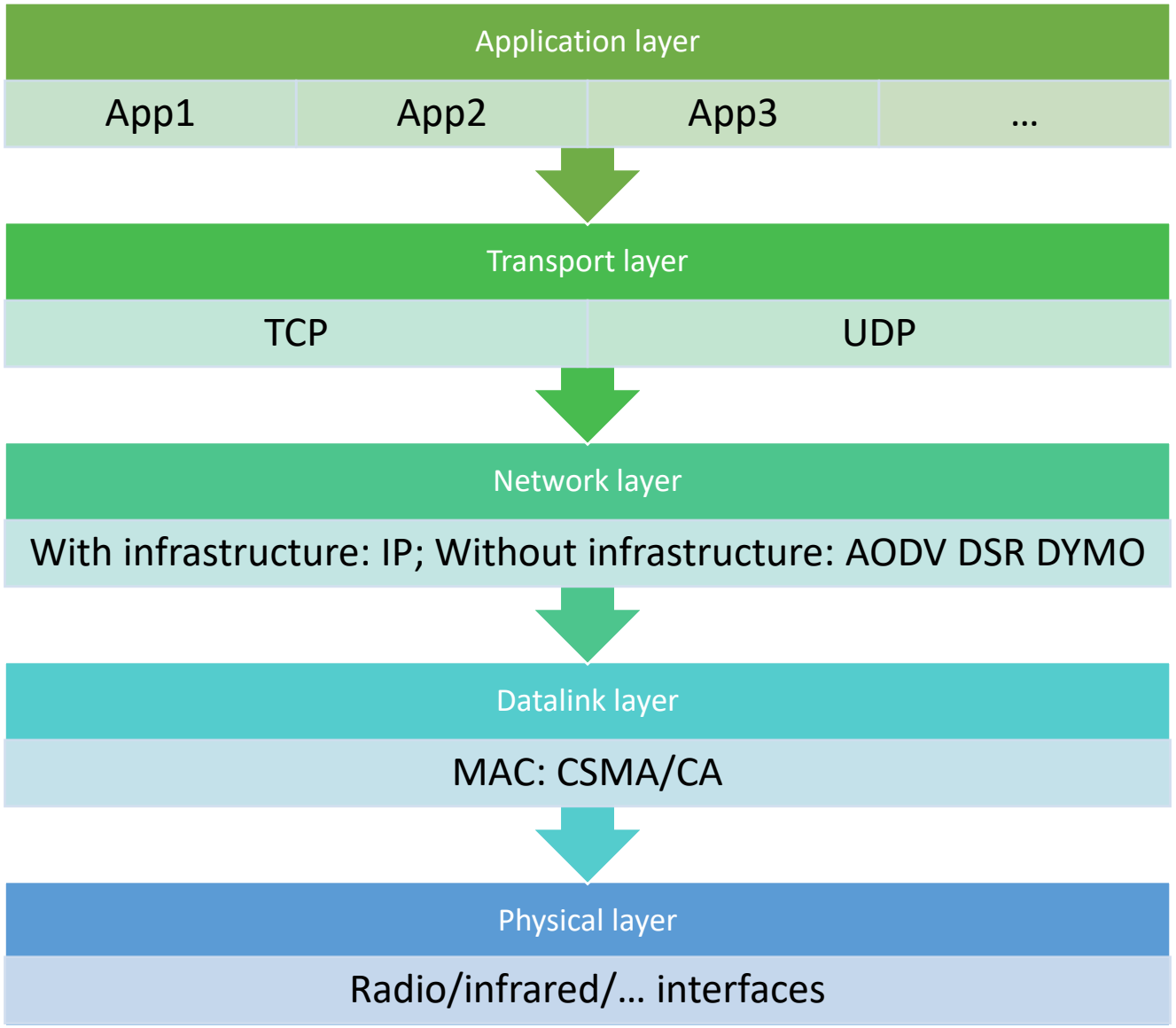
Privacy

- eavesdropping of ongoing communications

# Wireless networks: required mechanisms

- Access to a shared wireless channel
  - CSMA/CD cannot be used…
- Hand-off (Networks with infrastructure)
  - moving a terminal into the range of a different BS
- Routing (multi-hop ad hoc networks)
  - finding a path from source to destination in multi hop networks
  - dealing with arbitrary changes in neighborhood

# Wireless networks protocol stack



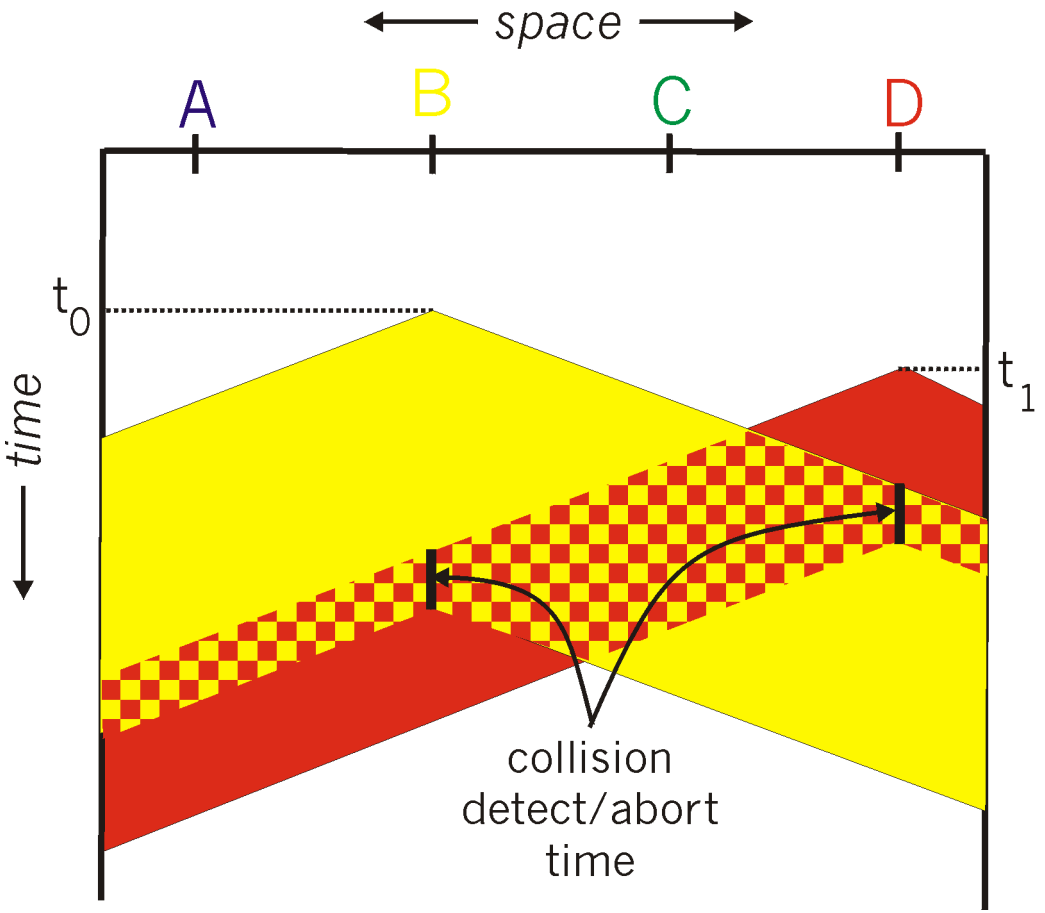
# RECAP: MAC protocols for **wired networks**

- Basic assumptions:
  - a single channel is available for all communications
  - all stations can transmit on it and receive from it
  - if frames are sent simultaneously on the channel the resulting signal is garbled (a **collision**)
  - all stations can detect collisions

- Different protocols
  - ALOHA, slotted ALOHA, CSMA, CSMA/CD, …

# Carrier Sense Multiple Accesses with Collision Detection (CSMA/CD)

- Basic idea of CSMA:
  - When a station has a frame to send it listens to the channel to see if anyone else is transmitting
  - *if the channel is busy*, the station waits until it becomes idle
  - when channel is idle, the station transmits the frame
  - if a collision occurs the station waits a random amount of time and repeats the procedure.



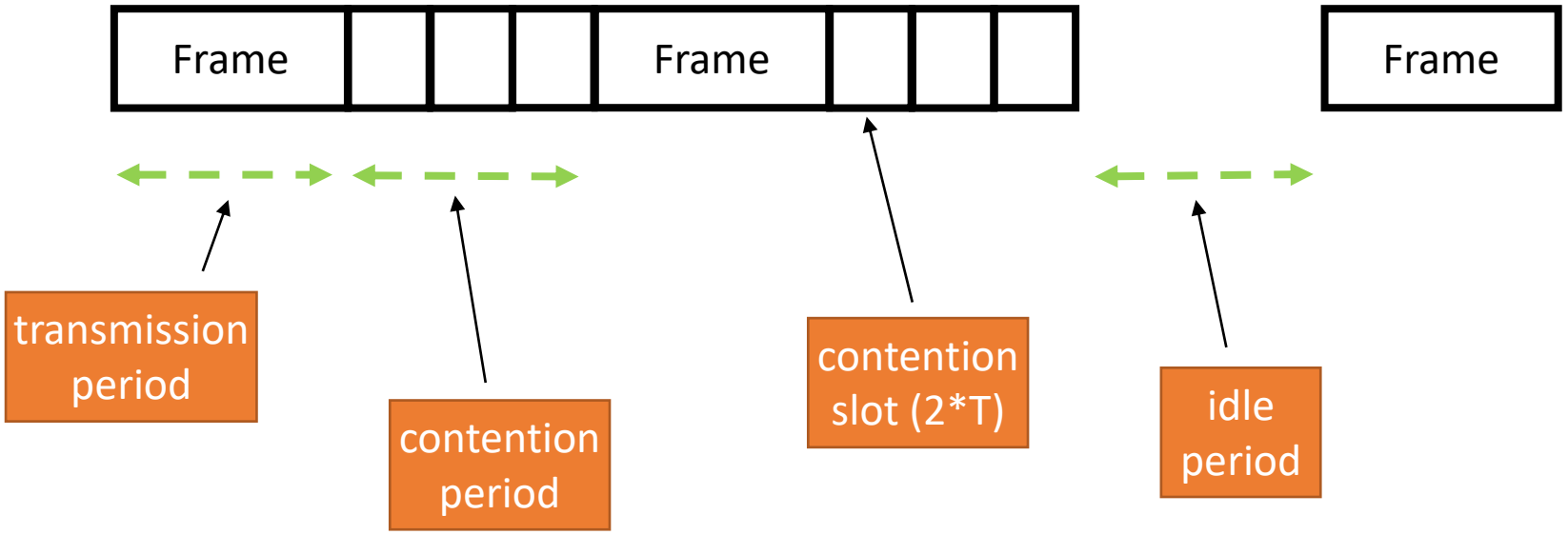
# CSMA/CD (2)

- CSMA with *Collision Detection*
  - a station aborts its transmission as soon as it detects a collision
    - if two stations sense the channel idle simultaneously and start transmitting, they quickly abort the frame as soon as collision is detected
  - it is widely used on LANs in MAC sub-layer
  - IEEE 802.3 Ethernet

# CSMA/CD (3)

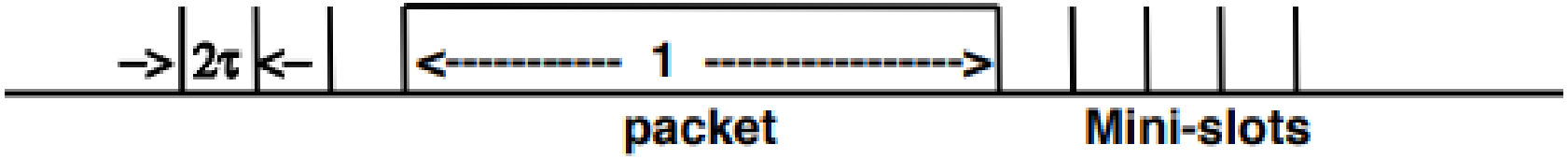
CSMA/CD behavior

- T is the time required to reach the farthest station
- It takes minimum of RTT time (2*T) to detect collision.



# CSMA/CD (4)

- Consider a slotted system with “mini-slots” of duration 2τ
- 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



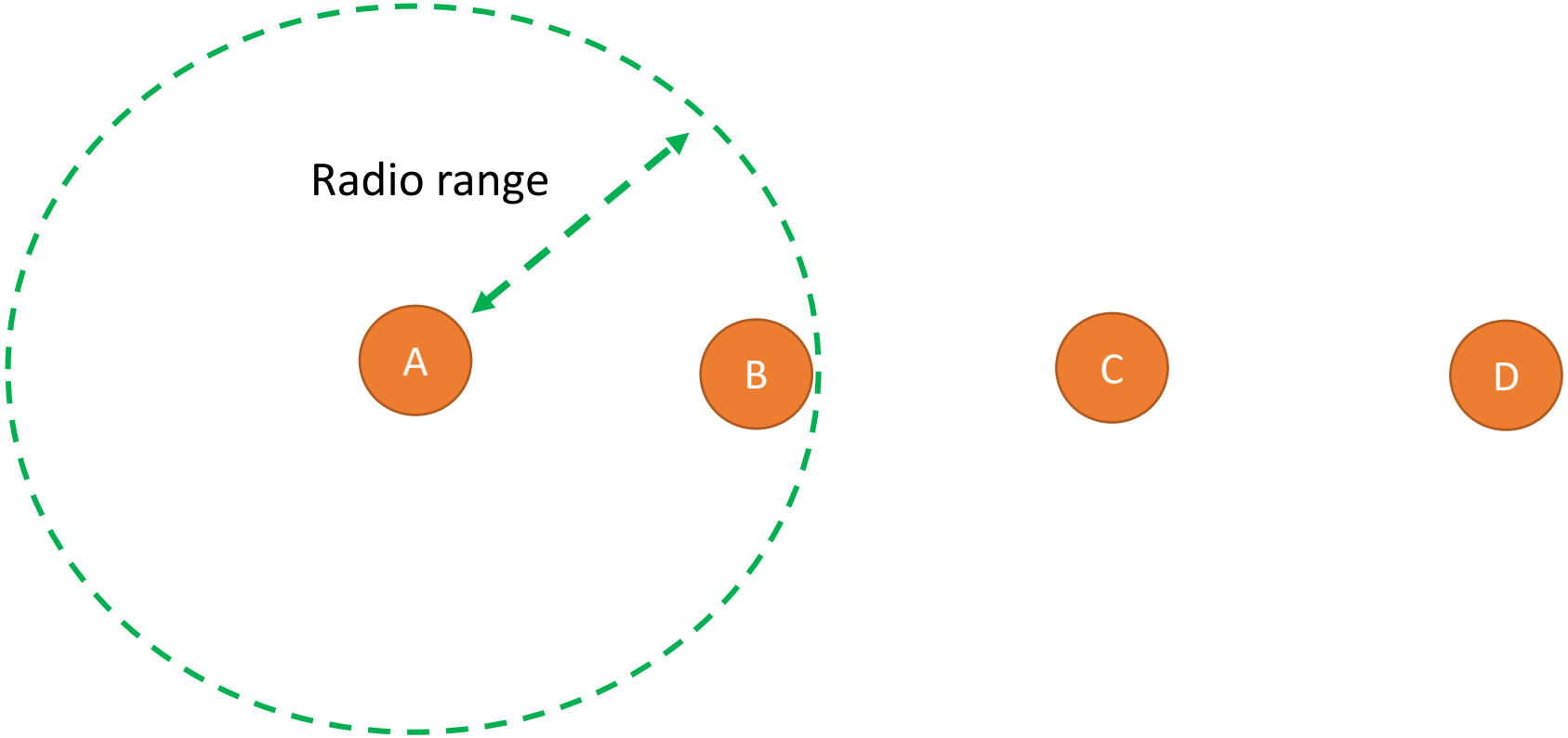
# Binary Exponential Backoff

- Time after a collision is divided in contention slots
  - length of a contention slot is equal to the worst case round propagation time (2T if T is the time to reach the most distant station)
- After the first collision
  - each station waits 0 or 1 slot before trying again
- After collision *i*
  - chooses *x* at random in [0, $2^i$-1]
  - skips *x* slots before retrying
- After 10 collisions:
  - the randomization interval is frozen at 0..1023
- After 16 collisions
  - failure is reported back to upper levels

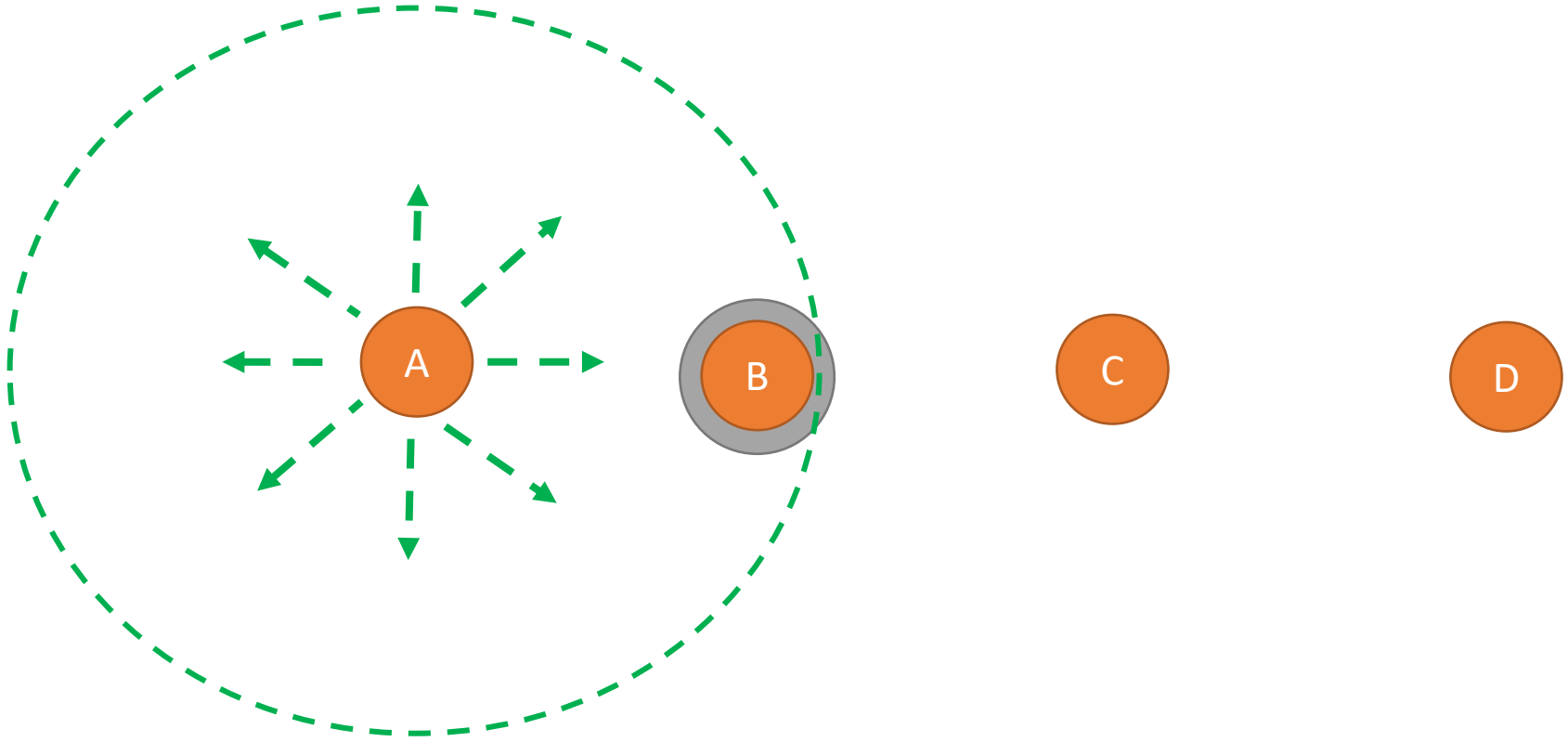
# Wireless networks: MAC

| | |
|---|---|
| CSMA/CD detects interference while trasmitting! | in wired networks it's OK, but not in wireless! |
| Hidden terminal problem | what matters is **interference at the receiver** ***not*** at the sender |
| Exposed terminal problem | what matters is **interference at the receiver** ***not*** at the sender |

# The hidden terminal problem

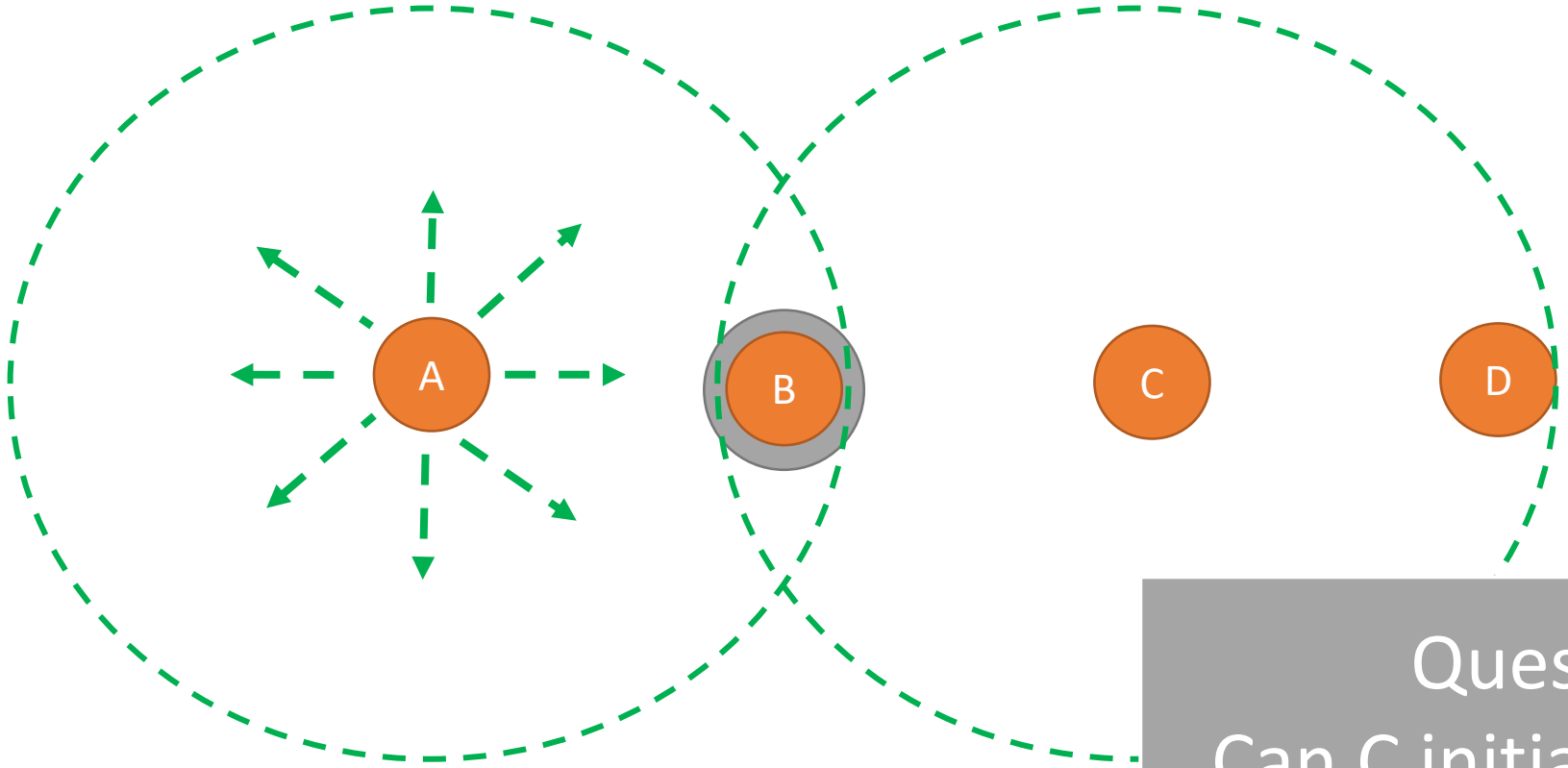


# The hidden terminal problem (2)




A is sending to B

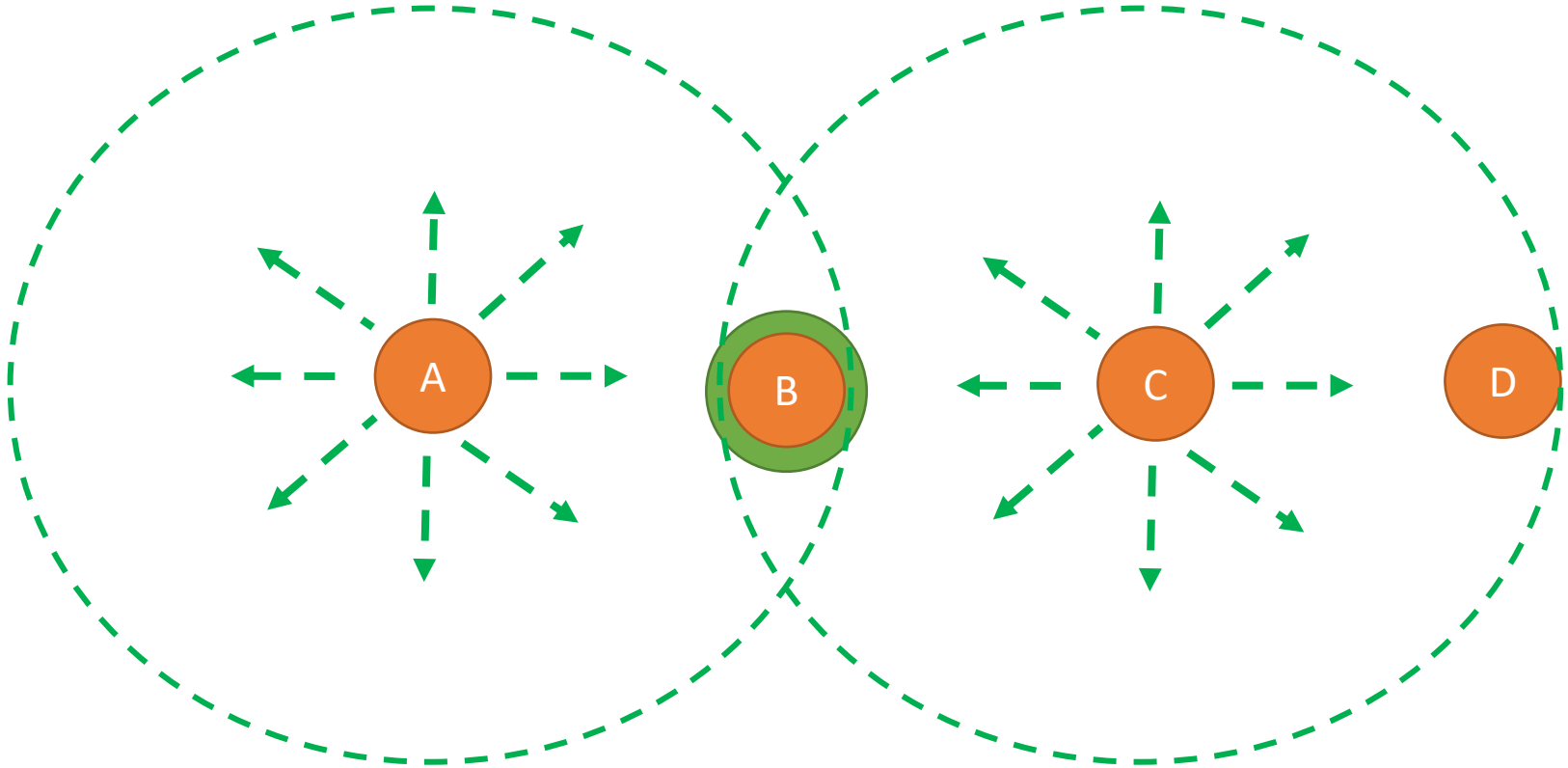
# The hidden terminal problem (3)




A is sending to B
C senses the medium: it will NOT hear A, out of range

Question for you:
Can C initiate a transmission?
What happens if C transmits?

# The hidden terminal problem (4)




A is sending to B

C senses the medium: it will NOT hear A, out of range

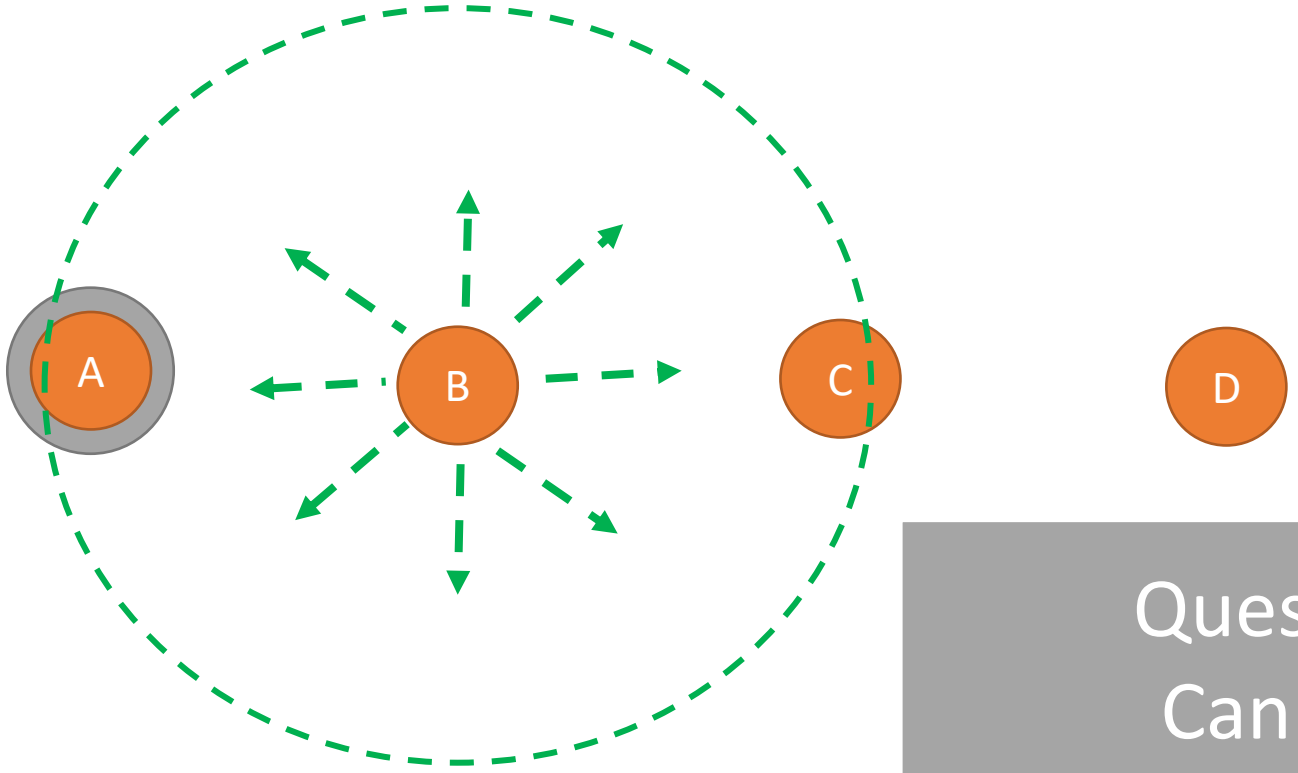
C transmits to anybody (either B or to D) : **COLLISION at B!**

| Hidden terminal problem | C is not able to detect a potential competitor because it is out of range:<br>a collision happens at B (the receiver)<br>For the same reason A does not detect the collision<br>C is **hidden** with respect to the communication from A to B |
|---|---|

# Hidden terminal problem

two or more stations which are out of range of each other transmit simultaneously to a common recipient

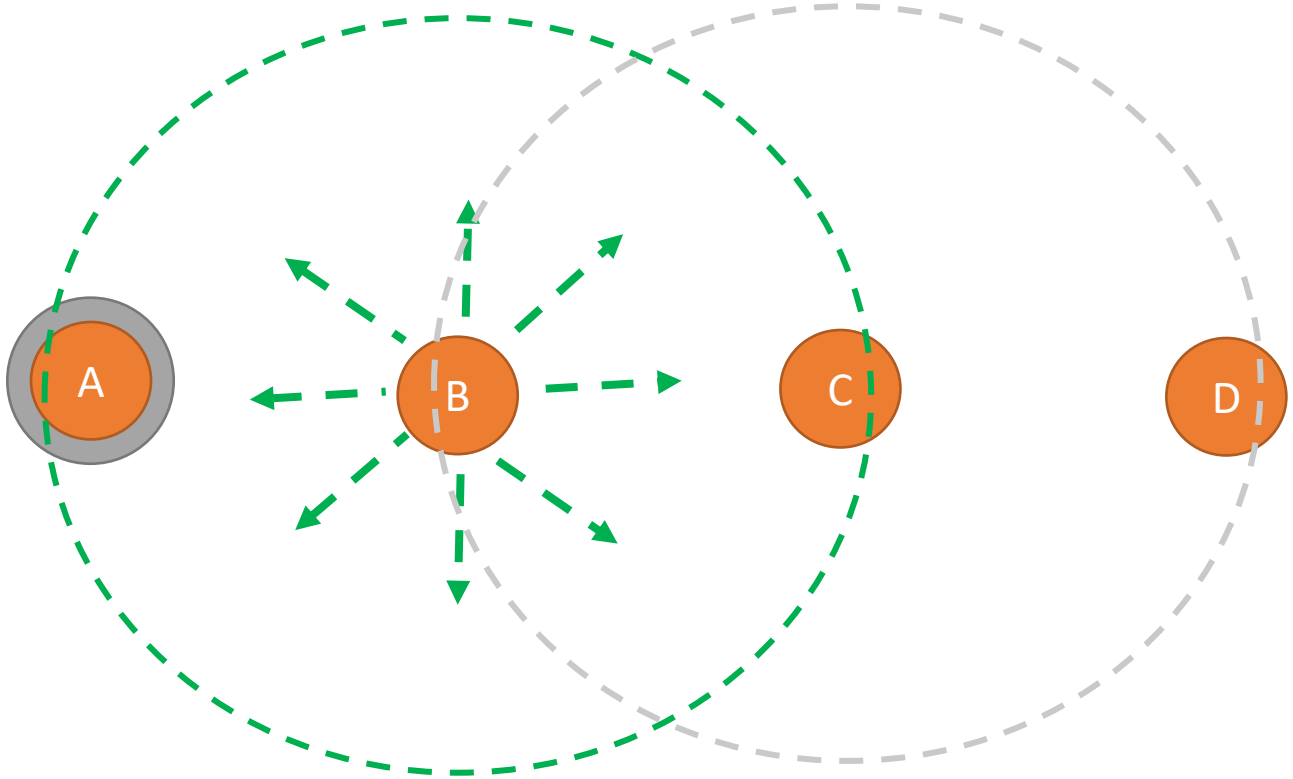
# The exposed terminal problem




1. B is transmitting to A, C wants to transmit to D

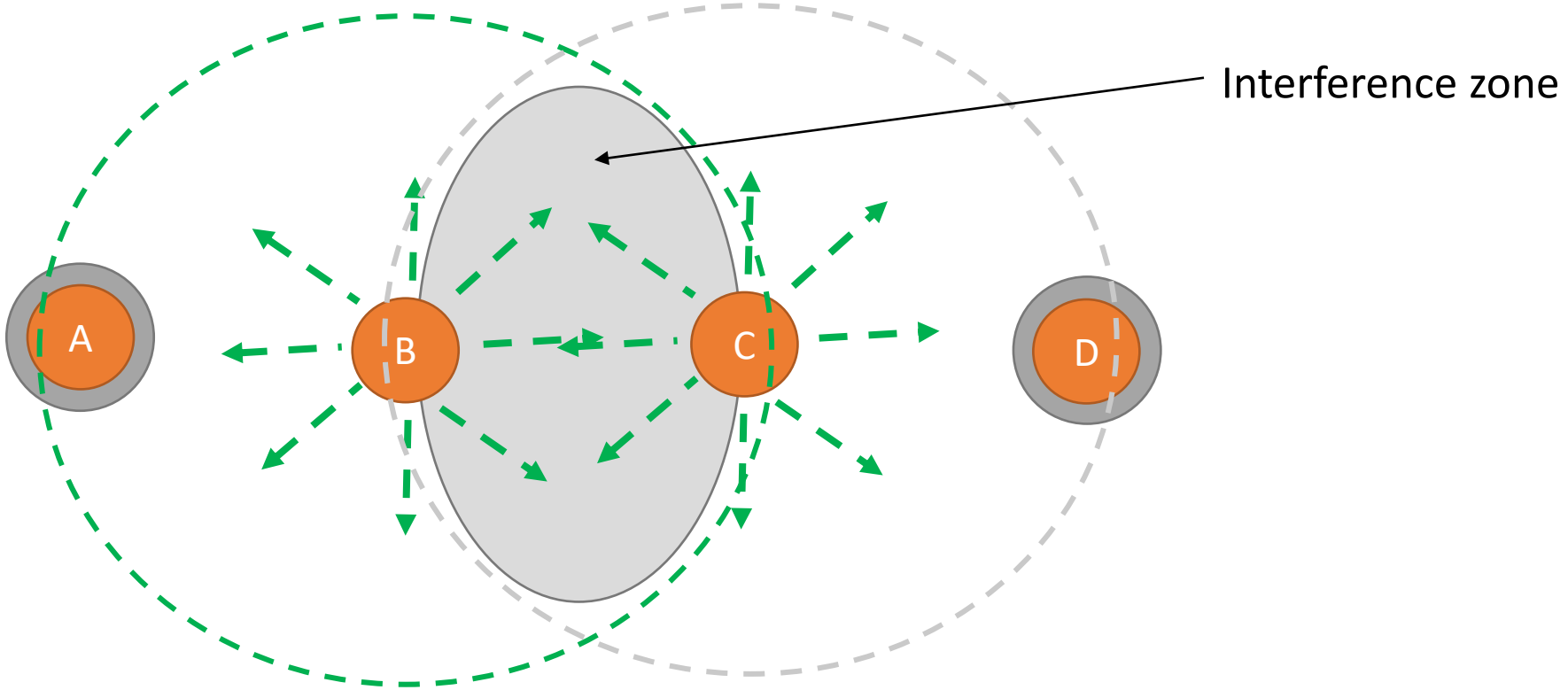
Question for you:
Can C transmit?
What happens if C transmits?

# The exposed terminal problem (2)




1. B is transmitting to A, C wants to transmit to D
2. C senses the medium, concludes: **cannot transmit** to D

# The exposed terminal problem (3)




1. B is transmitting to A, C wants to transmit to D
2. C senses the medium, concludes: **cannot transmit** to D
3. The two transmissions can actually happen in parallel.

| Exposed terminal problem | C hears a transmission<br>C does not send to D although its transmission would be OK<br>C is **exposed** with respect to the communication from B to A |
| --- | --- |

# Exposed terminal problem

a transmitting station is prevented from sending frames due to interference with another transmitting station

# Wireless networks

What matters **is interference at the receiver** not at the sender

- this cannot be checked by sensing the carrier at the sender

Multiple transmissions can occur simultaneously if destinations are out of range of each other

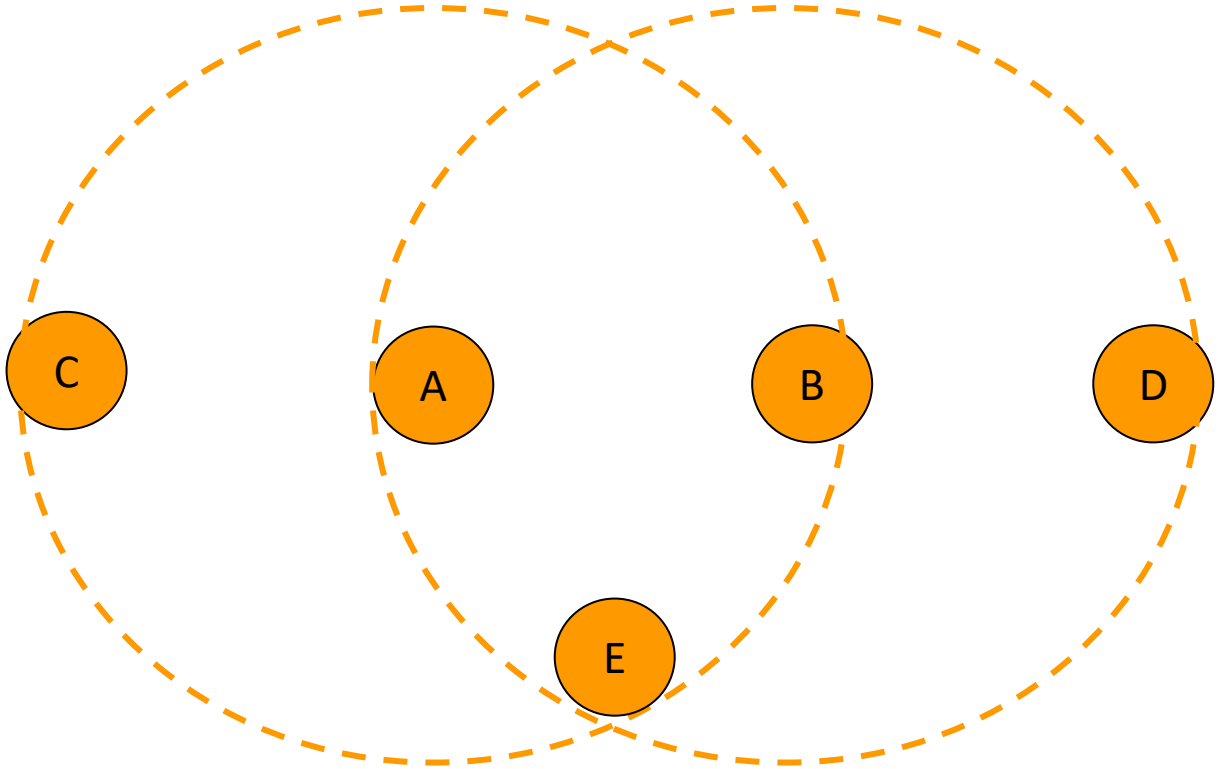
- a station may hear a transmission and be able to transmit without interfere with it

Need sensibly different MAC protocols from wired LANs

# The MACA protocol

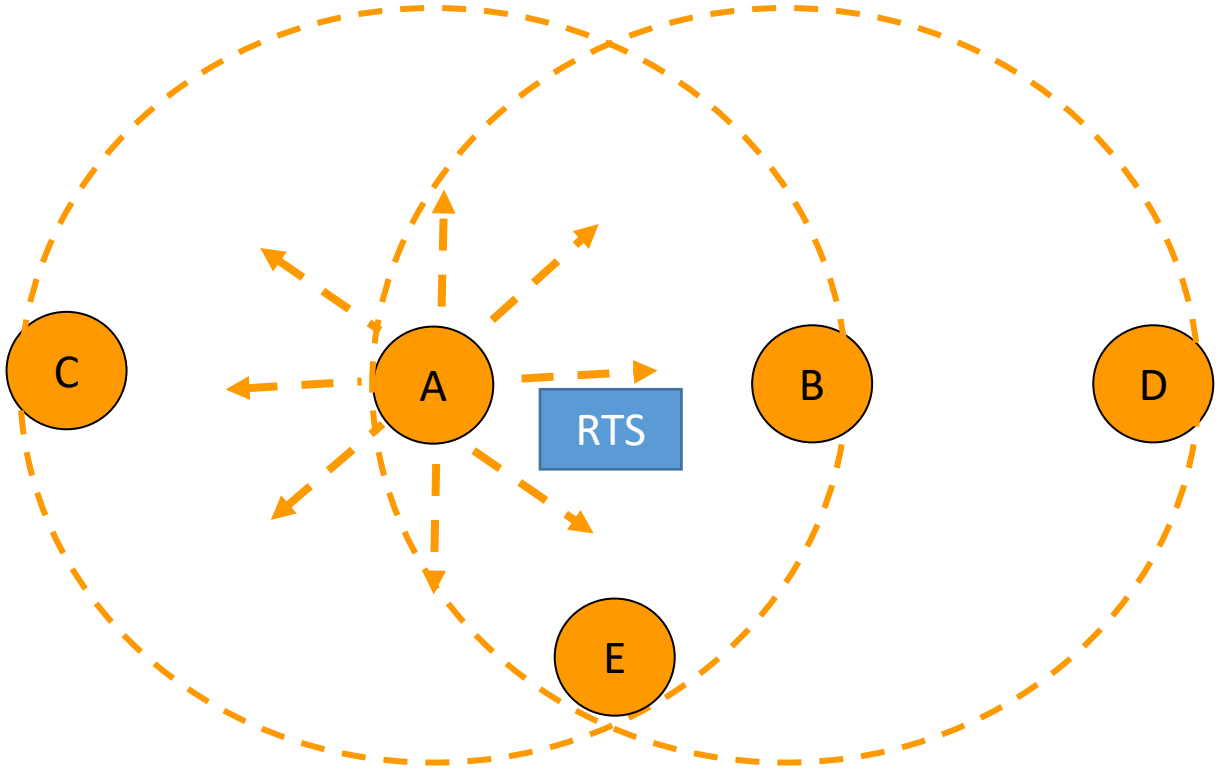
- Multiple Accesses with Collision Avoidance
- Basic idea:
  - stimulate the receiver into transmitting a short frame first
  - then transmit a (long) data frame
  - stations hearing the short frame **refrain from transmitting** during the transmission of the subsequent data frame

# The MACA protocol



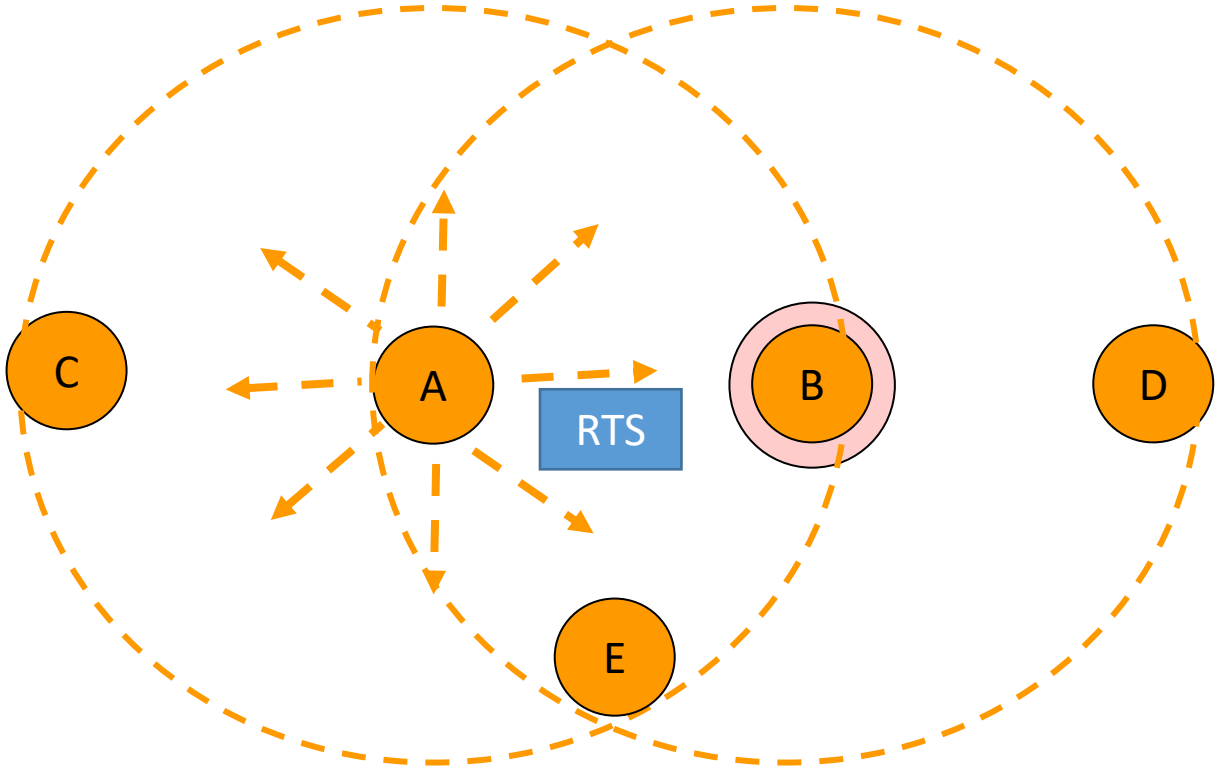

C is within range of A and *out of range of B and D*
D is within range of B and *out of range of A and C*
E is within range of both A and B

# The MACA protocol (2)




1. A wants to transmit to B, sends a **Request To Send (RTS)** to B

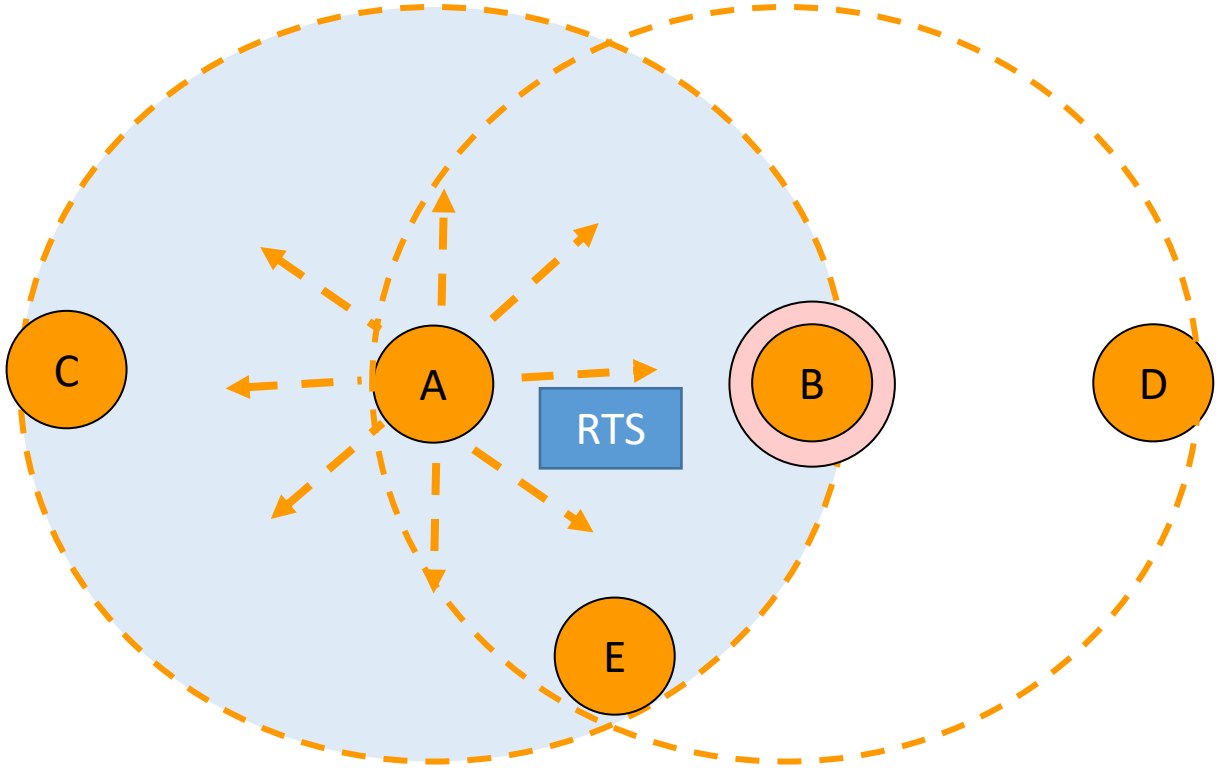
# The MACA protocol (3)




1. A wants to transmit to B, sends a **Request To Send** to B

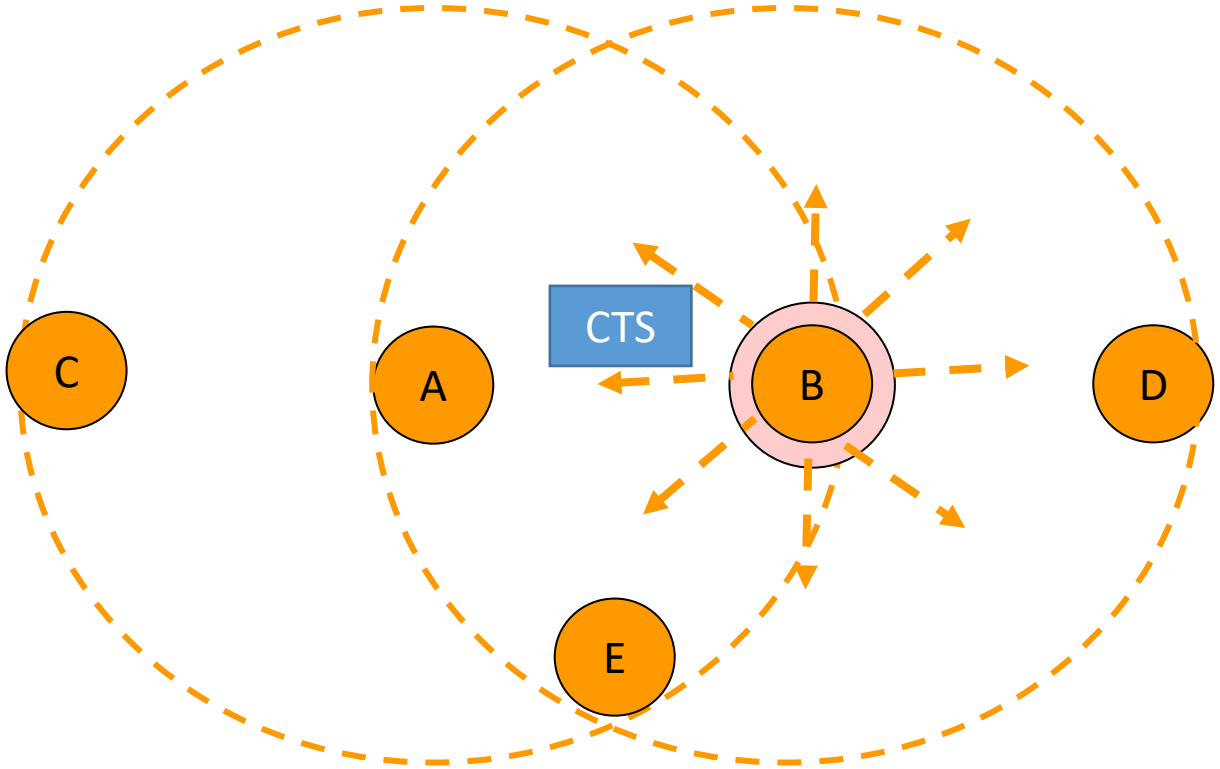
   RTS is a short frame including the length of the data frame that will eventually follow

# The MACA protocol (4)




1. A wants to transmit to B, sends a **RTS** to B
   B, C and E receive the **RTS** from A

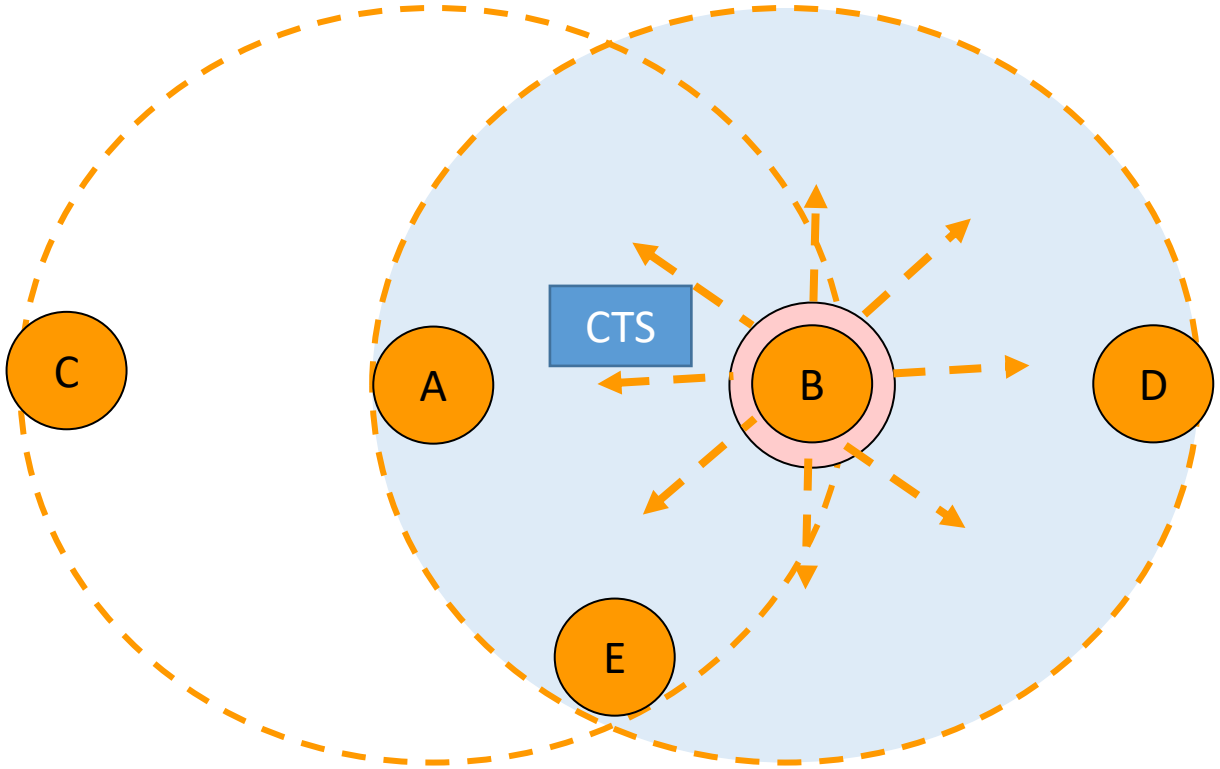
# The MACA protocol (5)




1. A wants to transmit to B, sends a **RTS** to B
2. If B wants to receive the message, it replies with a **Clear To Send**

   CTS is a short frame with data length copied from RTS

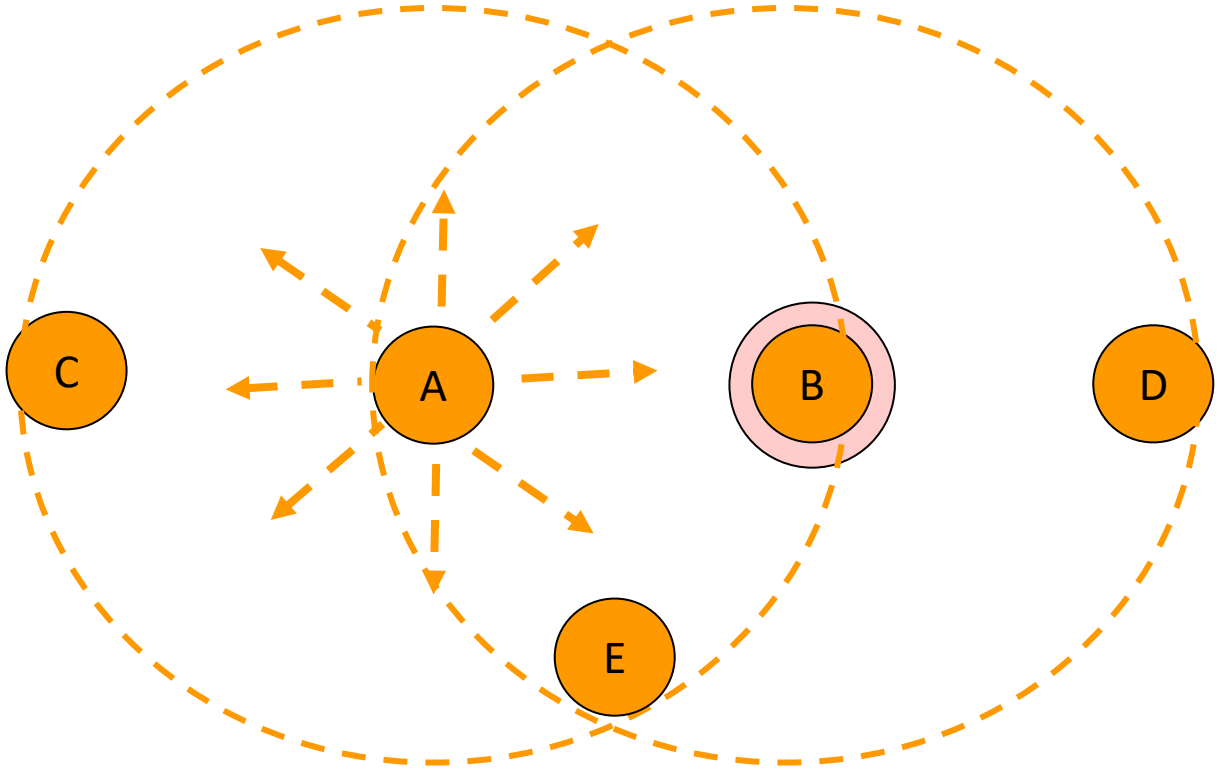
# The MACA protocol (6)




1. A wants to transmit to B, sends a **RTS** to B
2. If B wants to receive the message replies with a **CTS**

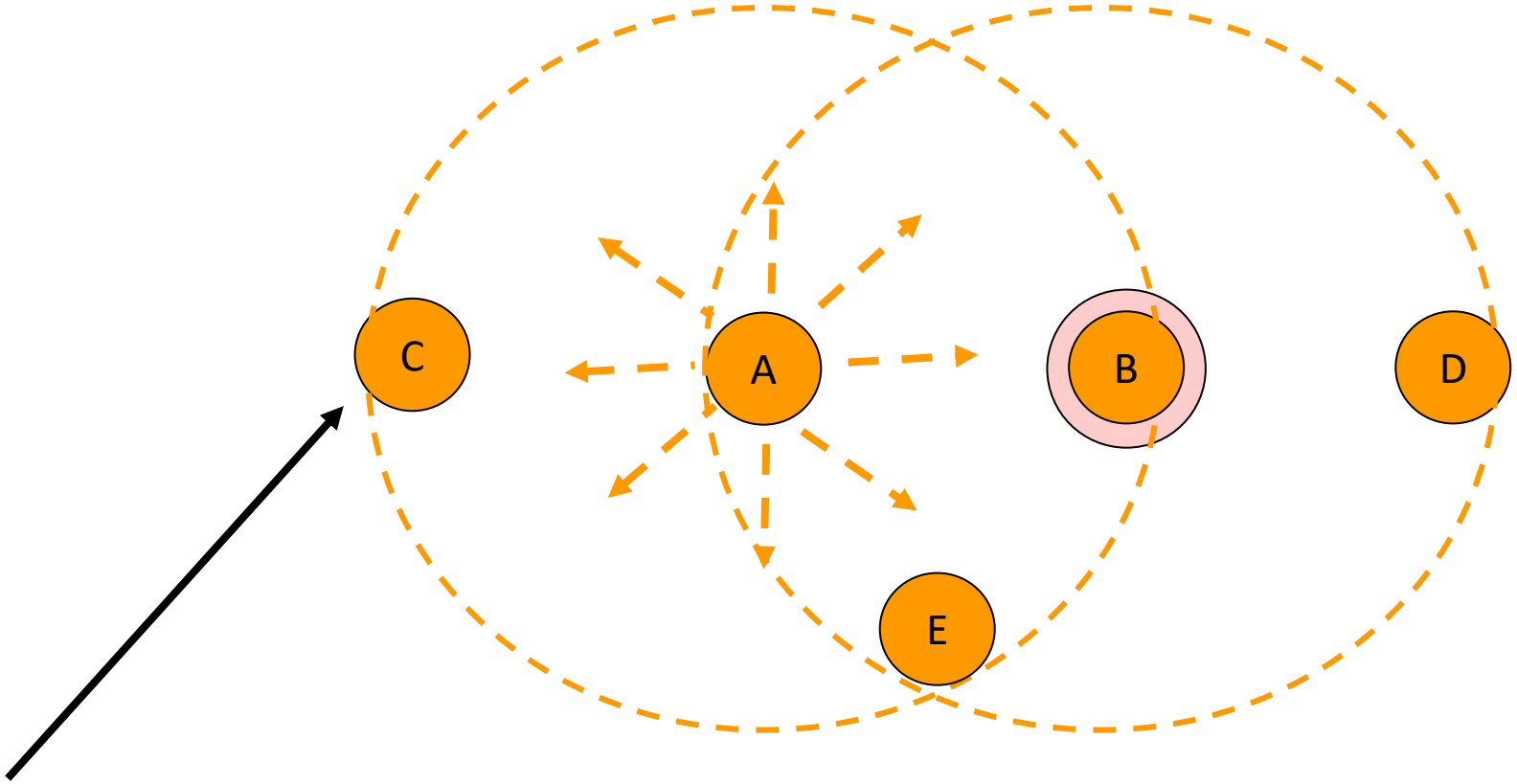
   **CTS** received by A, D, E

# The MACA protocol (7)




1. A wants to transmit to B, sends a **RTS** to B
2. If B wants to receive the message replies with a **CTS**
3. Upon reception of the CTS frame, A transmits the data frame

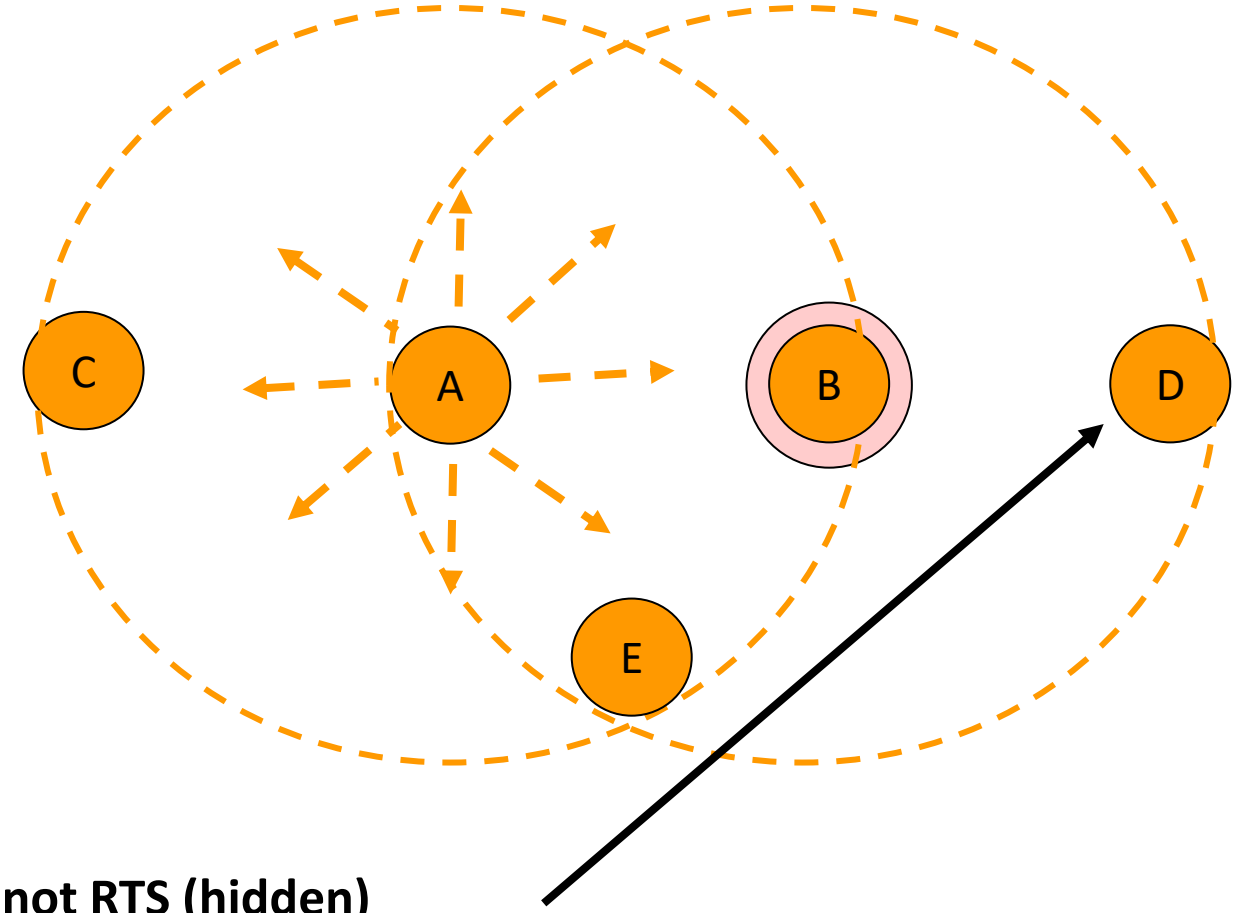
# The MACA protocol (8)




**C hears RTS, but not CTS (exposed)**

it is free to transmit

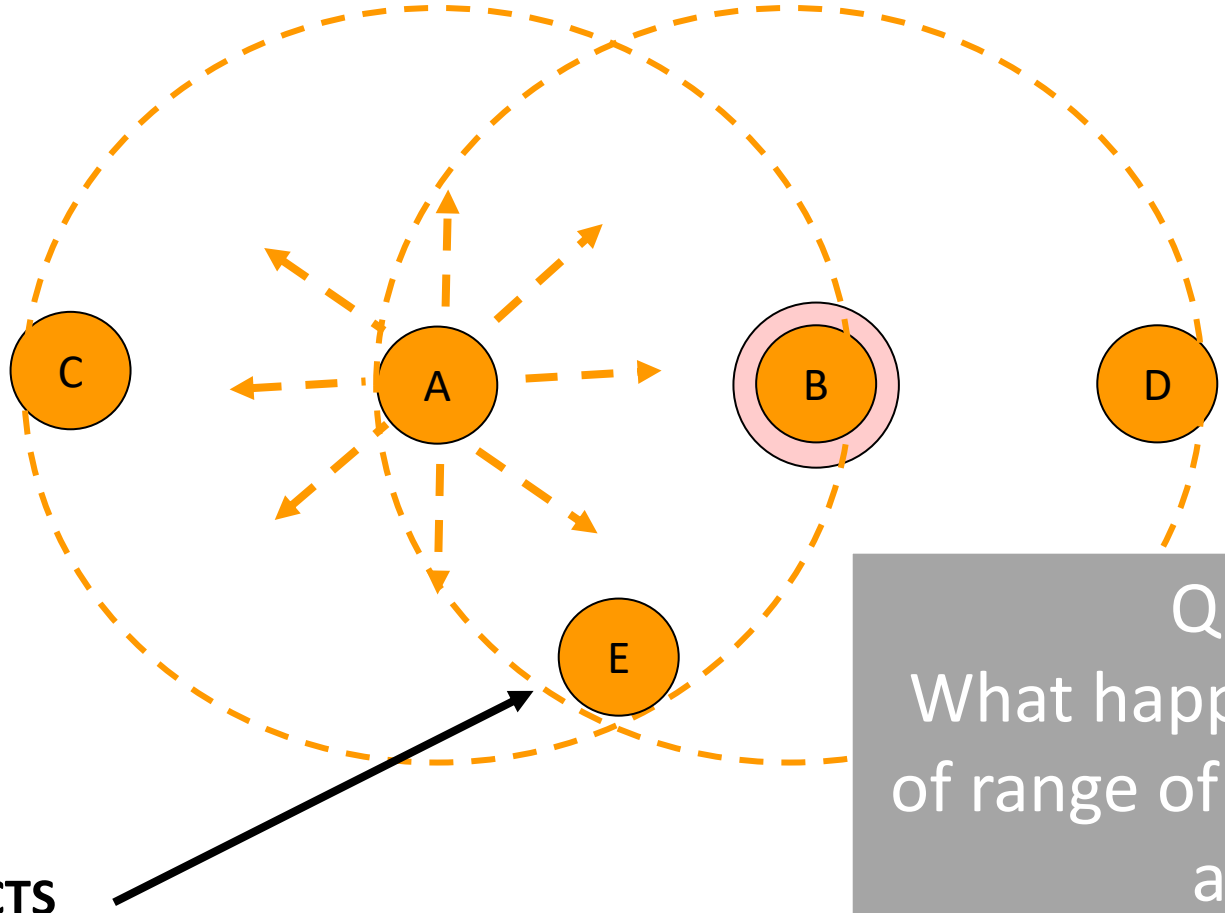
# The MACA protocol (9)




**D hears CTS, but not RTS (hidden)**

it should stay silent until data frame transmission completes (just waits for the required time)

# The MACA protocol (10)

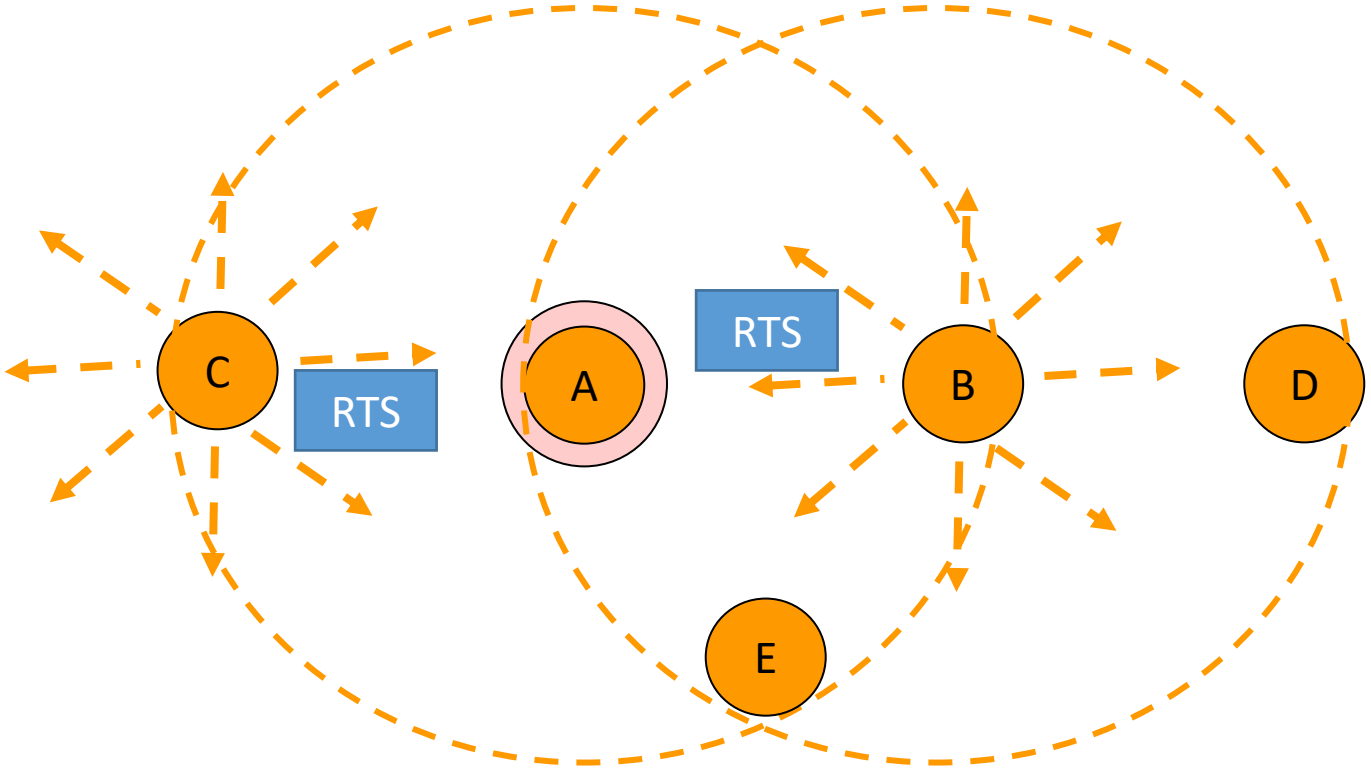



Question for you:
What happens if another node out of range of A and B wish to transmit a message to E?

**E hears RTS and CTS**

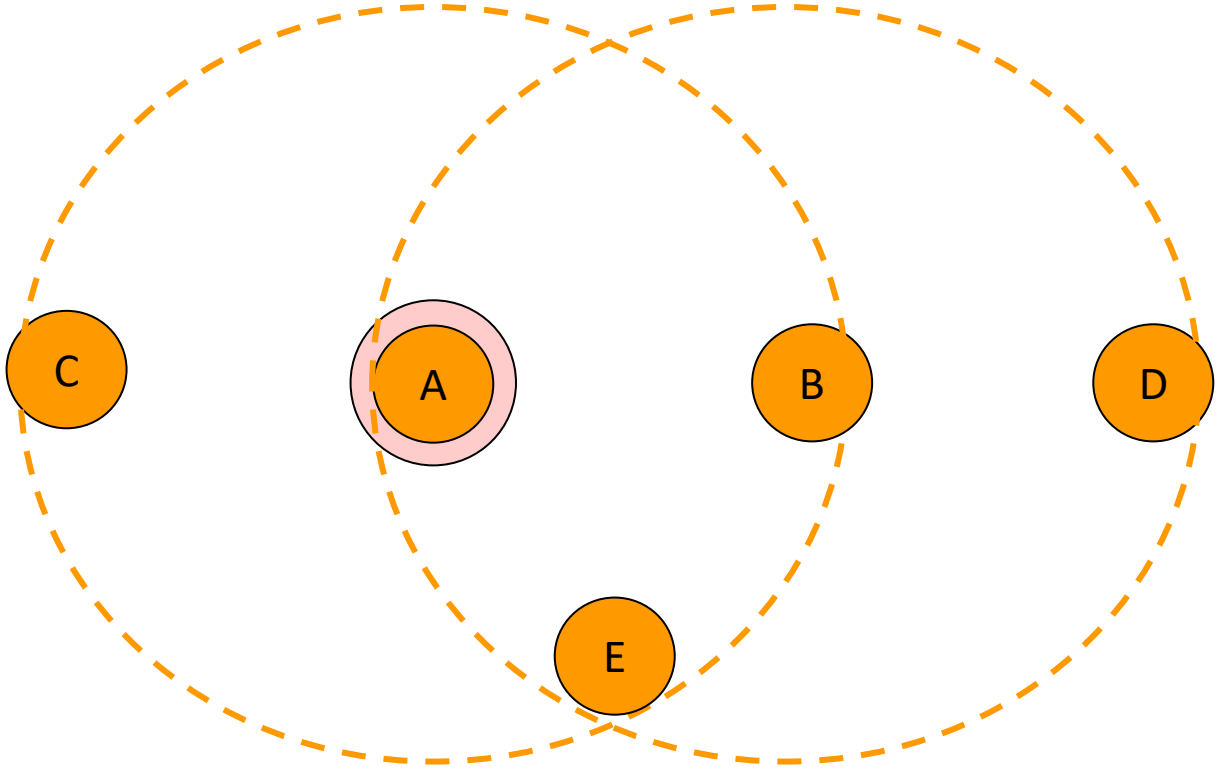
it should stay silent until data frame transmission completes

# The MACA protocol: collisions




C and B send RTS simultaneously to A

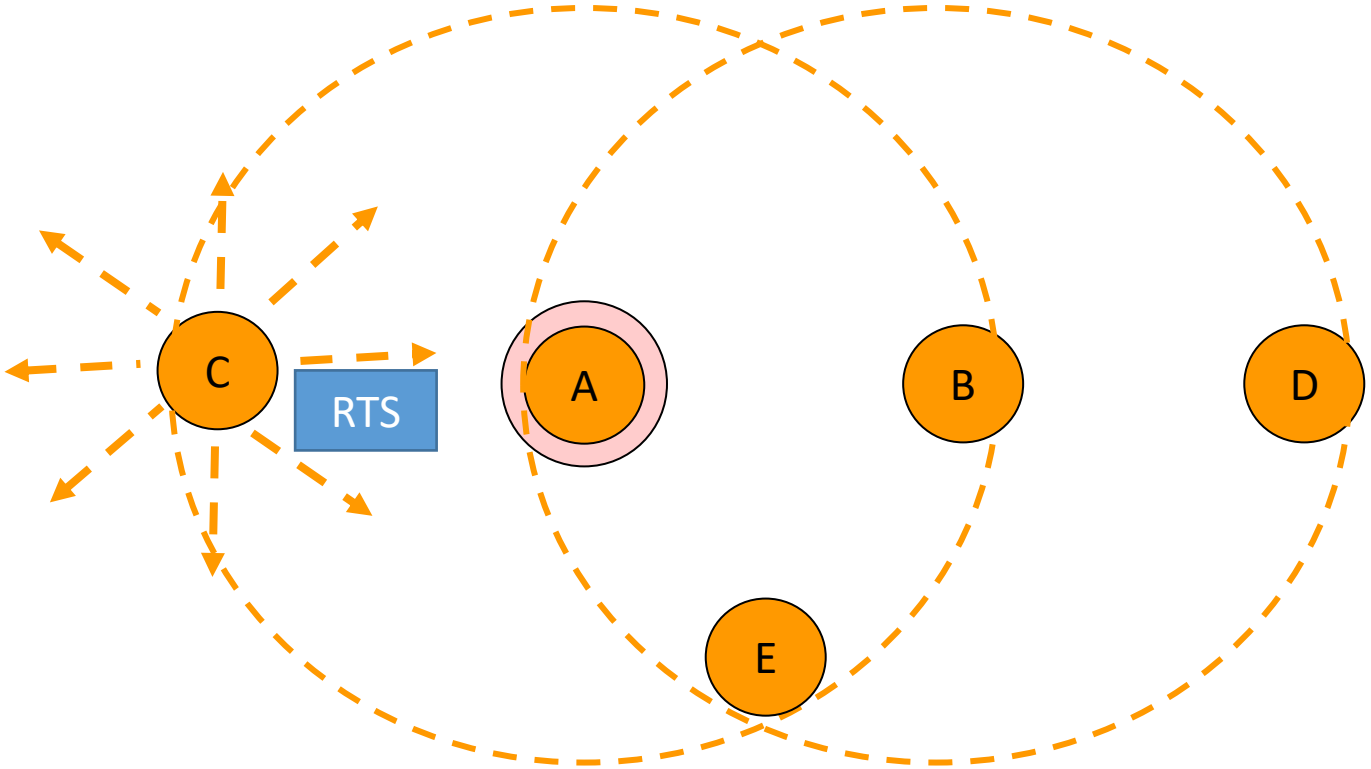
# The MACA protocol: collisions (2)




C and B send RTS simultaneously to A

The two messages collide: No CTS is generated

# The MACA protocol: collisions (3)




C and B use *Binary Exponential Backoff* (same as Ethernet) to retry RTS

# MACAW: MACA for Wireless networks

Fine tunes MACA to improve performance:

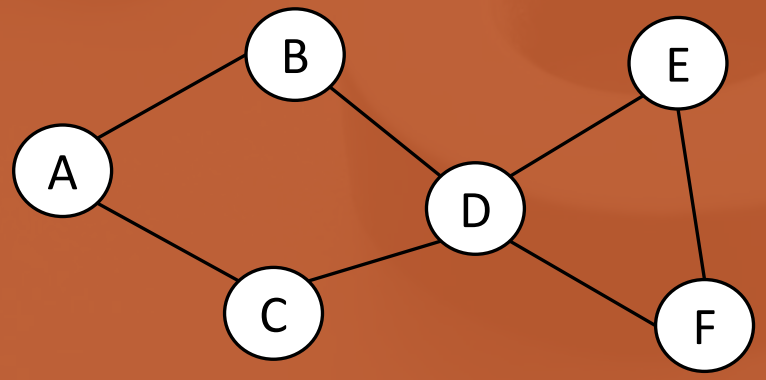
- introduces an ***ACK frame*** to acknowledge a successful data frame
- added ***Carrier Sensing*** to keep a station from transmitting RTS when a nearby station is also transmitting an RTS to the same destination
- exponential backoff is run for each separate pair source/destination and not for the single station
- mechanisms to exchange information among stations and recognize temporary congestion problems
- CSMA/CA used in IEEE 802.11 is based on MACAW

# Question

Given the network in the figure, assume that the MAC protocol uses the RTS/CTS mechanism for the channel access.

Discuss which nodes detect themselves as hidden or exposed as consequence of the RTS/CTS handshake in the following cases:

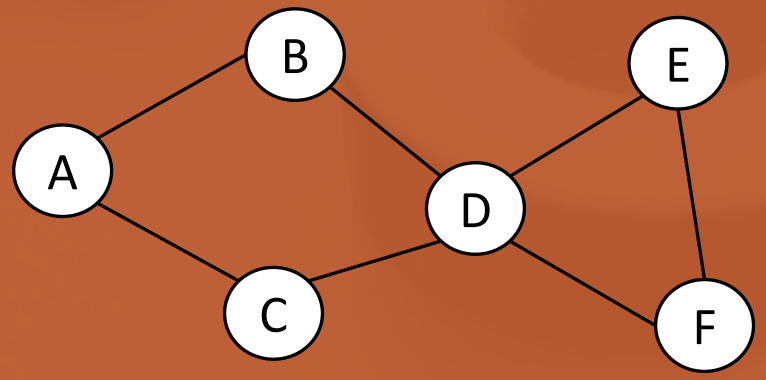
1. Hidden terminals with respect to a transmission from E to D
2. Hidden terminals with respect to a transmission from D to C
3. Exposed terminals with respect to a transmission from D to B
4. Exposed terminals with respect to a transmission from B to A

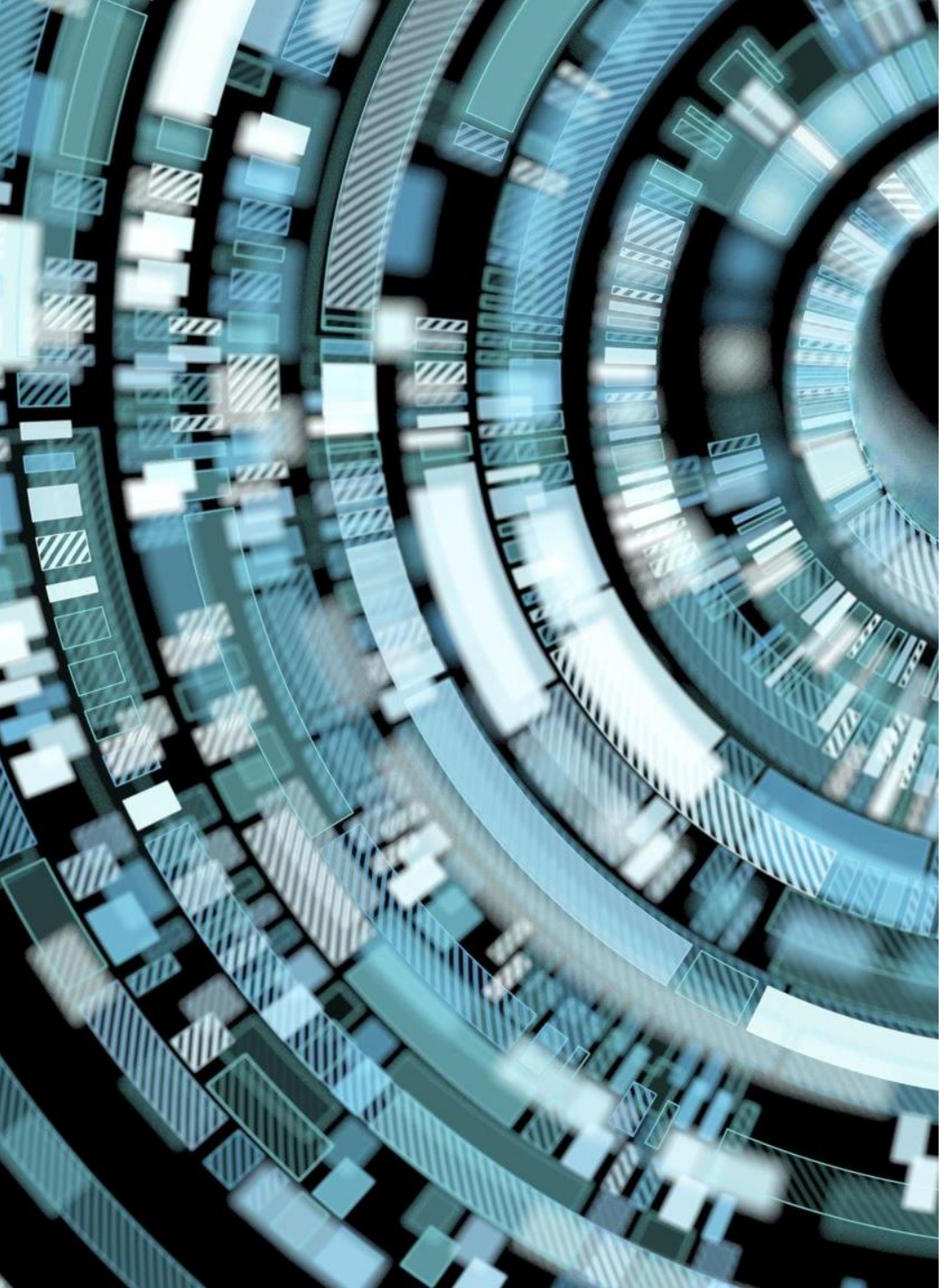


# Question

Given the network in the figure:

1. assume that D hears the RTS sent by E but it does not hear the corresponding CTS. What does D can do?
2. assume that B hears the CTS sent by D but it does not hear the corresponding RTS. What does B can do?
3. Assume D is receiving a communication from a node, and B did not receive the corresponding RTS & CTS and it does not hear the signal transmitted to D. If B wishes to transmit to D what happens?





# IEEE 802.11

# The IEEE 802.11 family

- IEEE 802.11 (Legacy mode)
  - First released in 1997 and clarified in 1999
  - rarely used today
  - 1-2 Mbps data rate implemented via:
    - infrared (IR) signals,
    - radio frequencies in the 2.4GHz band (ISM -- Industrial Scientific Medical Frequency band)
  - many degrees of freedom: interoperability among different products was a challenge
  - rapidly supplemented (and made popular) by 802.11b
  - most used today 802.11a/b/g/n

# IEEE 802.11 family (2)

- IEEE 802.11a
  - Released in 1999
  - Operating frequency: 5 GHz band (Unlicensed National Information Infrastructure U-NII band)
  - Throughput (typ): 23 Mbps
  - Data rate (max): 54 Mbps
- IEEE 802.11b
  - Released in 1999
  - Operating frequency: 2.4GHz band (ISM band)
    - potential interference with other appliances : cordless telephones, microwave ovens etc
  - Throughput (typ): 4.3 Mbps
  - Data rate (max): 11 Mbps

# IEEE 802.11 family (3)

- IEEE 802.11g
  - Released in 2003
  - Operating frequency: 2.4GHz band (ISM band)
  - Throughput (typ): 19 Mbps and more…
  - Data rate (max): 54 Mbps
- IEEE 802.11n
  - Released in 2009
  - Operating frequency: 2.4GHz band and 5GHz band
  - Throughput (typ): 74 Mbps
  - Data rate (max): 248 Mbps
  - Support of MIMO technologies for using multiple antennas at the transmitter and the receiver

# IEEE 802.11 family (4)

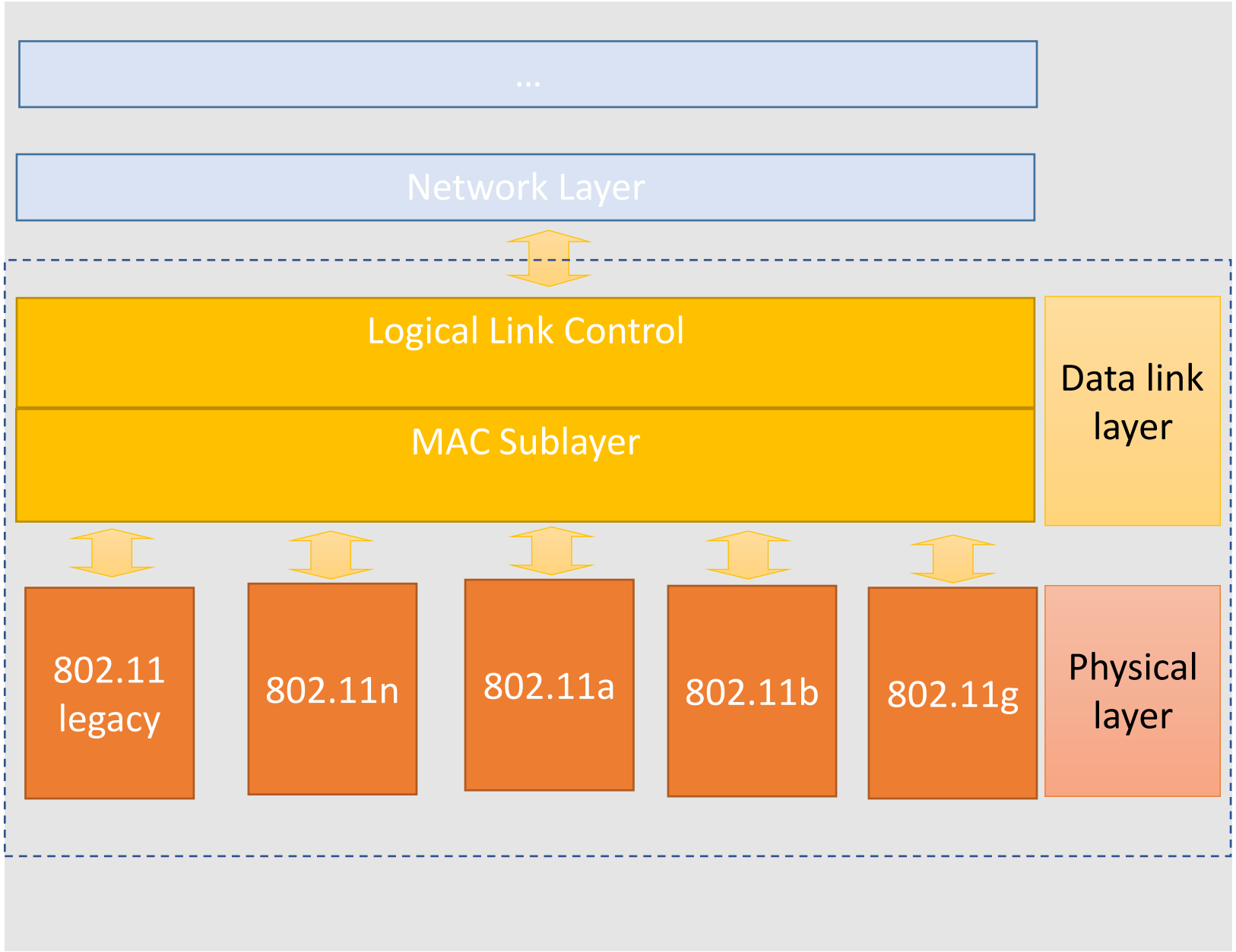
- Now available newer versions:
- WiFi 5 - IEEE 802.11ac
  - Released in 2013
  - Operating frequency: 2.4GHz and 5 GHz bands
  - Data rate (max): 1.3 Gbps at 5 GHz
  - Data rate (max): 450 Mbps at 2.4 GHz
- WiFi 6 - IEEE 802.11ax
  - Released in 2019
  - reaches up to 10 Gbps
  - improvements in power consumption and security

# IEEE 802.11 Wireless LAN

| IEEE 802.11 standard | Year | Max data rate | Range | Frequency |
|---|---|---|---|---|
| 802.11b | 1999 | 11 Mbps | 30 m | 2.4 Ghz |
| 802.11g | 2003 | 54 Mbps | 30m | 2.4 Ghz |
| 802.11n (WiFi 4) | 2009 | 600 | 70m | 2.4, 5 Ghz |
| 802.11ac (WiFi 5) | 2013 | 3.47Gpbs | 70m | 5 Ghz |
| 802.11ax (WiFi 6) | 2020 (exp.) | 14 Gbps | 70m | 2.4, 5 Ghz |
| 802.11af | 2014 | 35 – 560 Mbps | 1 Km | unused TV bands (54-790 MHz) |
| 802.11ah | 2017 | 347Mbps | 1 Km | 900 Mhz |

- all use CSMA/CA for multiple access, and have base-station and ad-hoc network versions

# IEEE 802.11: protocol stack



# IEEE 802.11 Architecture

- A group of stations operating under a given coordination function
  - may (or may not) use a base station (Access Point - AP)
  - if using AP a station communicates with another by channeling all the traffic through a centralized AP
  - AP can provide connectivity with other APs and other groups of stations via fixed infrastructure

# IEEE 802.11 Architecture

- Supports ad hoc networks, which are, in the IEEE 802.11 view :

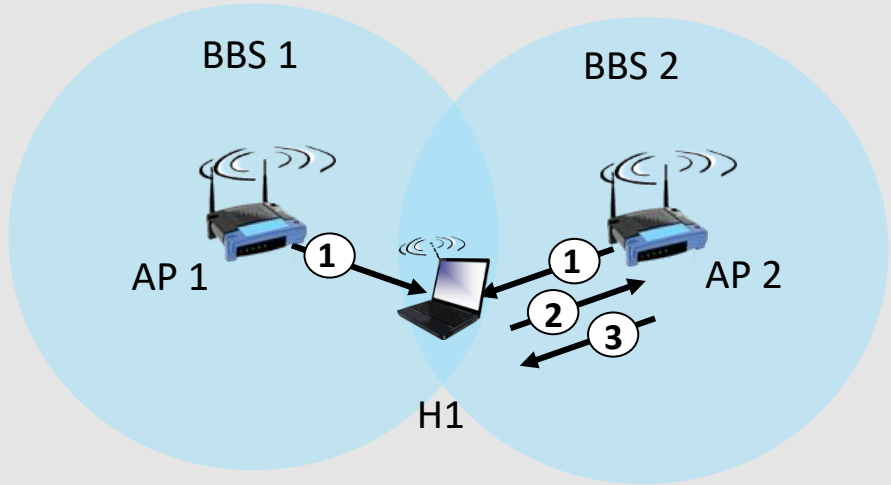
*a group of stations that are under the direct control of a single coordination function without the aid of an infrastructure network*

- a station can communicate directly with another without channeling all the traffic through AP

# IEEE 802.11 Channels, association

- spectrum divided into channels at different frequencies
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- arriving host: must associate with an AP
  - scans channels, listening for *beacon frames* containing network's name (SSID) and MAC address of the AP (BSSID)
  - selects AP to associate with
  - then may perform authentication
  - then typically run DHCP to get IP address in AP's subnet

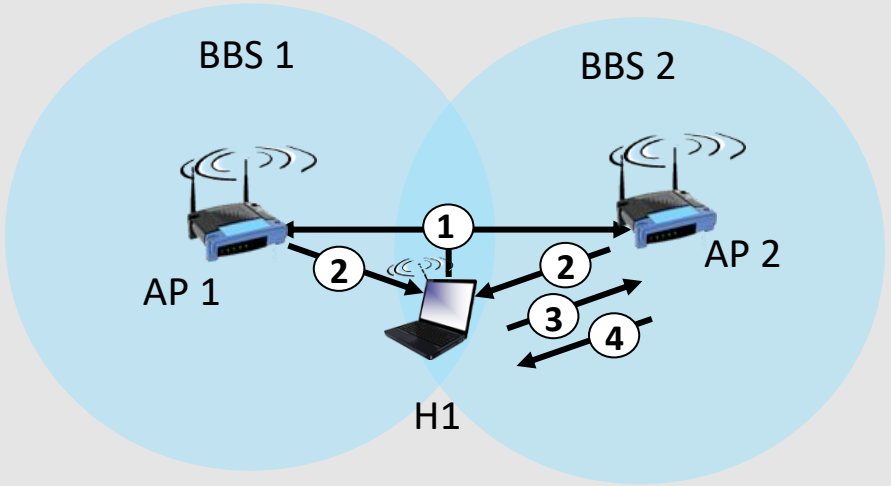
# IEEE 802.11 passive/active scanning




passive scanning:

(1) beacon frames sent from APs
(2) association Request frame sent: H1 to selected AP
(3) association Response frame sent from selected AP to H1

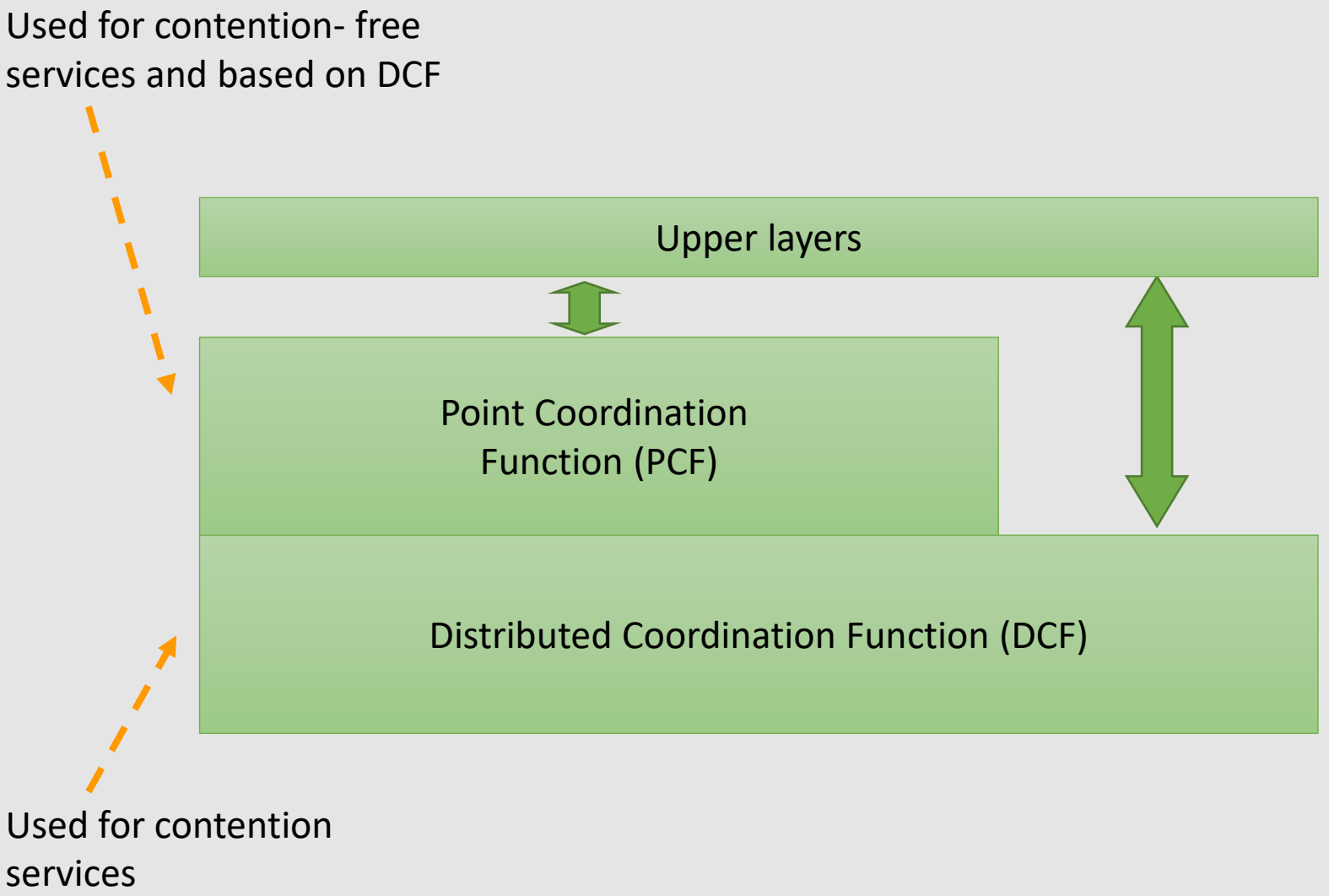
# IEEE 802.11 passive/active scanning




active scanning:

(1) Probe Request frame broadcast from H1
(2) Probe Response frames sent from APs
(3) Association Request frame sent: H1 to selected AP
(4) Association Response frame sent from selected AP to H1

# IEEE 802.11 Architecture: MAC Sublayer



# IEEE 802.11 Architecture: MAC Sublayer

Two modes of operations:

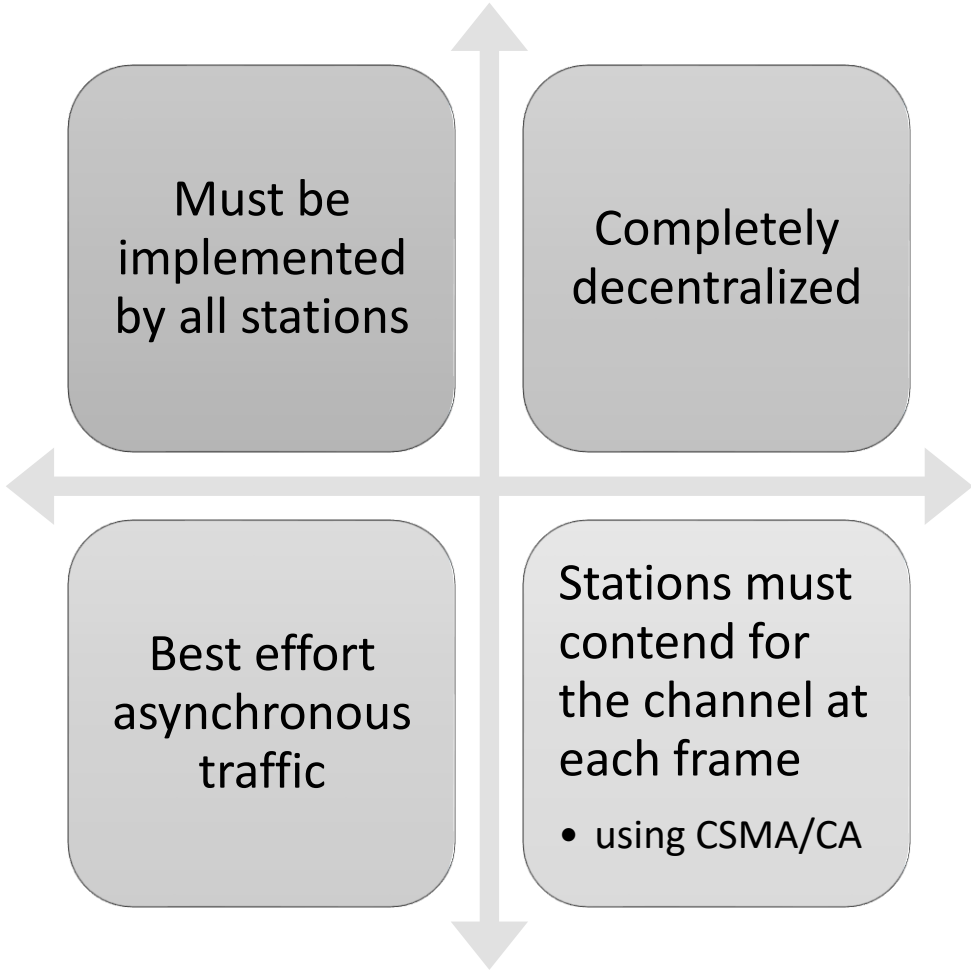
- DCF : Distributed Coordination Function
  - completely decentralized
  - thought for best effort asynchronous traffic
- PCF : Point Coordination Function
  - uses base station to control all activity in its cell
  - thought for delay-sensitive traffic
  - AP polls stations for transmissions
  - based on DCF

DCF **must** be implemented by all stations

DCF and PCF can be active at the same time in the same cell

# IEEE 802.11:

# Distributed Coordination Function – DCF (1)



# IEEE 802.11:

# Distributed Coordination Function – DCF (2)

- Carrier sensing is performed at two levels:
  - *physical CS*
    - checking the frequency to determine whether the medium is in use or not
    - physical carrier sense to detect an incoming signal
    - detects any activity in the channel due to other sources
  - *virtual CS*
    - performed sending duration information in the header of an RTS, CTS and data frame
    - Keeps the channel “virtually busy” up to the end of a data frame transmission
  - A channel is marked busy if either the physical or the virtual CS indicate busy

# IEEE 802.11:

# Distributed Coordination Function – DCF (3)

- Priority access to the medium is controlled through the use of interframe space (IFS) time intervals
  - IFS: mandatory periods of idle time on the transmission medium
- Three IFS specified by the standard:
  - short IFS (SIFS)
  - point coordination function IFS (PIFS)
  - Distributed coordination function IFS (DIFS)
  - SIFS < PIFS < DIFS
  - stations only required to wait a SIFS have the highest priority

# Summary

INFRASTRUCTURED AND INFRASTRUCTURE-LESS WIRELESS NETWORKS

PROPERTIES OF WIRELESS CHANNELS

HIDDEN AND EXPOSED TERMINALS

MACA PROTOCOL

IEEE 802.11