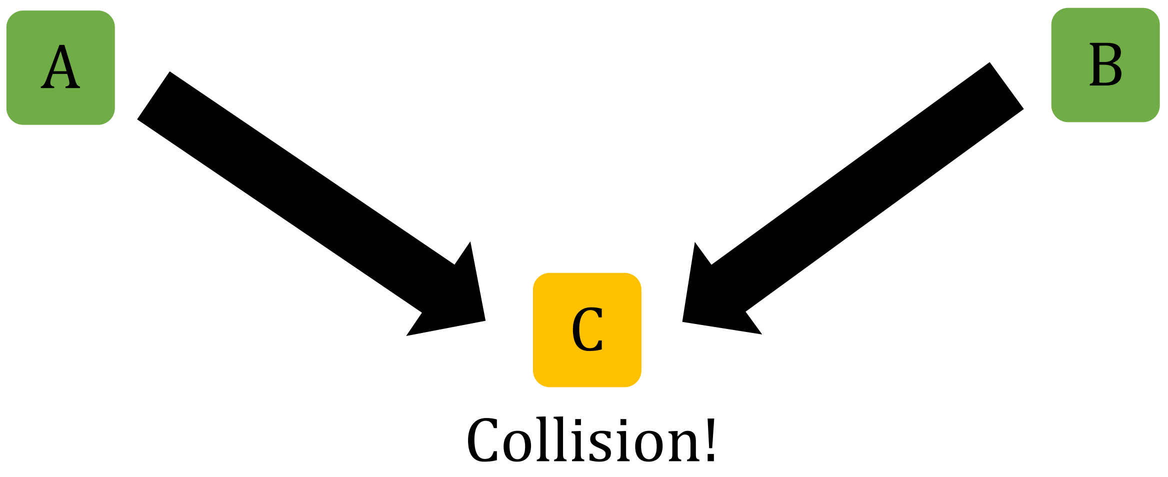
Introduction to Data Communications and Networking

MAC Protocol

郭桐惟

The Problem of Sharing a Channel

- If two transmissions happen at the same time (and use the same frequency), a collision may happen
- We need to properly arrange the transmissions



Design Guidelines of MAC Protocols

- MAC: Medium Access Control
- Guidelines:

1. Reasonable throughput
2. Fairness

Approaches of MAC Protocols

1. Random access protocols
    - There is no scheduled time for a node to transmit
    - Used in Wi-Fi and legacy Ethernet
2. Controlled-access protocols
    - The nodes consult one another to find out which node has the right to send
    - Sometimes used in Wi-Fi
3. Channelization protocols
    - Divide the channel into smaller channels
    - Used in cellular networks

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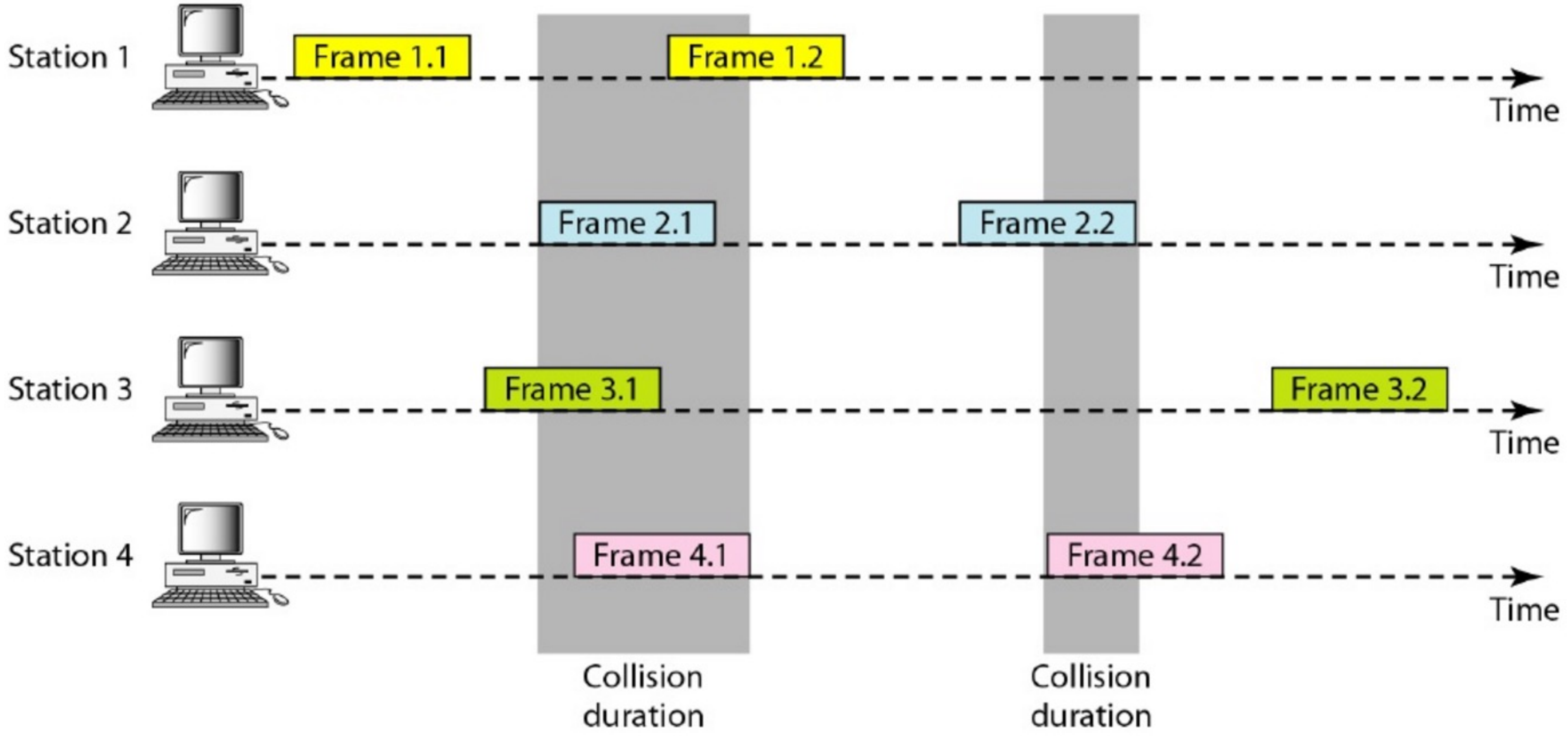
Pure ALOHA

- Developed in early 1970 at University of Hawaii
- Designed for wireless LAN

- Q: When to transmit a frame?
- A: Whenever you have a frame to send
- Consequence: A lot of collisions

$\overset{o}{R_A} \leftarrow \overset{o}{A}$ $\overset{o}{B} \rightarrow \overset{o}{R_B}$

Frames in a Pure ALOHA



Retransmission

- A node must retransmit frames if collisions happen
- How to detect collisions in **wireless channels**?
- The receiver must send an acknowledgement (ACK) once a frame is received
- If the ACK does not arrive after a **timeout**, the sender assumes that the frame is destroyed
- Q: What is a reasonable ACK timeout?
- A: the maximum round-trip propagation time

When to Retransmit

- Retransmit once you find the frame is destroyed?
- Consequence: Collision again
- Randomness comes to help

1. Wait a random amount of time after ACK timeout
2. Retransmit

- The random waiting time is the maximum propagation time (or the average transmission time of a frame) times a number chosen uniformly at random from $[0, W]$
- What should W be?

How to Determine W?

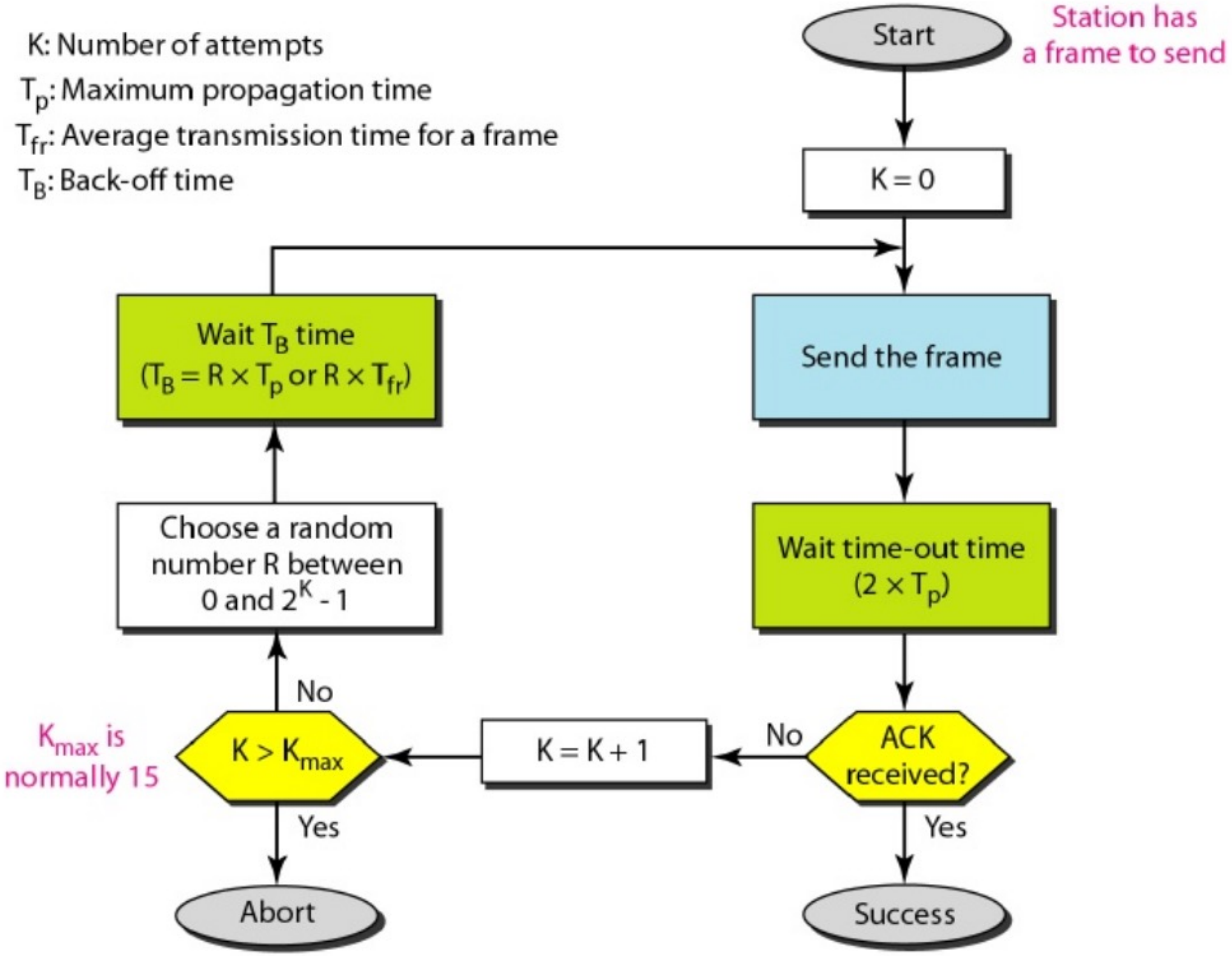
- Intuition:

\# of nodes contending for the channel $\uparrow \Rightarrow W \uparrow$

\# of collisions $\uparrow \Rightarrow$ # of nodes contending for the channel $\uparrow$

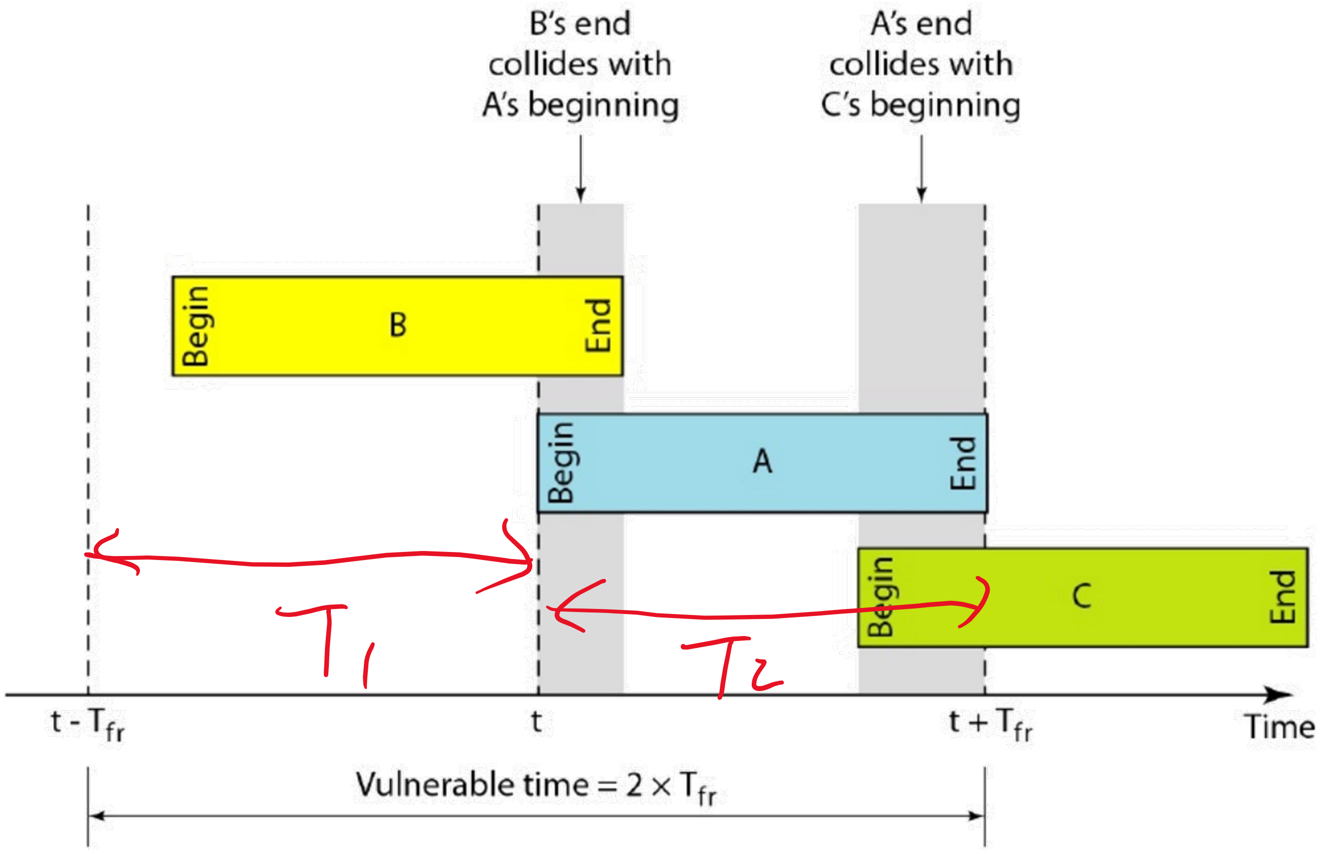
- \# of collisions $\uparrow \Rightarrow W \uparrow$
- Initially, $W = 1$
- Double the window size whenever a frame is destroyed
  - $W = 2^K - 1$ for some K
  - Increase K by 1 whenever a frame is destroyed

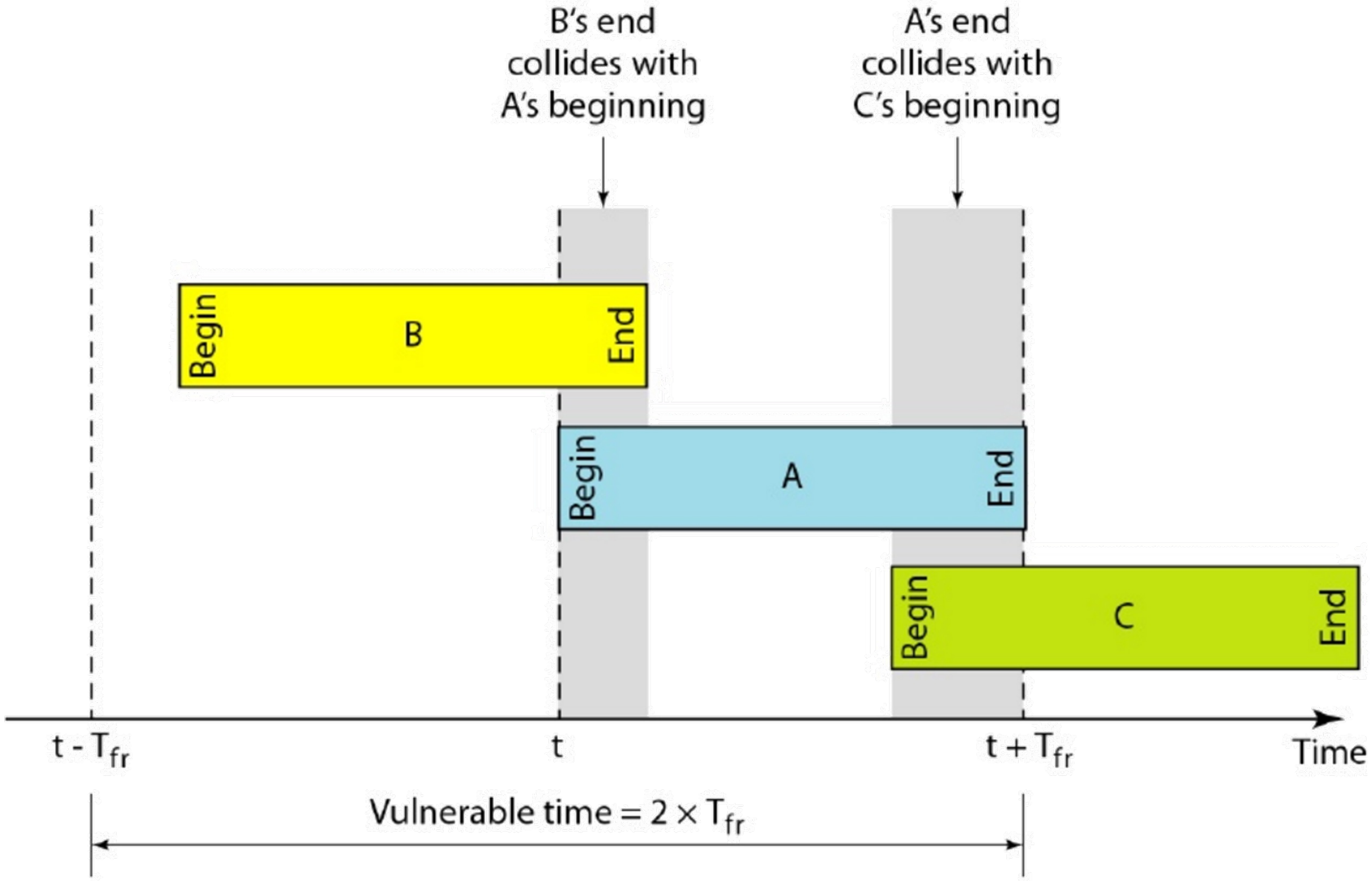
Procedure for Pure ALOHA



Vulnerable Time for Pure ALOHA

- Assume that all the frames in the network have the same length T_{fr}

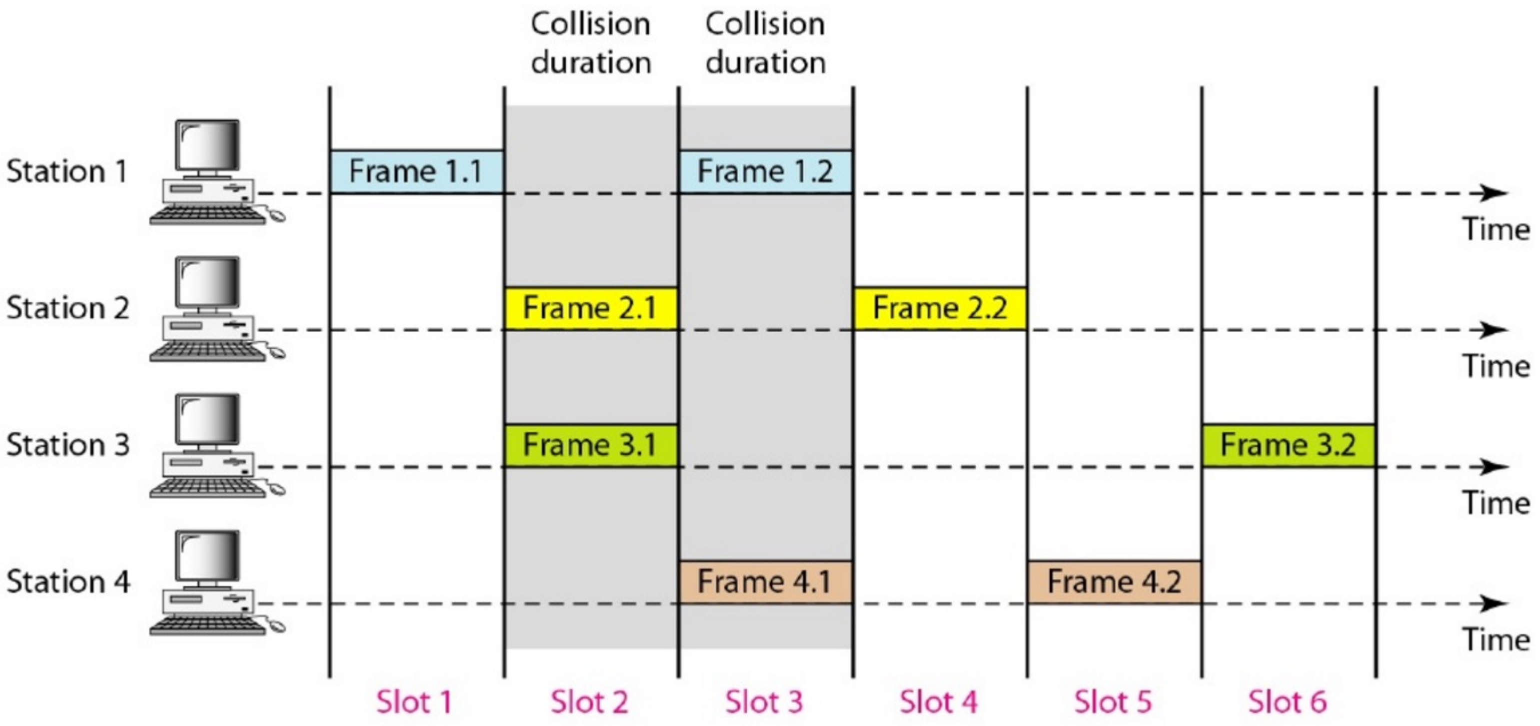




Collisions can be avoided
if B and C slightly shift their frames

Slotted ALOHA

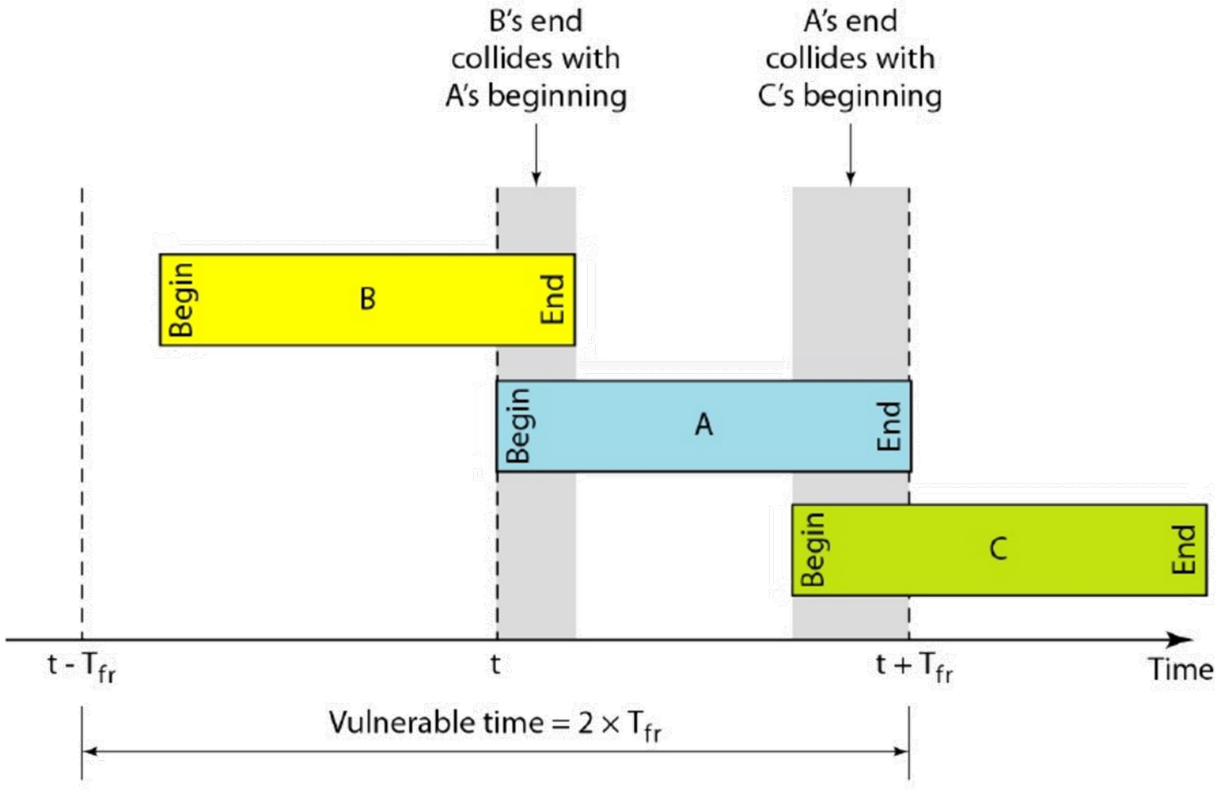
- In slotted ALOHA, we divide the time into slots of T_{fr}
- A node can only send a frame at the beginning of a slot



Analysis of Pure ALOHA & Slotted ALOHA

- n: the number of nodes
- p: the probability that a node sends a frame during one slot
- Let's calculate the average number of frames that can be received successfully in one slot
- This number can not be greater than 1
- Slotted ALOHA: $n \times p(1-p)^{n-1}$
  - It is maximized when $np = 1$. Intuition?
- Pure ALOHA: $n \times p(1-p)^{2(n-1)}$
  - It is maximized when $np = 0.5$. Intuition?
- $np(1-p)^{n-1} > np(1-p)^{2(n-1)}$

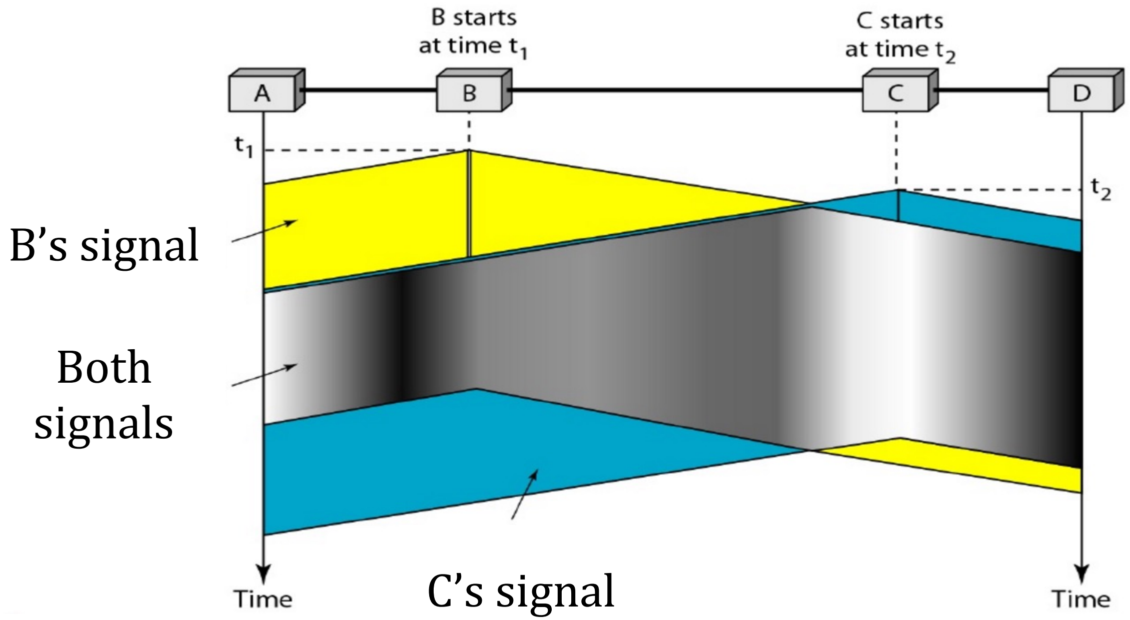
Carrier Sense Multiple Access



Collisions can be avoided
if A first listens to the channel

Carrier Sense Multiple Access (CSMA)

- Idea: sense before transmission
- If the channel is idle, send the frame
- Collisions may still happen. Why?



CSMA/CA
(Collision Avoidance)

- In wireless network, it is very difficult to detect collisions during frame transmission
- We need to avoid collisions
- What should a node do when it senses the channel and finds it idle?

1. Wait a period of time so that the signal from a distant node can be heard
2. Sense again
3. If the channel is still idle, send immediately?

- Q: What will happen?
- A: Collision

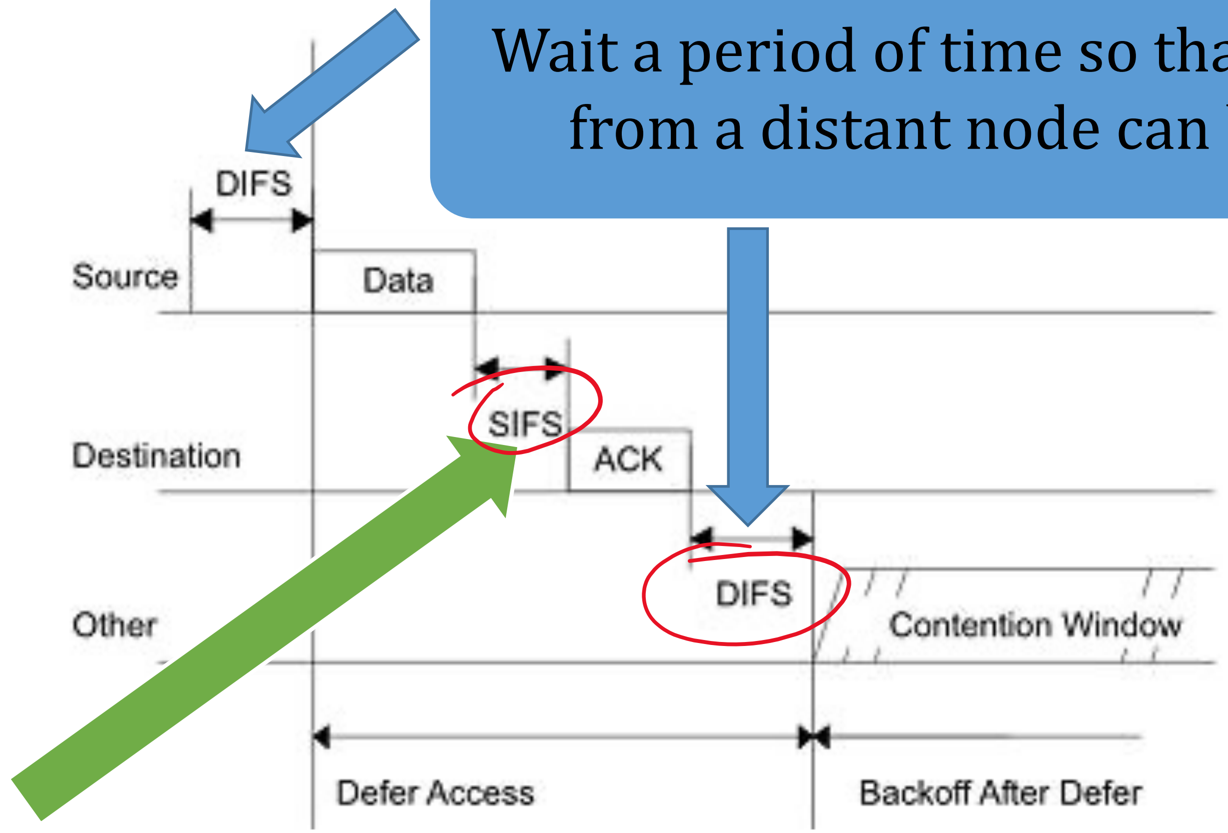
CSMA/CA (Collision Avoidance)

- If the channel is still idle, wait a random amount of time
  - Like slotted ALOHA, choose a number R from $[0, 2^k - 1]$
  - After each slot:
  - If the channel is idle $\Rightarrow$ decrease R by 1;
  - Otherwise, do nothing
  - Send the frame when R becomes 0
  - If no ACK is received (collision), increase k by 1

CSMA/CD
(collision detection)

Timing in CSMA/CA

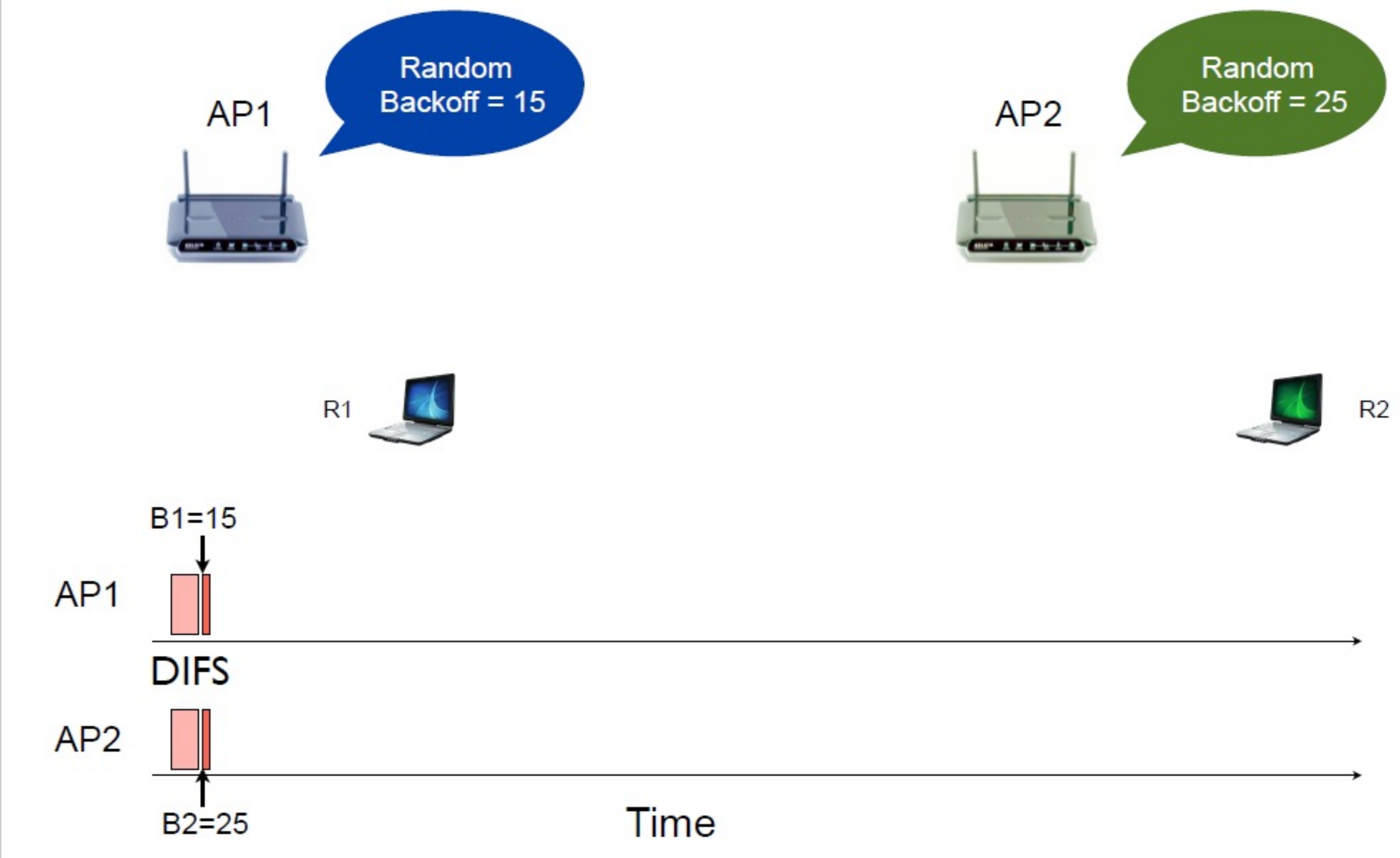
Wait a period of time so that the signal from a distant node can be heard



Inter
Frame
Space

DIFS is longer than SIFS.
What happens if DIFS is shorter than SIFS

Example of Wi-Fi MAC



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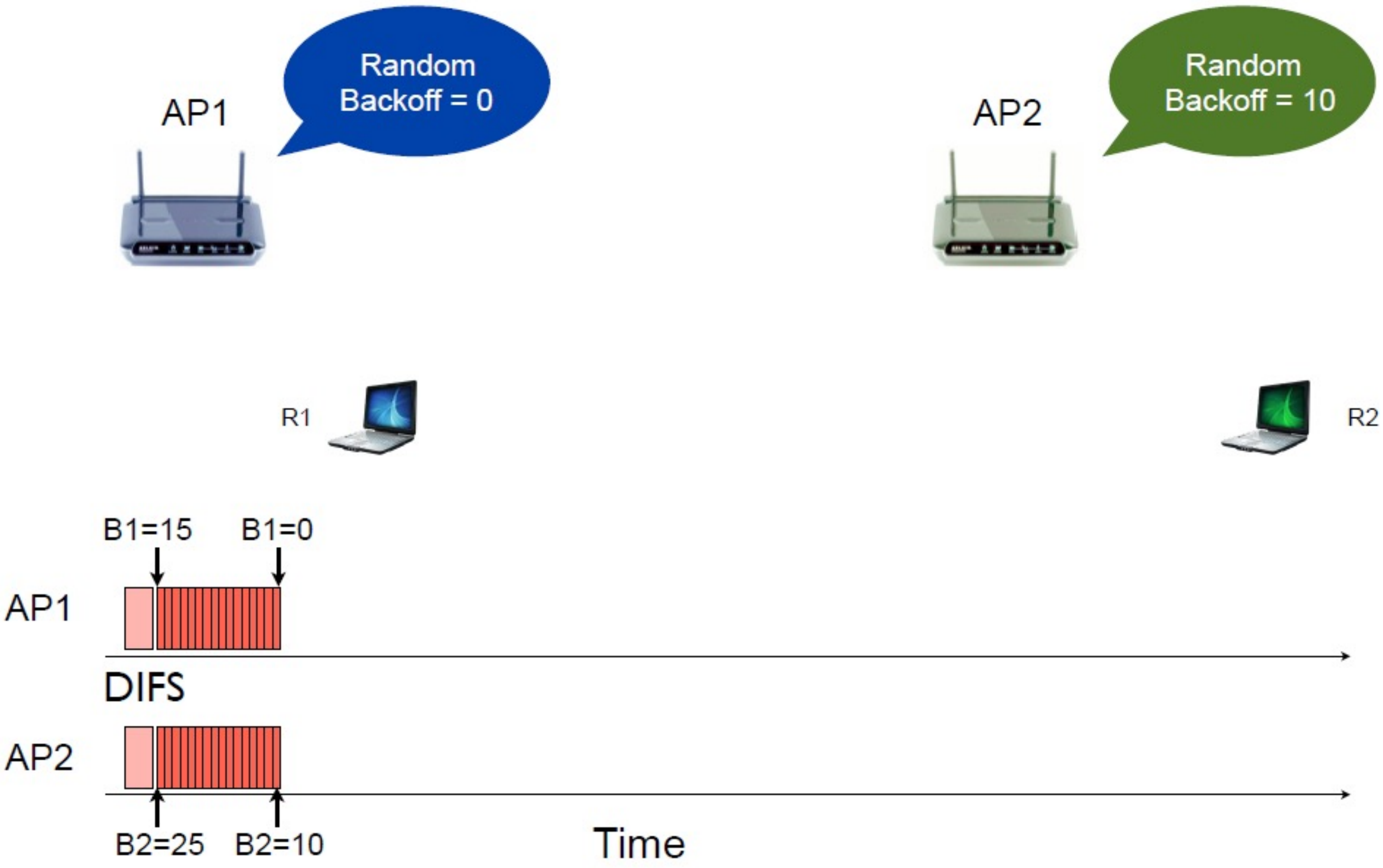

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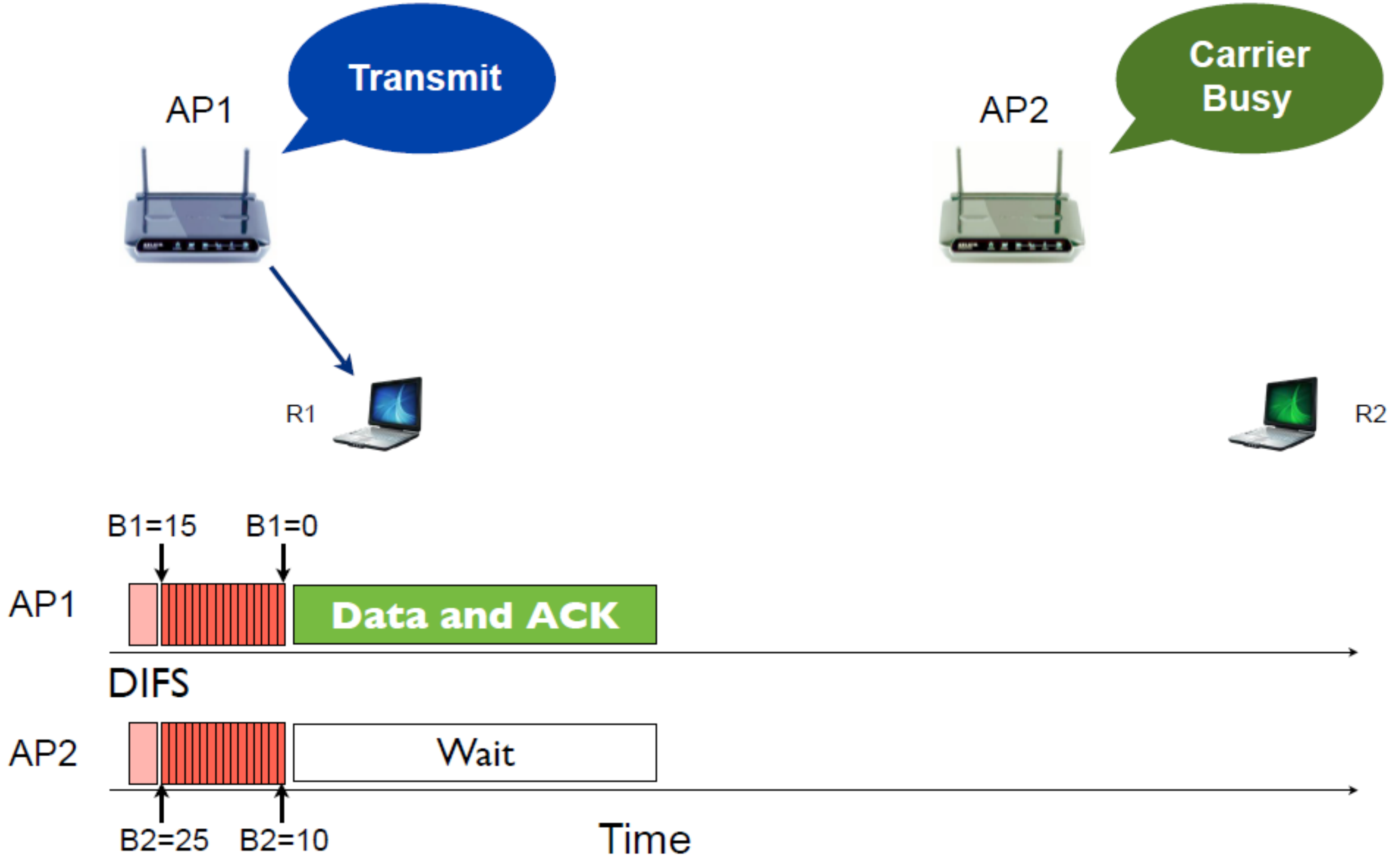

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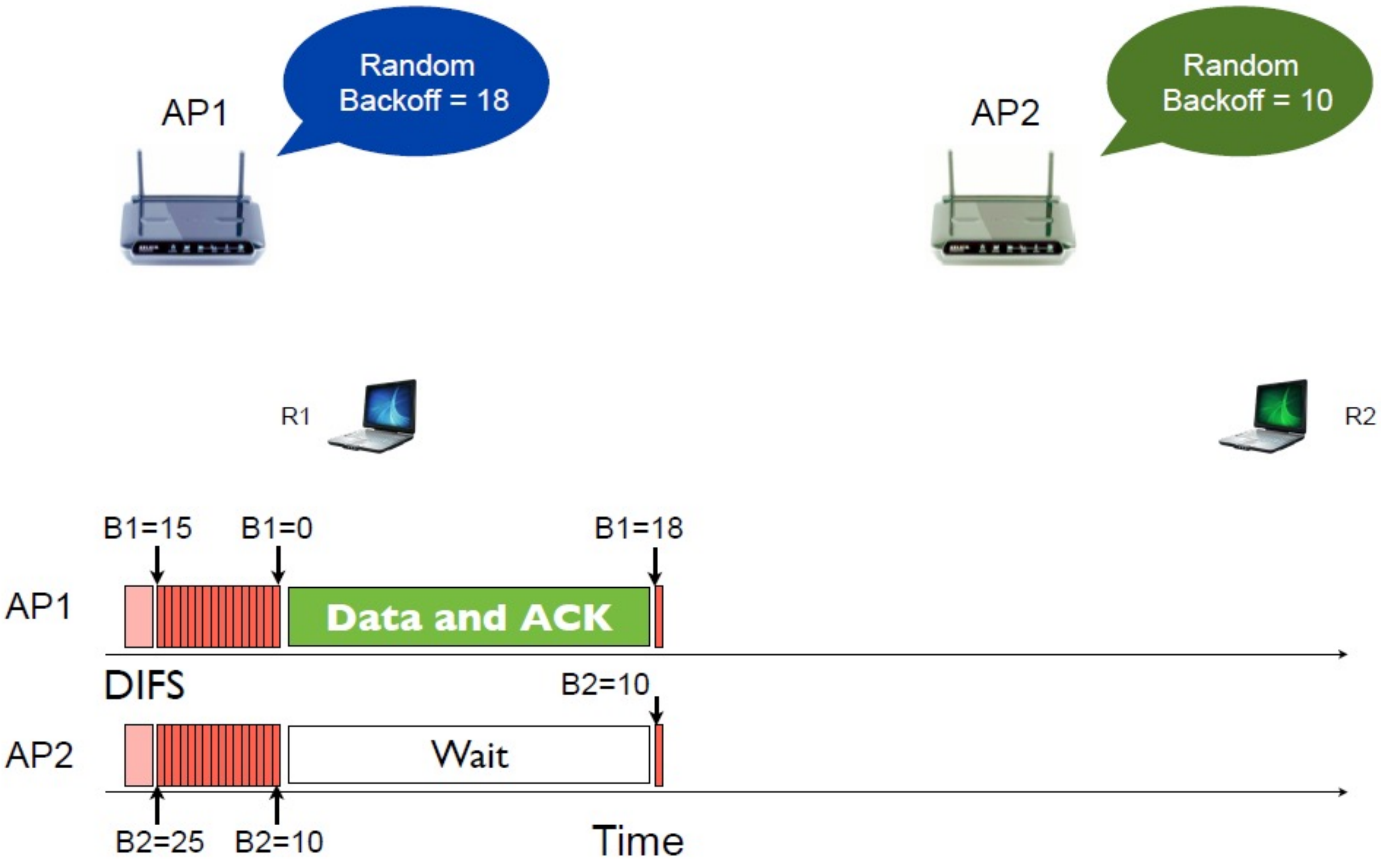

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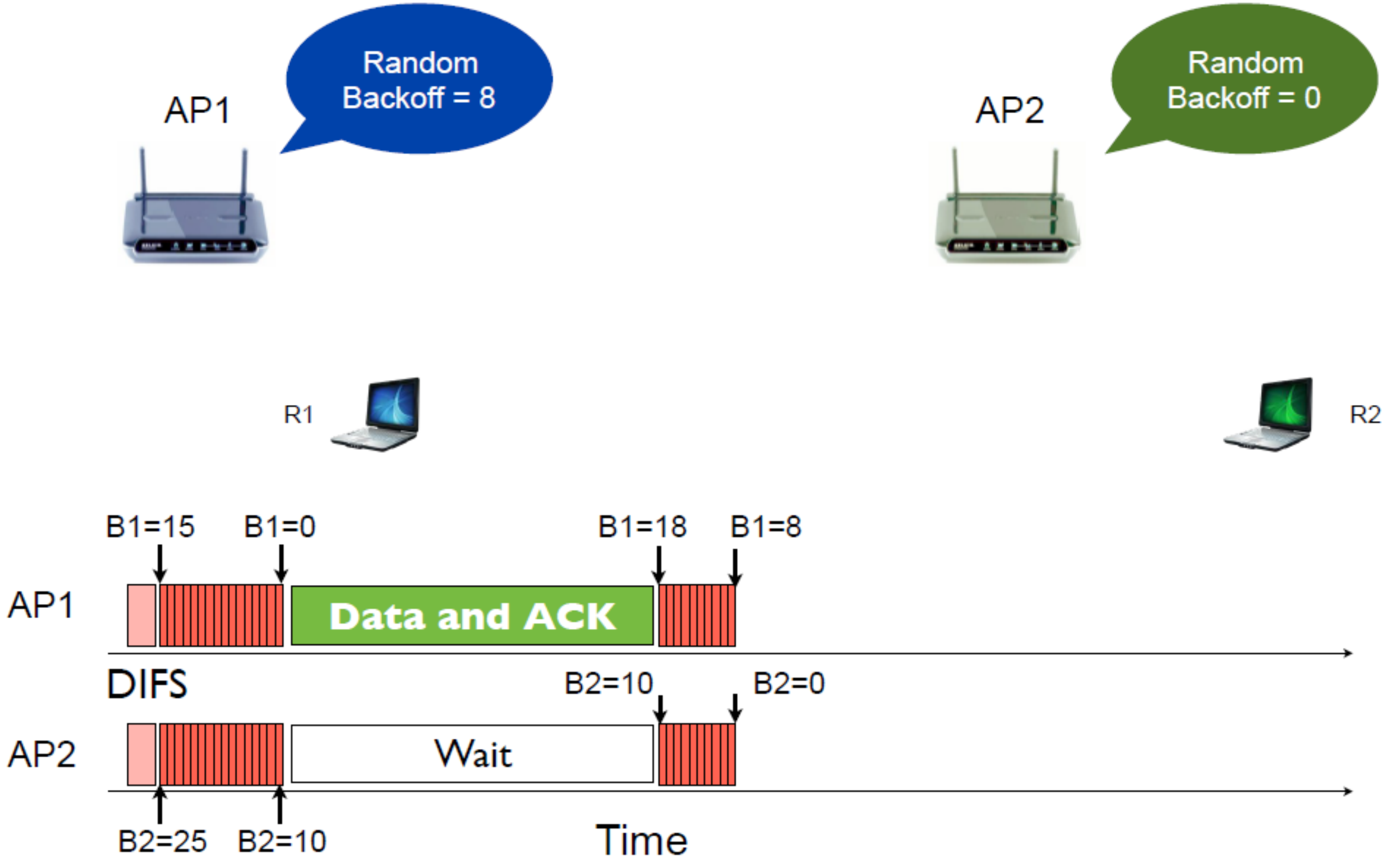

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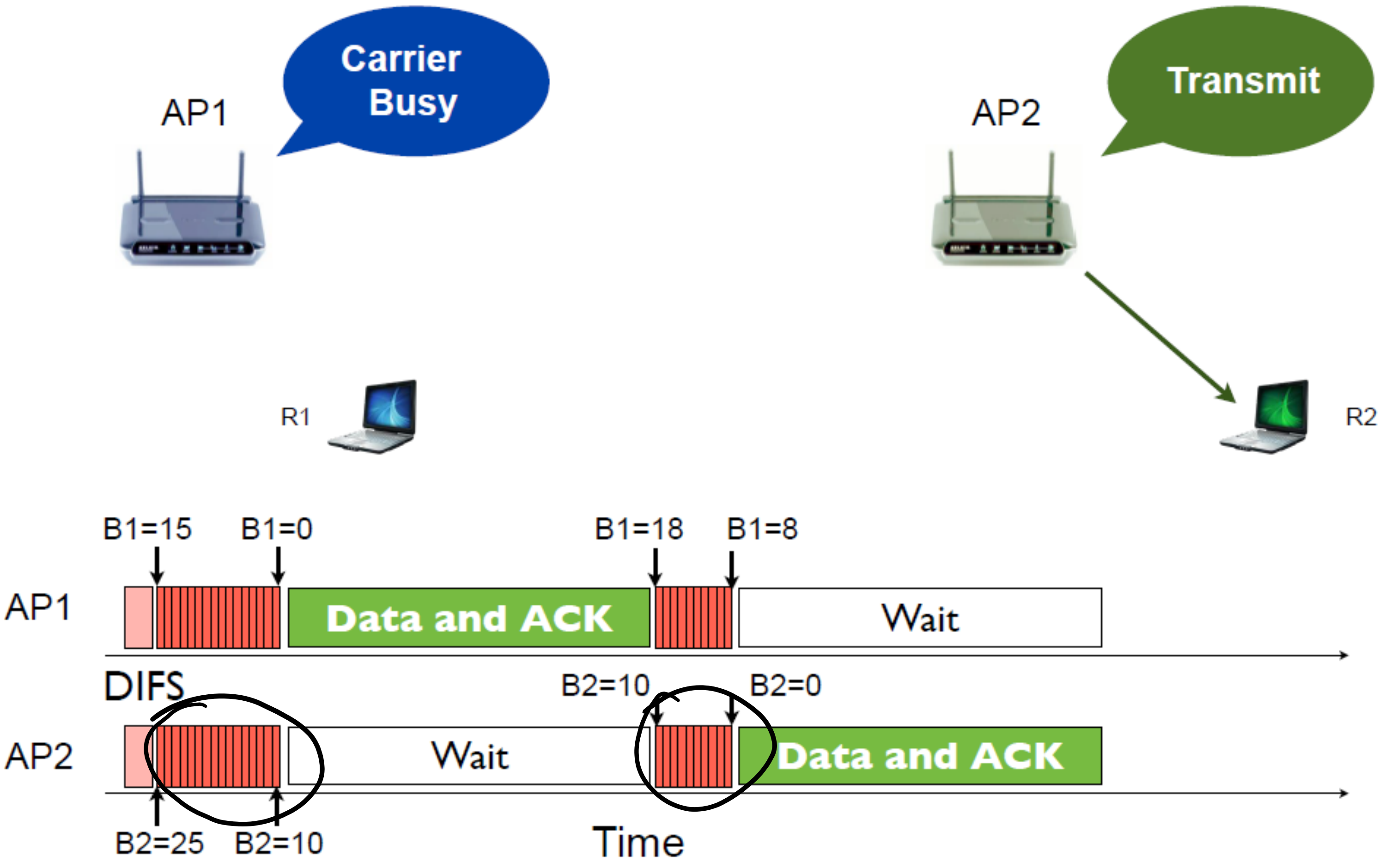

Approaches of MAC Protocols

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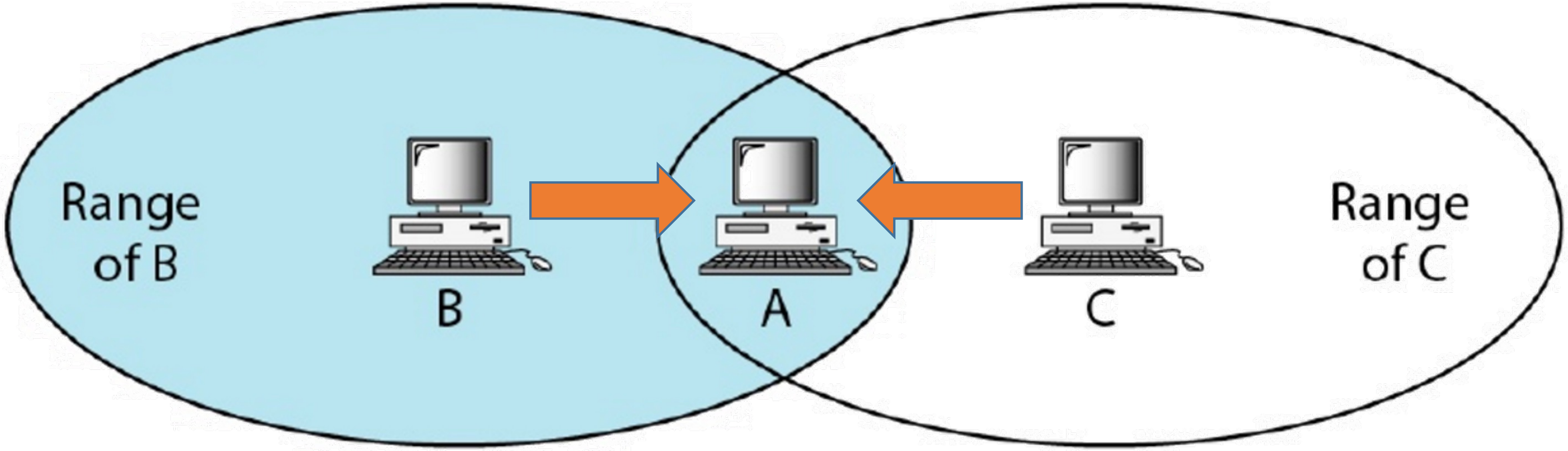
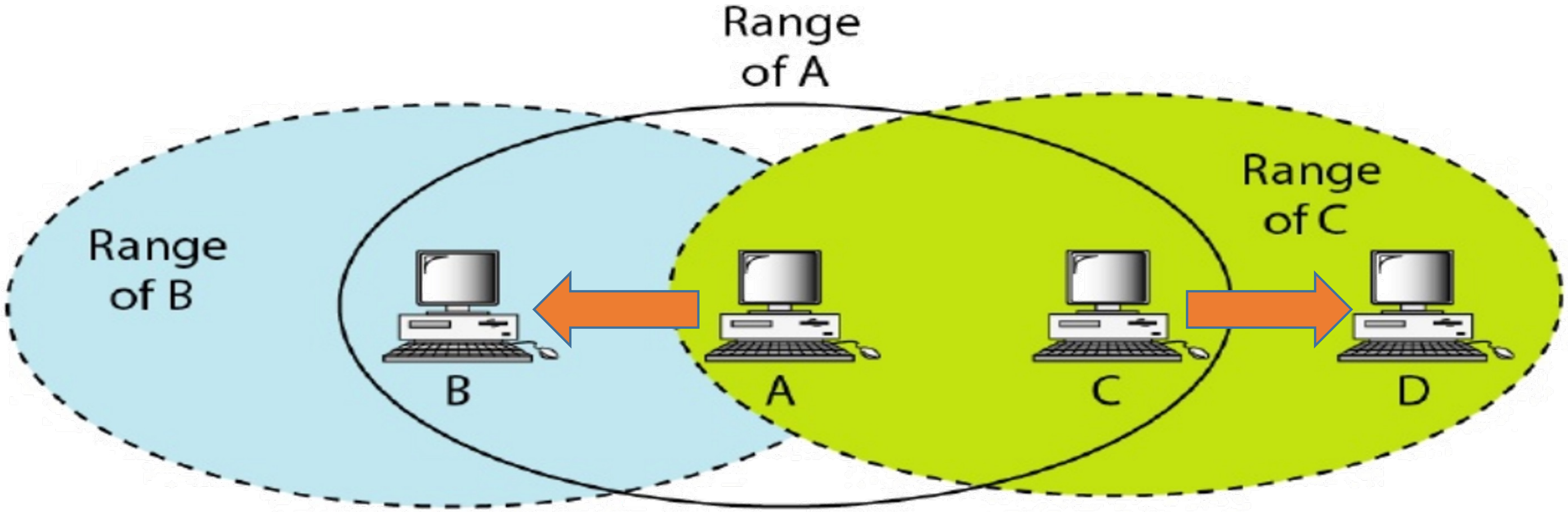
Drawbacks of CSMA/CA

- Hidden terminal problem
  - B is sending frames to A
  - C also tries to send frames to A
  - C senses the channel and finds it idle
  - C sends frames to A. Collision!



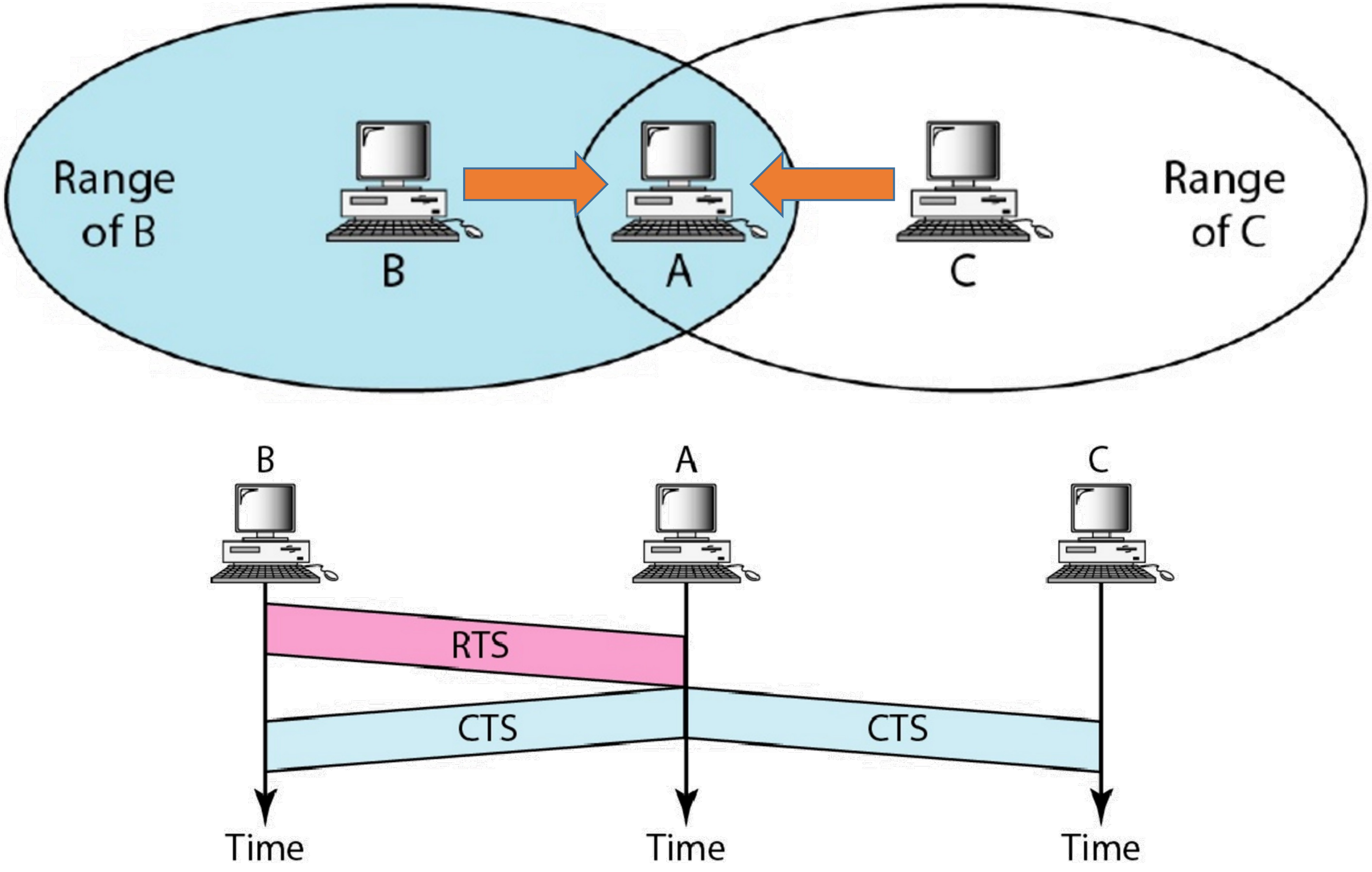
Drawbacks of CSMA/CA

- Exposed terminal problem
  - A is sending frames to B
  - C tries to send frames to D (should be allowed)
  - C senses the channel and finds it busy.
  - C does not send frames to A. A waste of time!

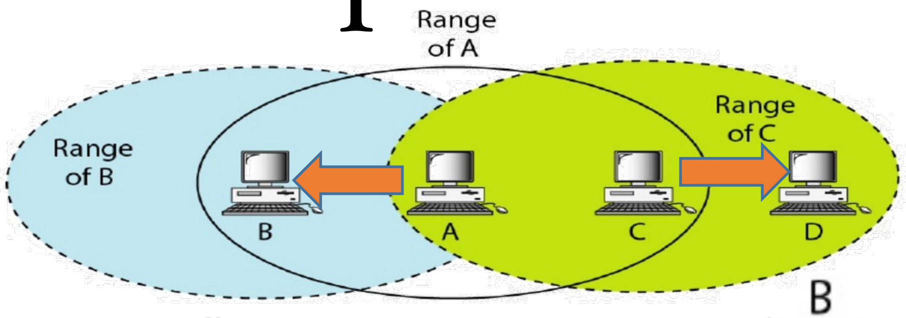


Solutions for the Hidden Terminal Problem

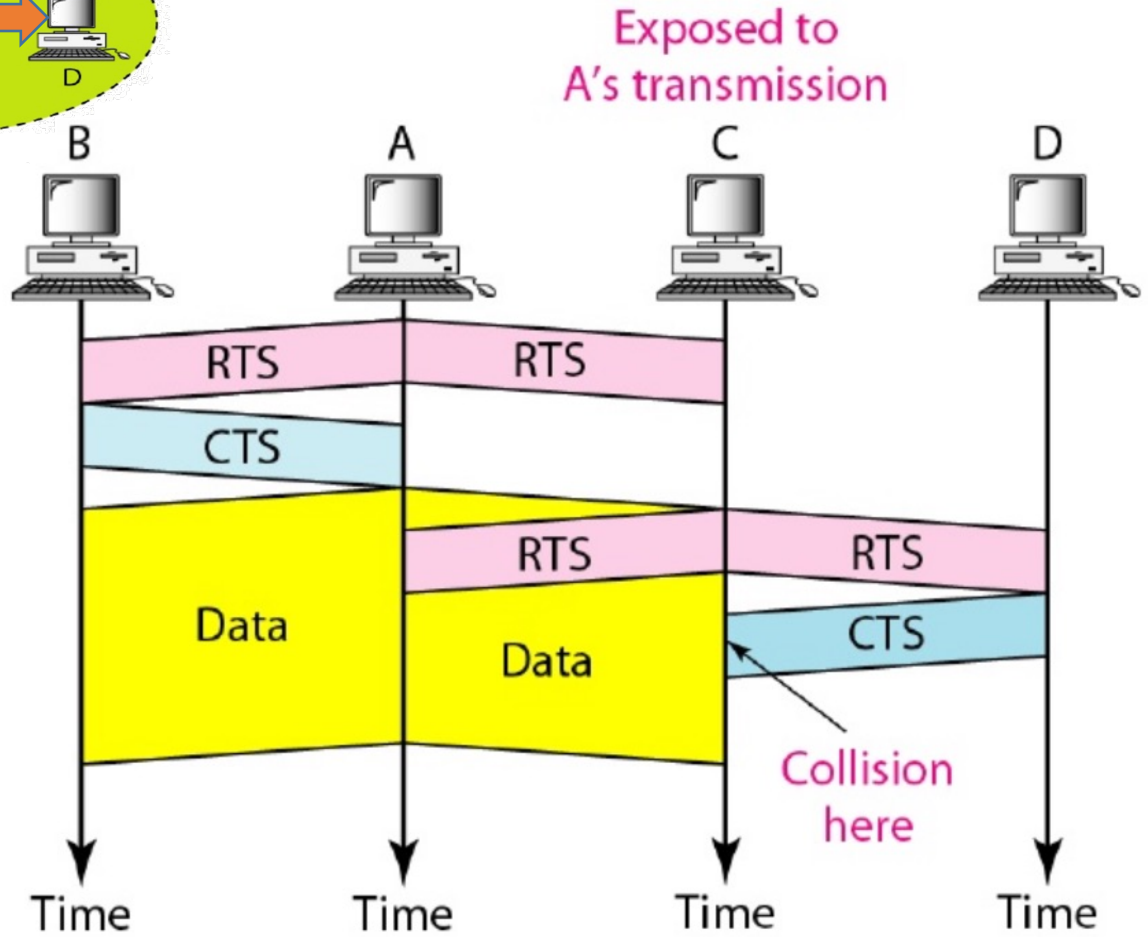
- Send a short control frame to the receiver first
  - RTS: request to send
  - CTS: clear to send
- Since these control frames are short, the probability of collision is less than the normal frames
- Can be combined with CSMA/CA
- Overhead is larger compared to pure CSMA/CA


Range of B
B
A
C
Range of C
B
A
C
RTS
CTS
CTS
Time
Time
Time

How About
Exposed Terminal Problems?



If A is sending,
then C cannot
hear CTS from D



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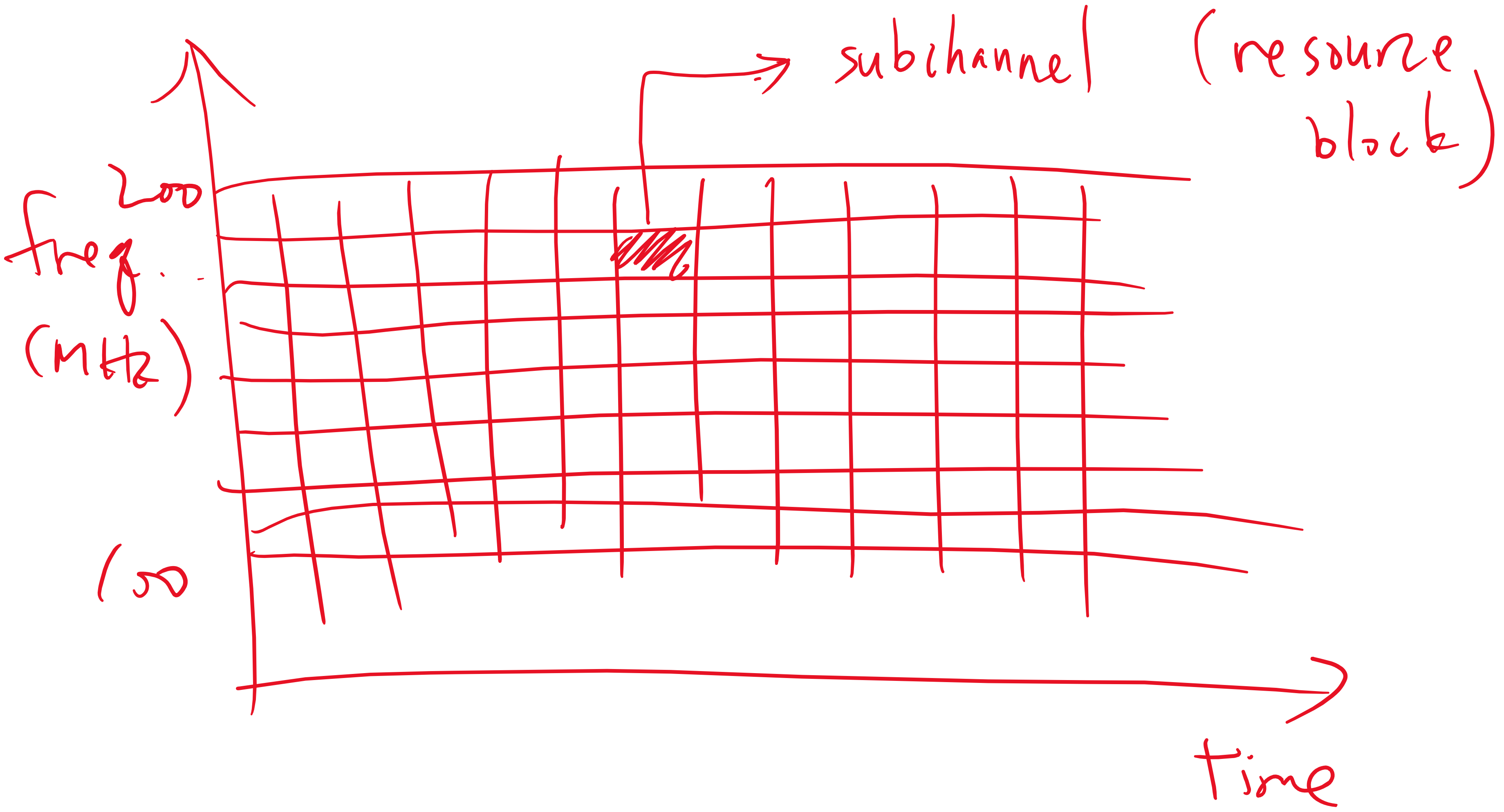
FDMA

- Frequency-Division Multiple Access (FDMA)
- The available bandwidth is divided into frequency bands
- Adjacent bands are separated by a guard band to interference since filters are not perfect
- Require a centralized control node, e.g., base stations
- Multiple users can share the channel at the same time

TDMA

- Time-Division Multiple Access (TDMA)
- Each node is allocated a time slot
- Requires a centralized control node, e.g., base stations
- Time synchronization is needed
- Adjacent time slots are separated by a guard time to prevent interference since time synchronization is not perfect

FDMA + TDMA



CDMA

- Code-Division Multiple Access
- Nodes can share the same frequency band and time slot
- Idea: Orthogonality
- Each node n_i is associated with a vector (code) v_i
- $v_i \cdot v_j = 0$ if $i \neq j$

Example

- S_1 sends a signal d_1 (+1 or -1) to D
- S_2 sends a signal d_2 (+1 or -1) to D'
- D receives $d_1 + d_2$ but still does not know what d_1 is
- Consider 2 orthogonal vectors c_1 and c_2
- S_1 sends $d_1 c_1$ to D
- S_2 sends $d_2 c_2$ to D'
- D receives $R = d_1 c_1 + d_2 c_2$
- If D knows c_1, then D knows that $d_1 = \frac{c_1 \cdot R}{||c_1||^2}$

An Example of 4 Senders

- $d_1 = -1, d_2 = -1, d_3 = +1, d_4 = +1$
- $c_1 = [+1, +1, +1, +1], d_1 c_1 = [-1, -1, -1, -1]$
- $c_2 = [+1, -1, +1, -1], d_2 c_2 = [-1, +1, -1, +1]$
- $c_3 = [+1, +1, -1, -1], d_3 c_3 = [+1, +1, -1, -1]$
- $c_4 = [+1, -1, -1, +1], d_4 c_4 = [+1, -1, -1, +1]$
- $c_i \cdot c_j = 0$, if $i \neq j$, and $c_i \cdot c_i = 4$
- Signal on the channel: $R = [0,0,-4,0]$ $= c_1 + c_2 + c_3 + c_4$
- $d_1 = -1 = \frac{[0,0,-4,0] \cdot [+1,+1,+1,+1]}{4} = \frac{R \cdot c_1}{c_1 \cdot c_1}$

An Example of 4 Senders

- $d_1 = -1, d_2 = -1, d_3 = +1, d_4 = +1$
- $c_1 = [+1, +1, +1, +1], d_1 c_1 = [-1, -1, -1, -1]$
- $c_2 = [+1, -1, +1, -1], d_2 c_2 = [-1, +1, -1, +1]$
- $c_3 = [+1, +1, -1, -1], d_3 c_3 = [+1, +1, -1, -1]$
- $c_4 = [+1, -1, -1, +1], d_4 c_4 = [+1, -1, -1, +1]$
- $c_i \cdot c_j = 0$, if $i \neq j$, and $c_i \cdot c_i = 4$
- Signal on the channel: $R = [0,0,-4,0]$
- $d_3 = +1 = \frac{[0,0,-4,0] \cdot [+1,+1,-1,-1]}{4} = \frac{R \cdot c_3}{c_3 \cdot c_3}$

How to Generate Orthogonal Vectors?

- A recursive approach
- When there are only two nodes,
$$c_1 = [+1, +1], c_2 = [+1, -1]$$
- How to generate codes for 4 users?
- Let's first generate the code for the first 2 nodes from c_1 and c_2
- Code for the first user: $[c_1, c_1]$
- Code for the second user: $[c_2, c_2]$
- These two codes are orthogonal. Why?

How to Generate Orthogonal Vectors?

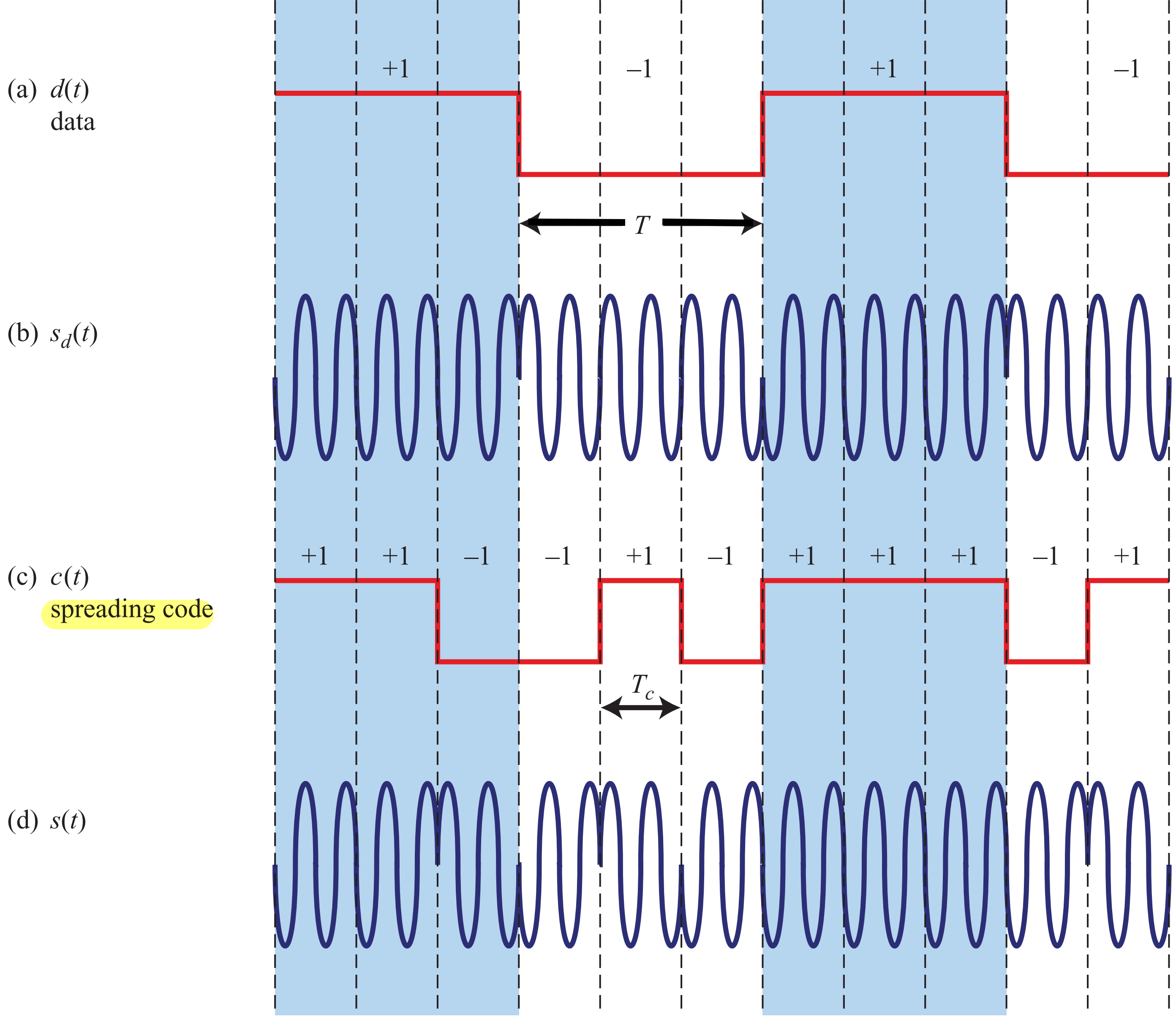
- A recursive approach
- When there are only two nodes,
$$c_1 = [+1, +1], c_2 = [+1, -1]$$
- How to generate codes for 4 users?
- Now we generate the code for the last 2 nodes
- Code for the third user: $[c_1, -c_1]$
- Code for the fourth user: $[c_2, -c_2]$

How to Generate Orthogonal Vectors?

- A recursive approach
- When there are only two nodes,
$$c_1 = [+1, +1], c_2 = [+1, -1]$$
- When there are four nodes,
- Code for the 1st node $= [c_1, c_1] = [+1, +1, +1, +1]$
- Code for the 2nd node $= [c_2, c_2] = [+1, -1, +1, -1]$
- Code for the 3rd node $= [c_1, -c_1] = [+1, +1, -1, -1]$
- Code for the 4th node $= [c_2, -c_2] = [+1, -1, +1, -1]$

How to Generate Orthogonal Vectors?

- Walsh table:
- $W_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}$
- $W_{2n} = \begin{bmatrix} W_n & W_n \\ W_n & -W_n \end{bmatrix}$
- **Rows** in Walsh table correspond to orthogonal vectors
- What if the number of nodes is not a power of 2?

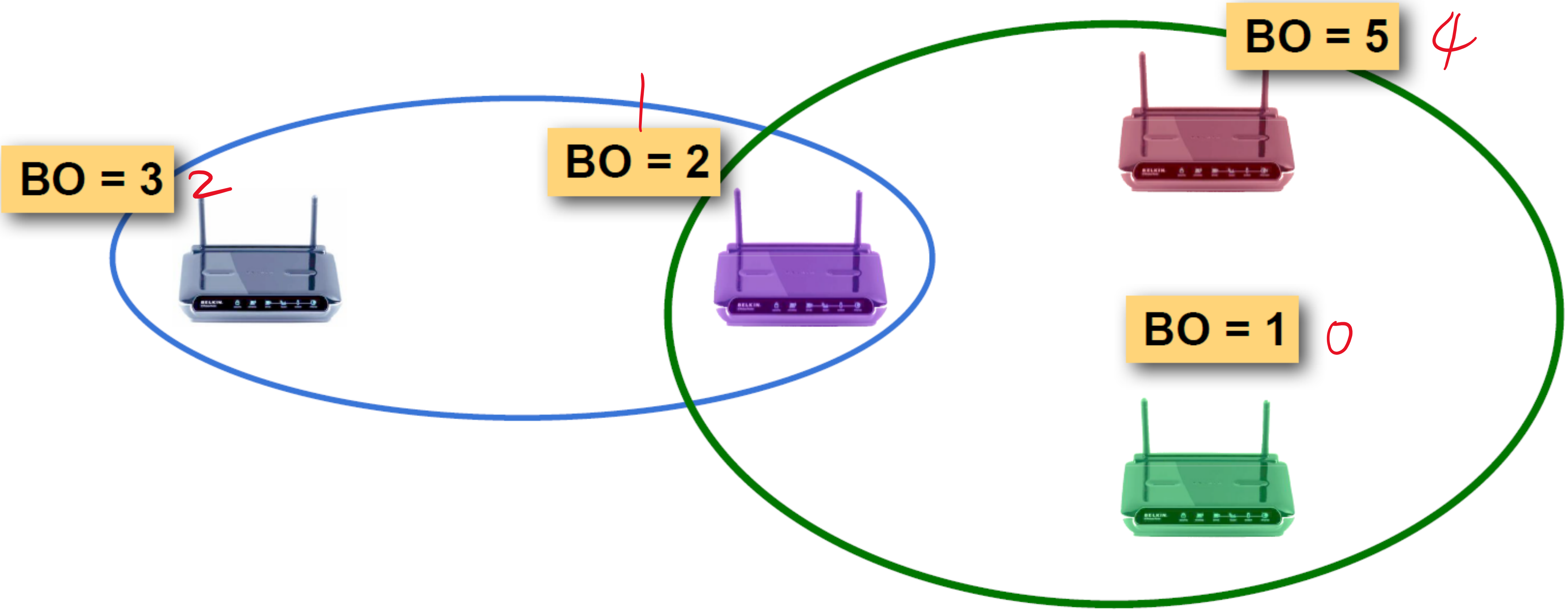


data from sender
(+1, −1, +1, −1)
×
carrier signal
×
digital signal
||

Compare $s_d(t)$ and $s(t)$. The spectrum is spread → spectrum (bandwidth) ↑

Multiple Collision Domains

- Does Back2F work with real-world scattered APs?



Reference

- B.A. Forouzan, Data Communications and Networking, McGraw Hill, 2007
- Wireless Communication Networks and Systems 1st edition, Global edition Cory Beard, William Stallings © 2016 Pearson Education, Ltd.
- http://alumni.cs.ucr.edu/~saha/stuff/cdma_gps.htm
- https://www.sigmobile.org/mobicom/2011/slides/349-notime-slides.pdf (No Time to Countdown: Backing Off in Frequency Domain)