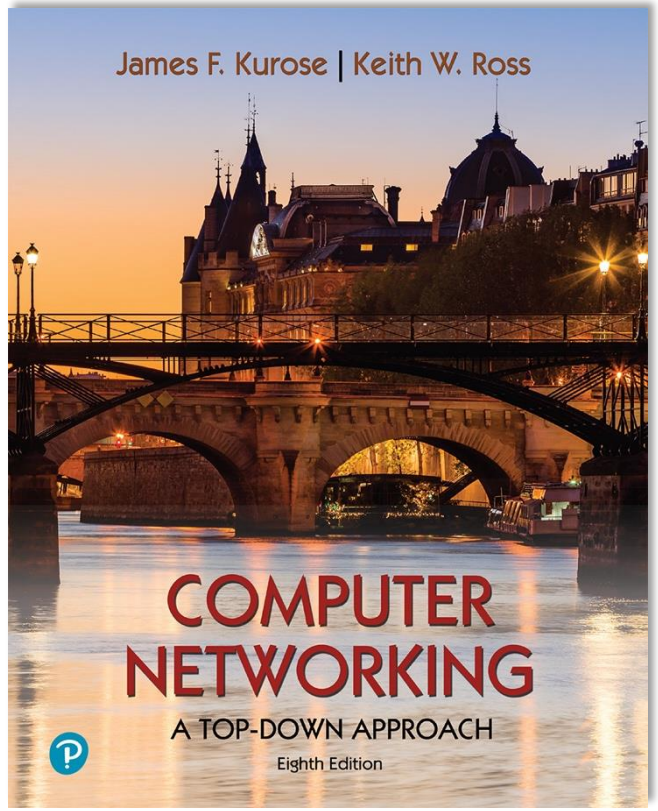
Chapter 7
Wireless and Mobile Networks

Yaxiong Xie

Department of Computer Science and Engineering
University at Buffalo, SUNY



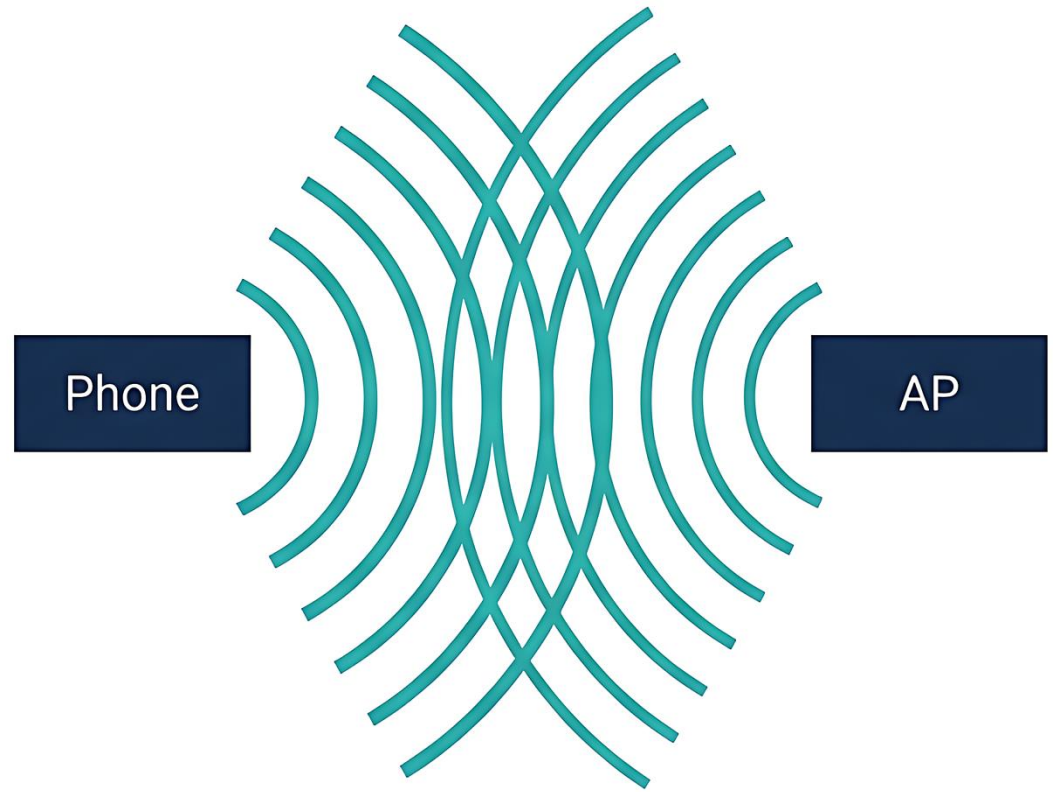
Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Adapted from the slides of the book's authors

From Wired Links to Wireless Links

The familiar baseline

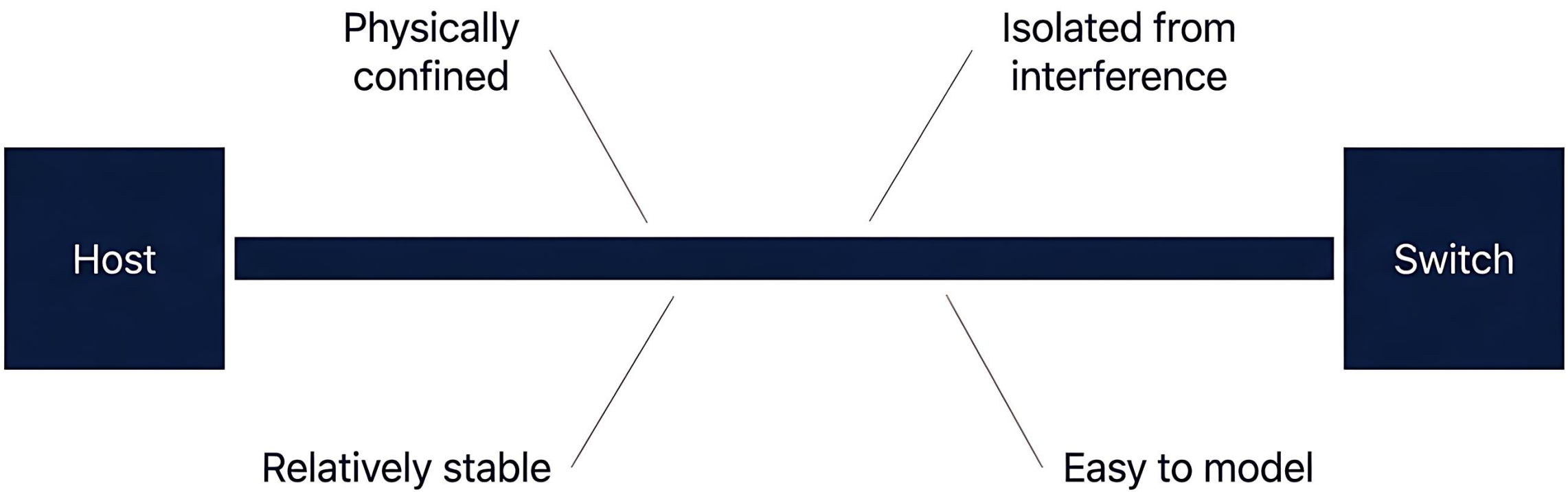
When the cable disappears



Wireless is not just wired networking without cables.

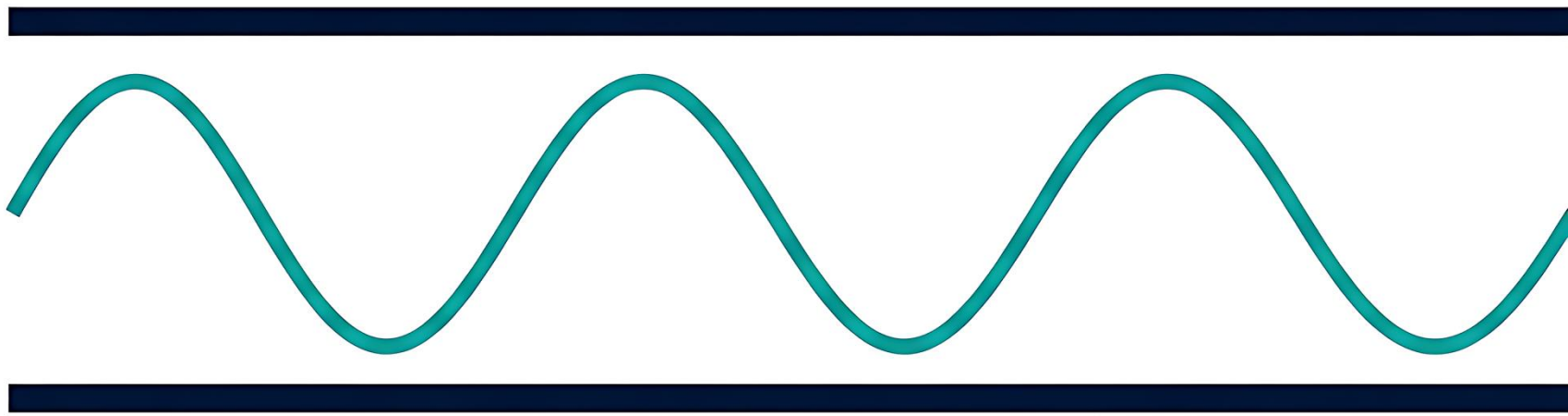
A Wired Link Is Usually a Clean Abstraction

A relatively stable pipe between two endpoints.



Wired Signals Are Confined

Clear physical boundaries

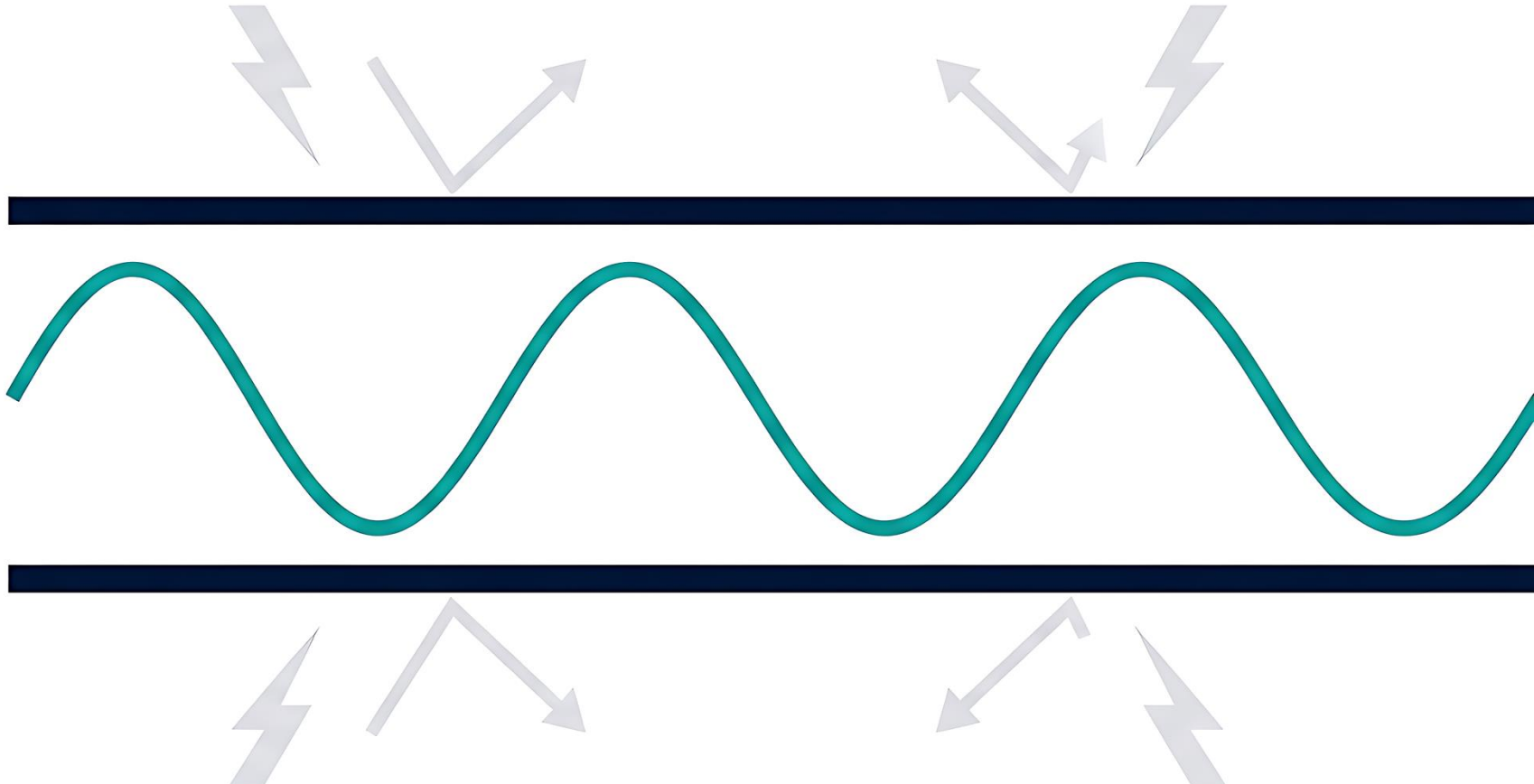


The physical isolation of the cable guarantees separation.

Wired Signals Are Confined

Clear physical boundaries

Limited outside interference



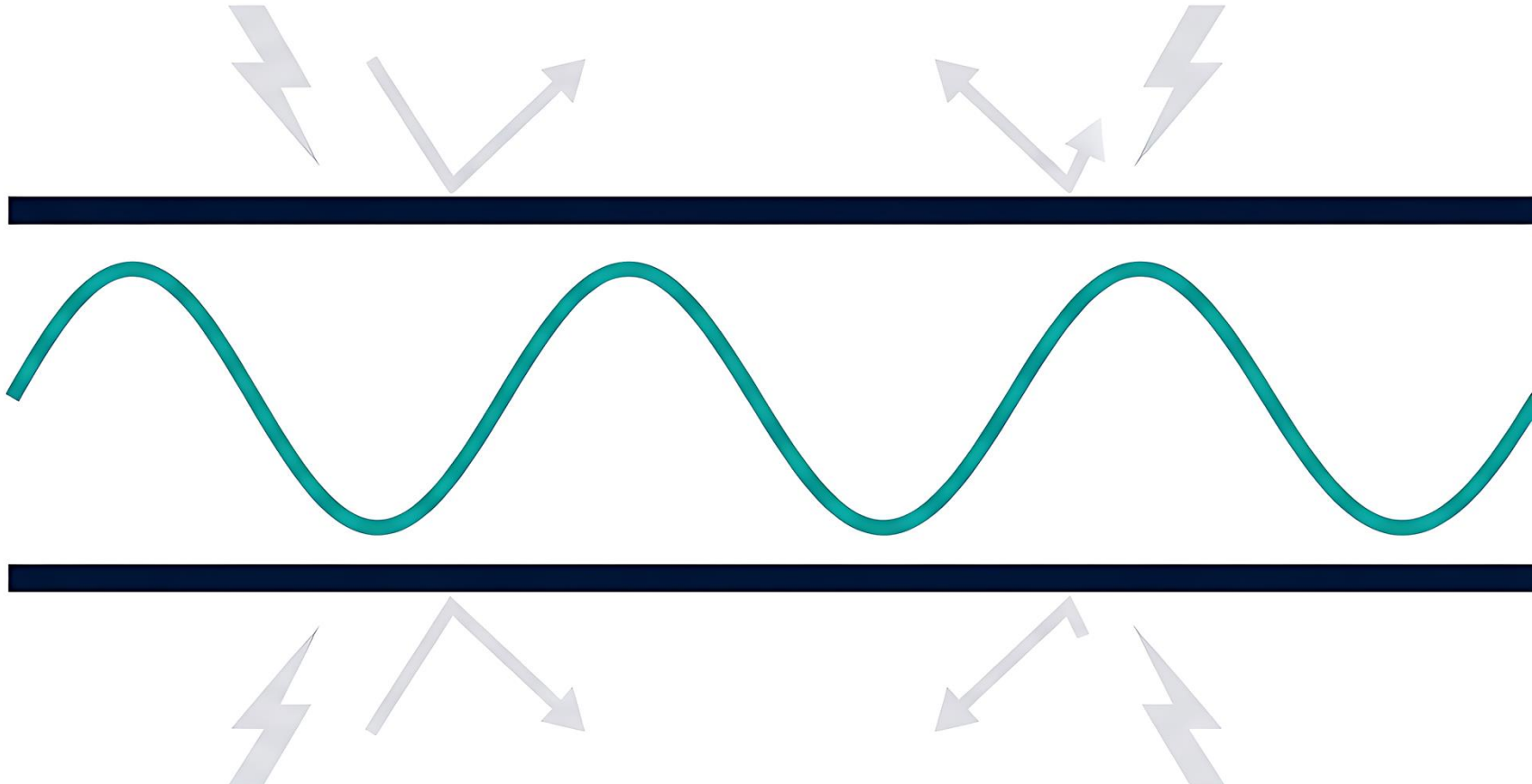
The physical isolation of the cable guarantees separation.

Wired Signals Are Confined

Clear physical boundaries

Limited outside interference

Predictable signal propagation



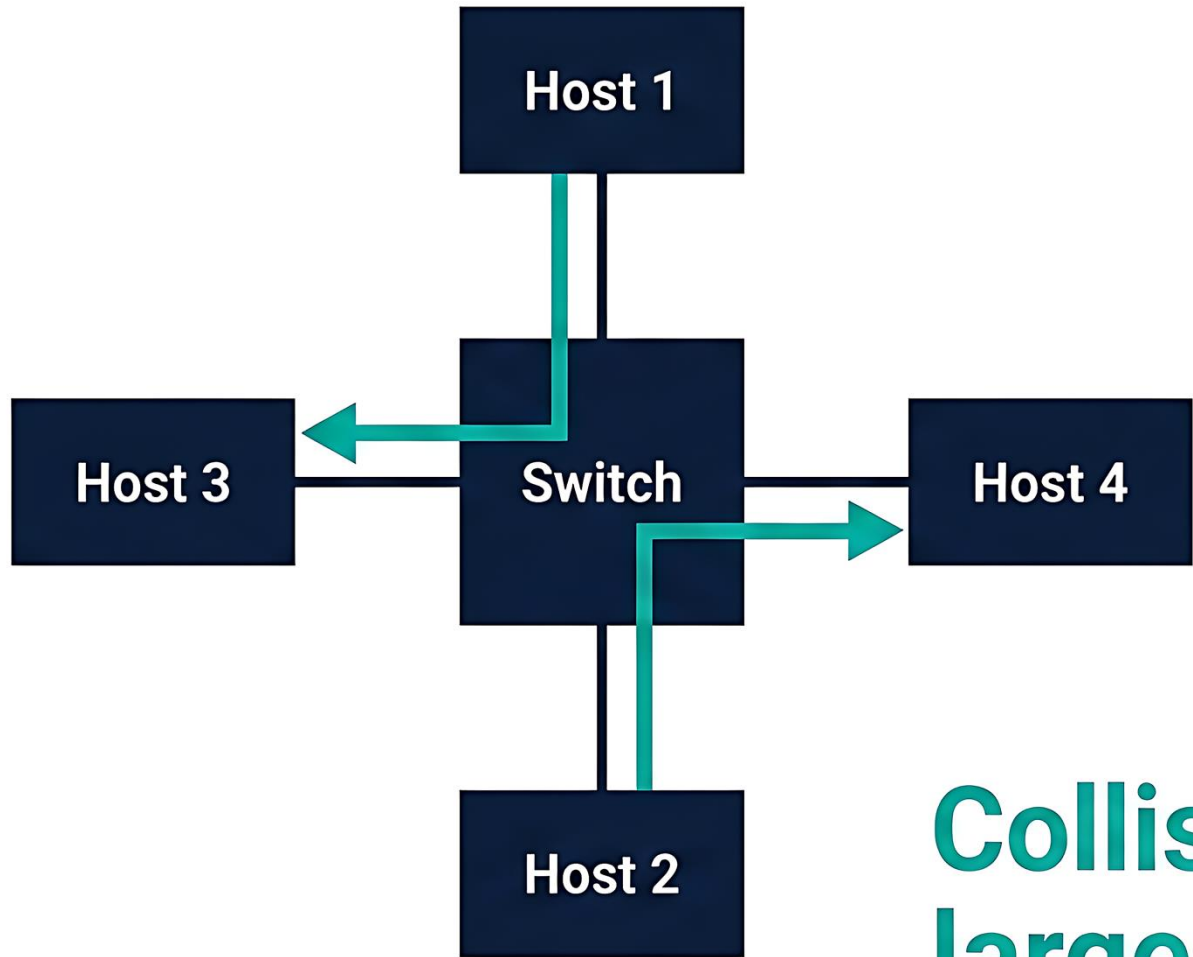
The physical isolation of the cable guarantees separation.

Switching Separates Communication

Dedicated links per host

Medium is no longer shared

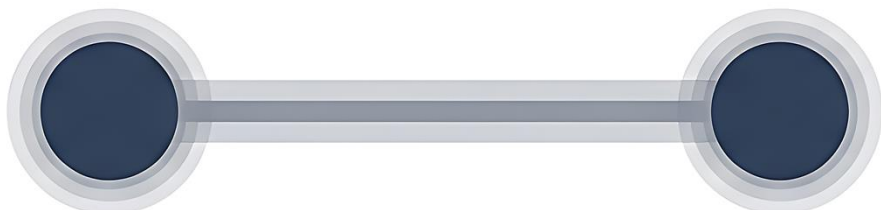
Simultaneous communications



Collisions largely avoided.

Wireless Uses the Air as the Medium

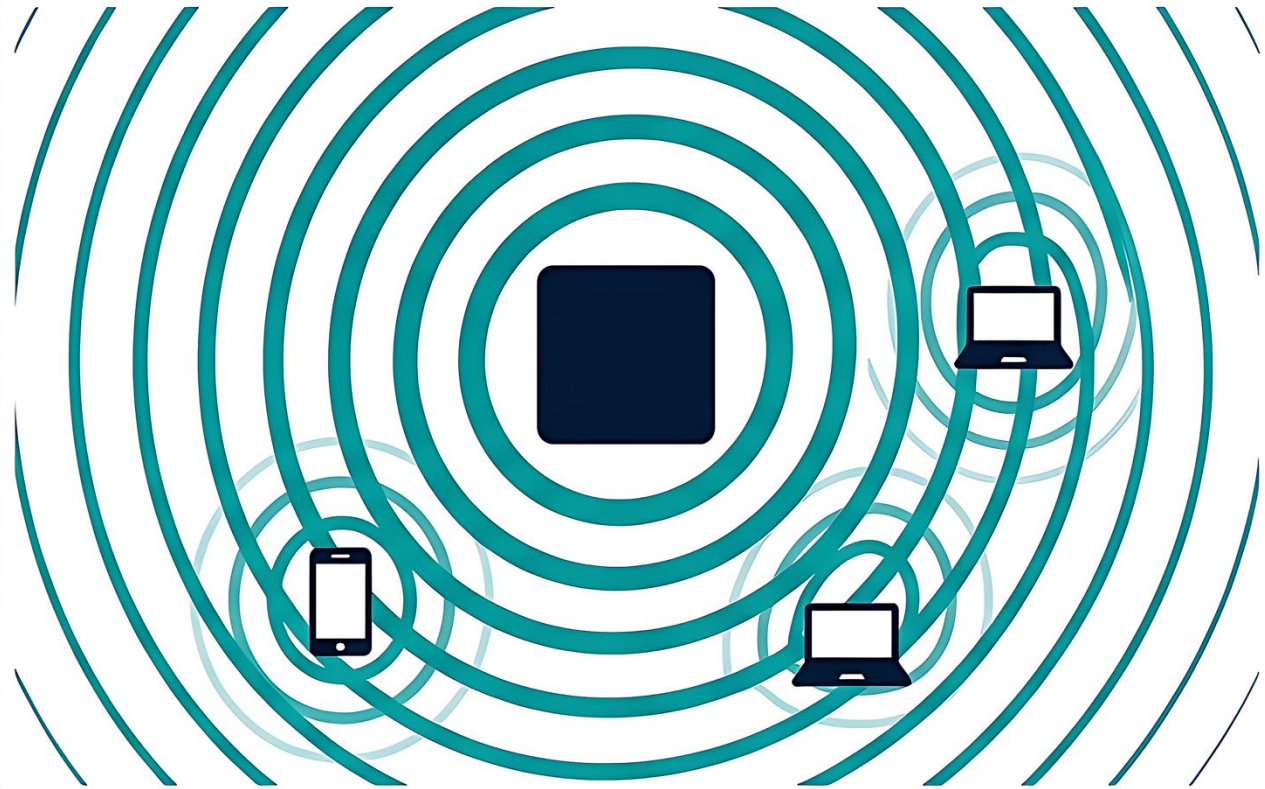
Confined Medium



Wireless Uses the Air as the Medium

Confined Medium

Shared Spatial Medium

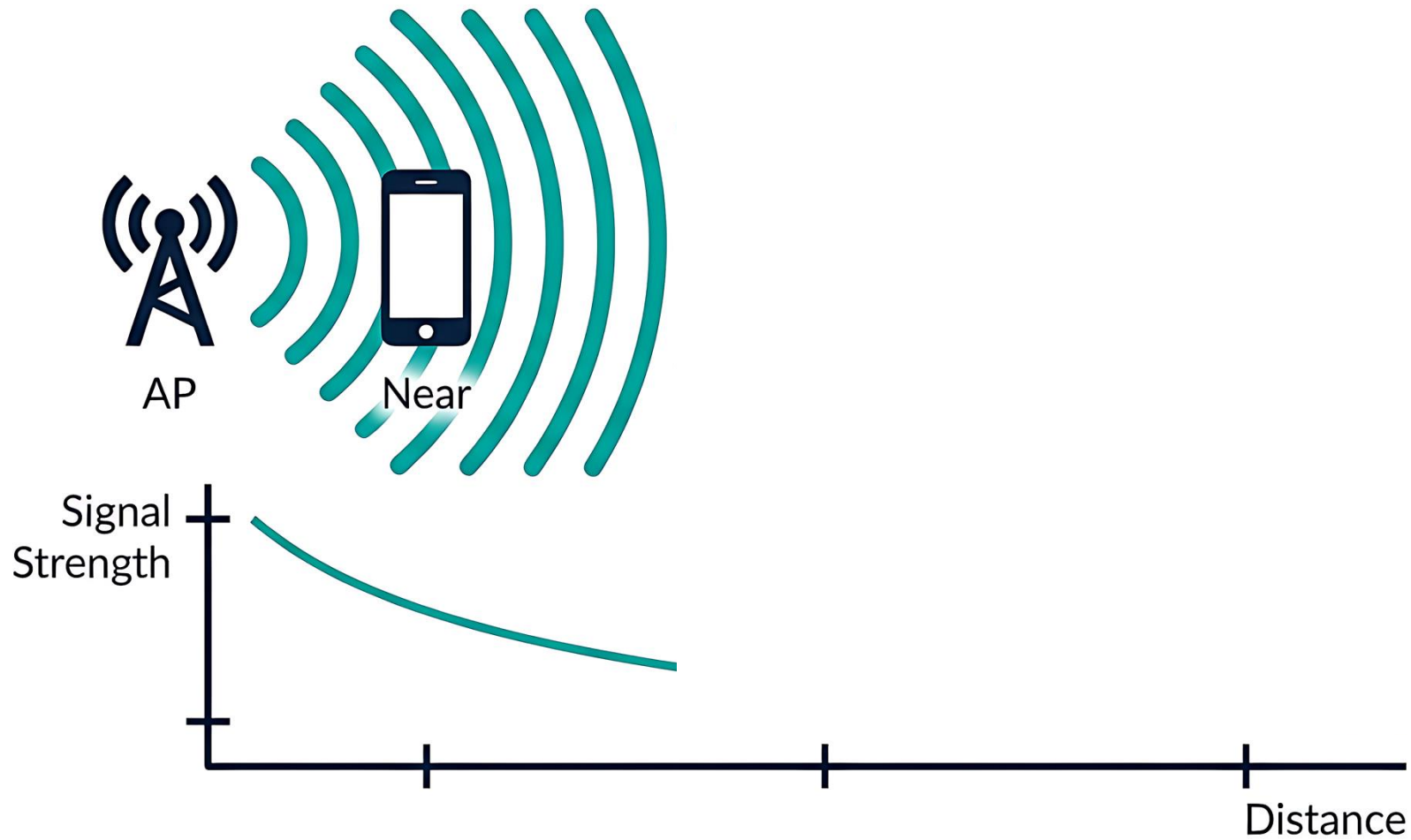


In wireless networks, the medium is open and shared.

Distance Weakens the Signal

Signal power decreases as distance increases.

A nearby receiver gets
a stronger signal

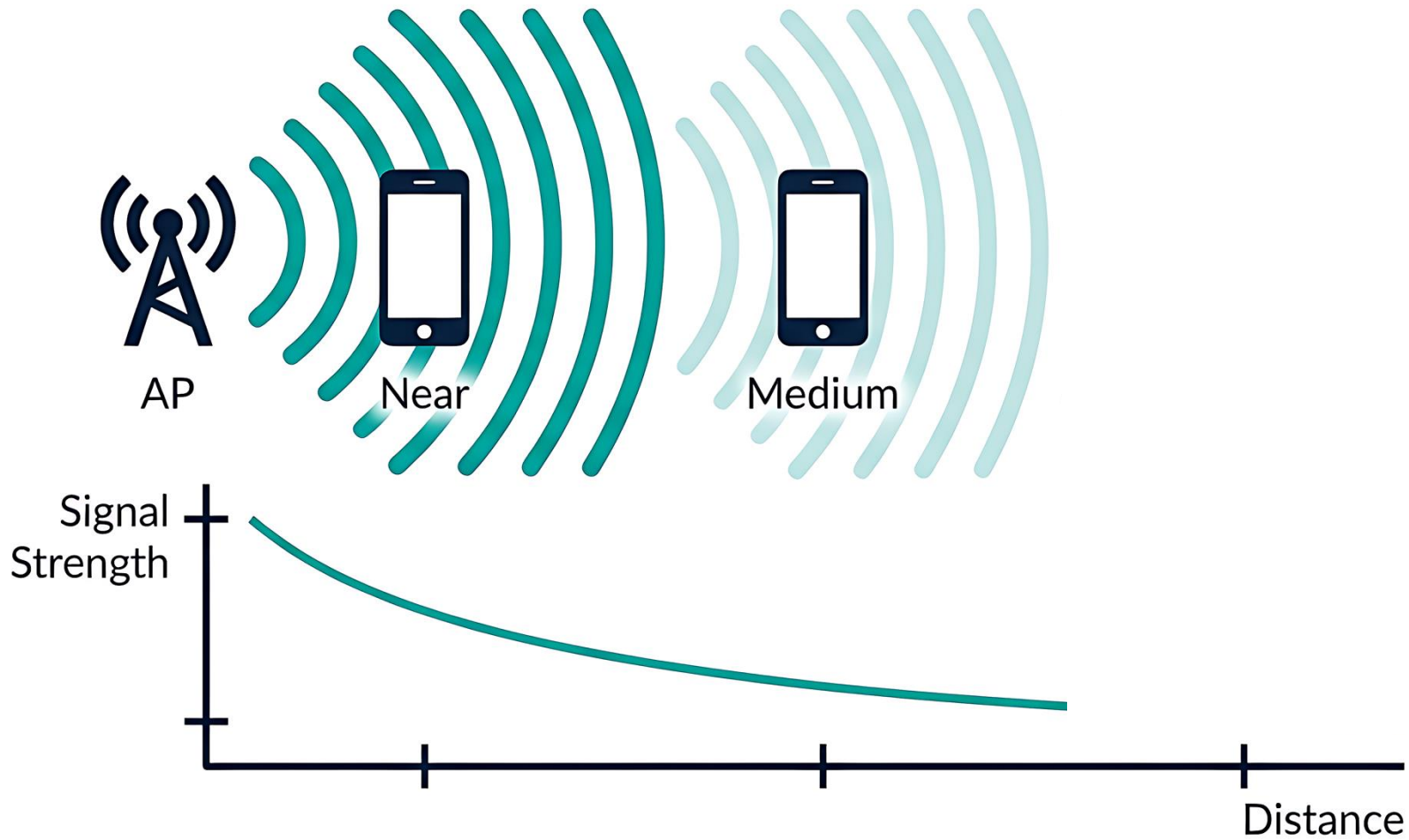


Distance Weakens the Signal

Signal power decreases as distance increases.

A nearby receiver gets a stronger signal

A farther receiver gets a weaker signal

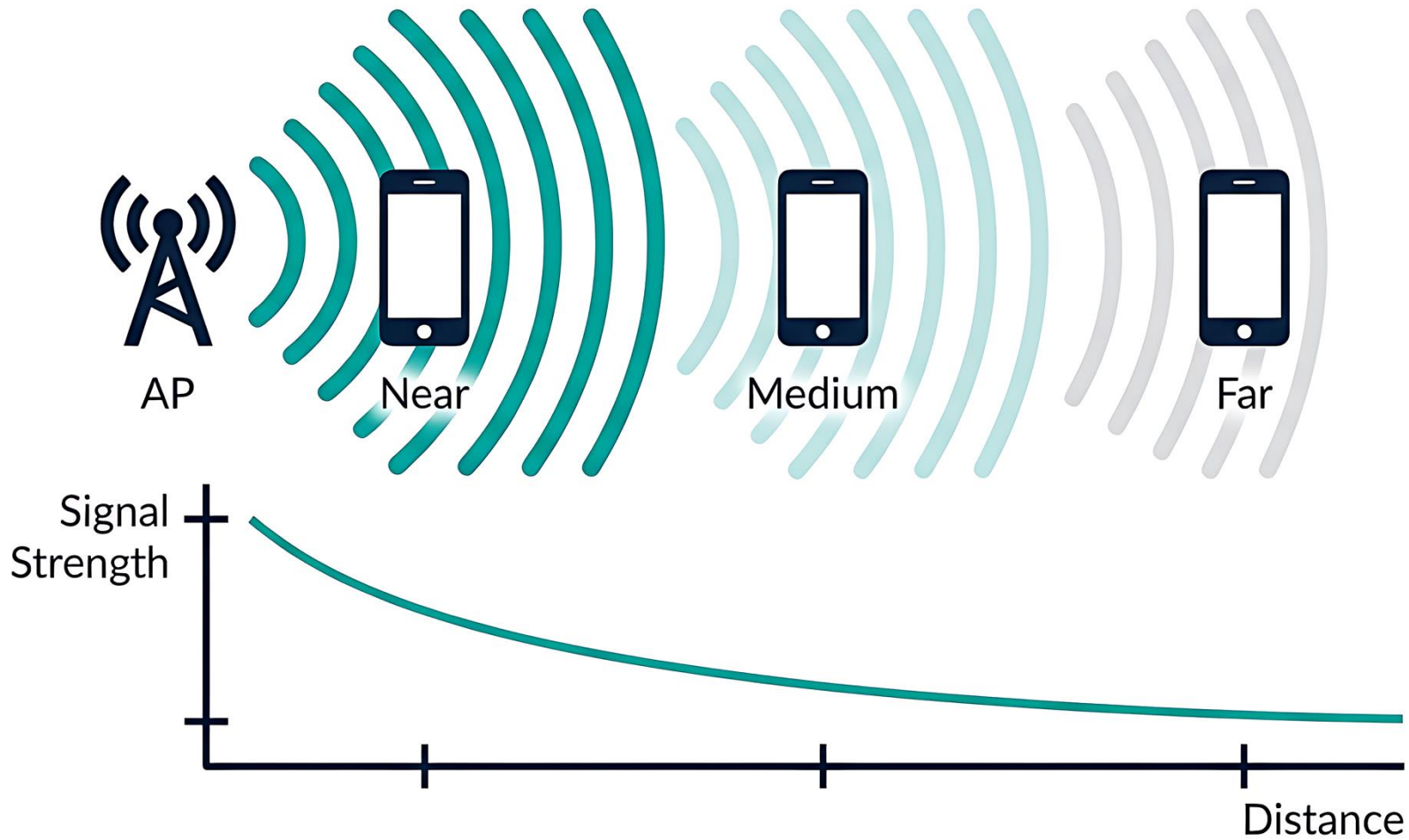


Distance Weakens the Signal

Signal power decreases as distance increases.

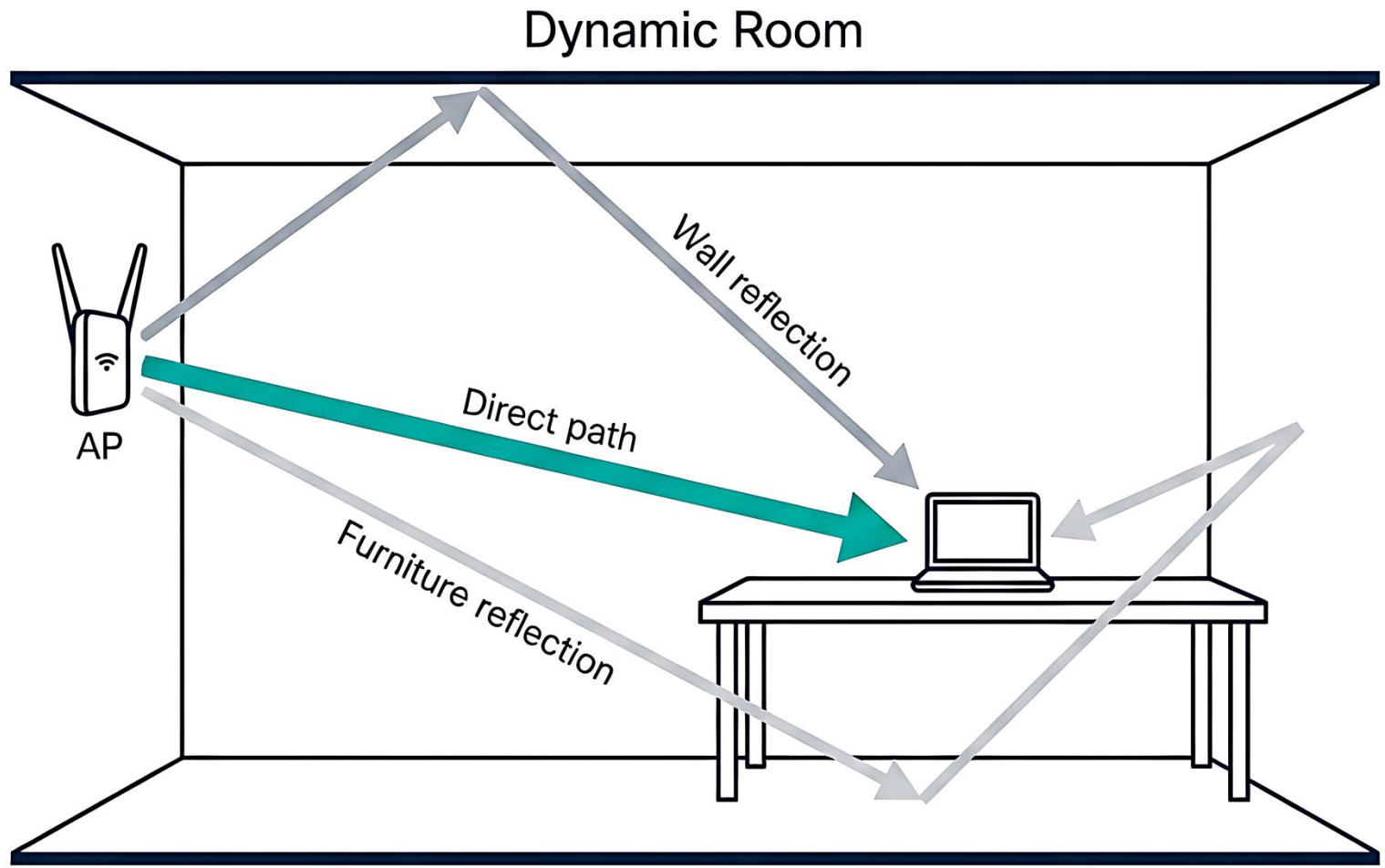
A nearby receiver gets a stronger signal

A farther receiver gets a weaker signal



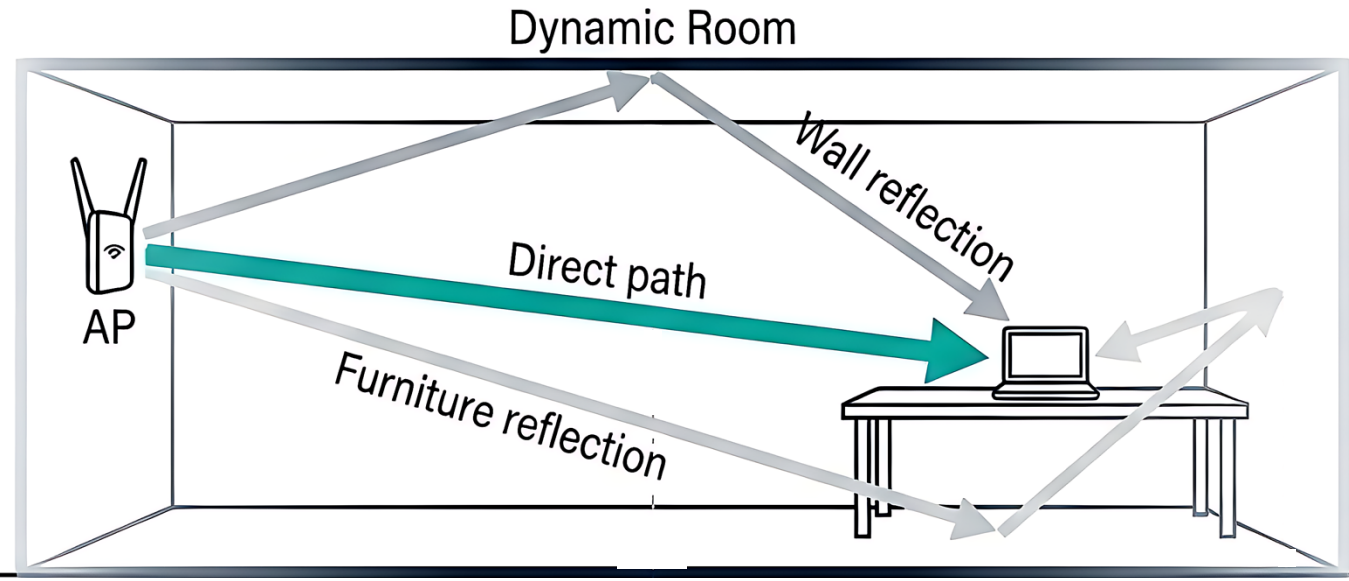
Indoor physical structures create multiple signal paths

Because signals reflect off objects, the receiver captures multiple copies of the exact same transmission. This is known as multipath propagation.



Reflected copies arrive with altered timing and strength

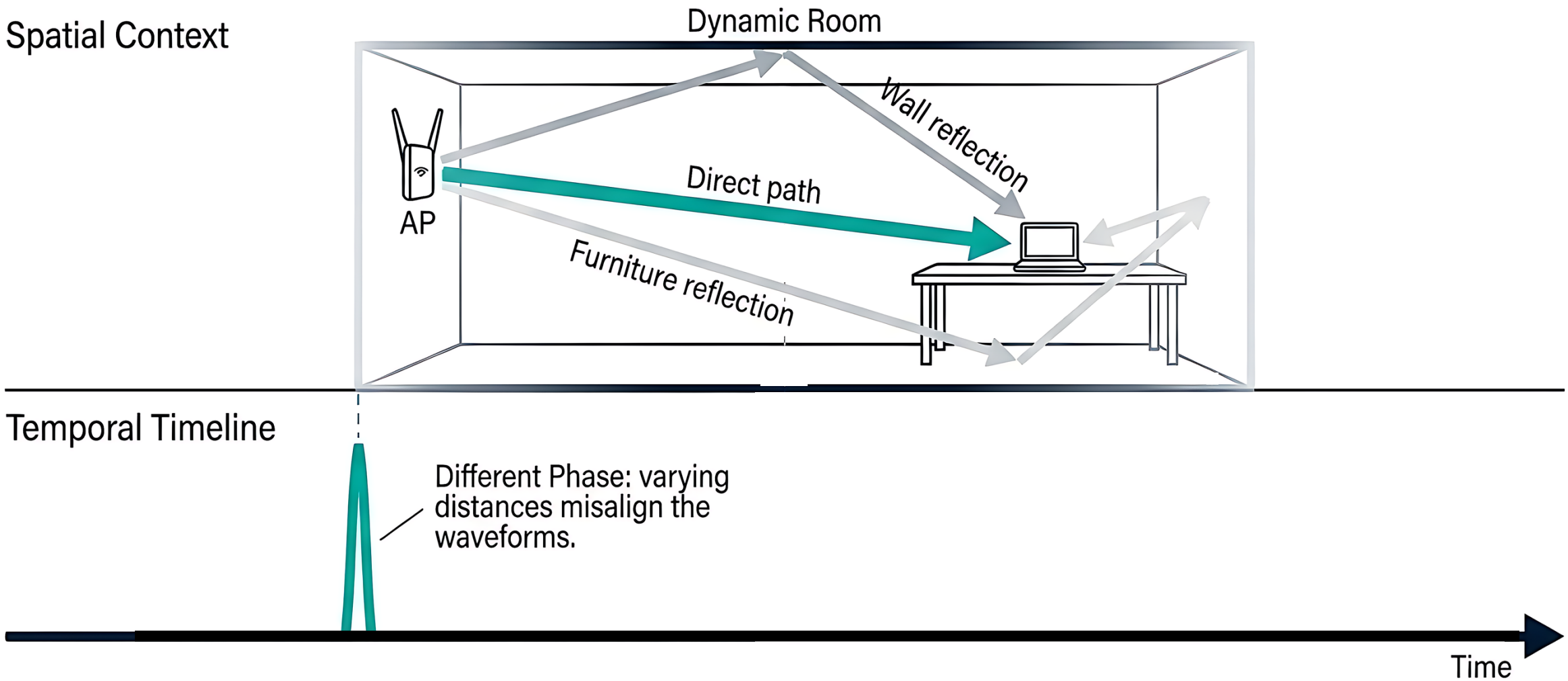
Spatial Context



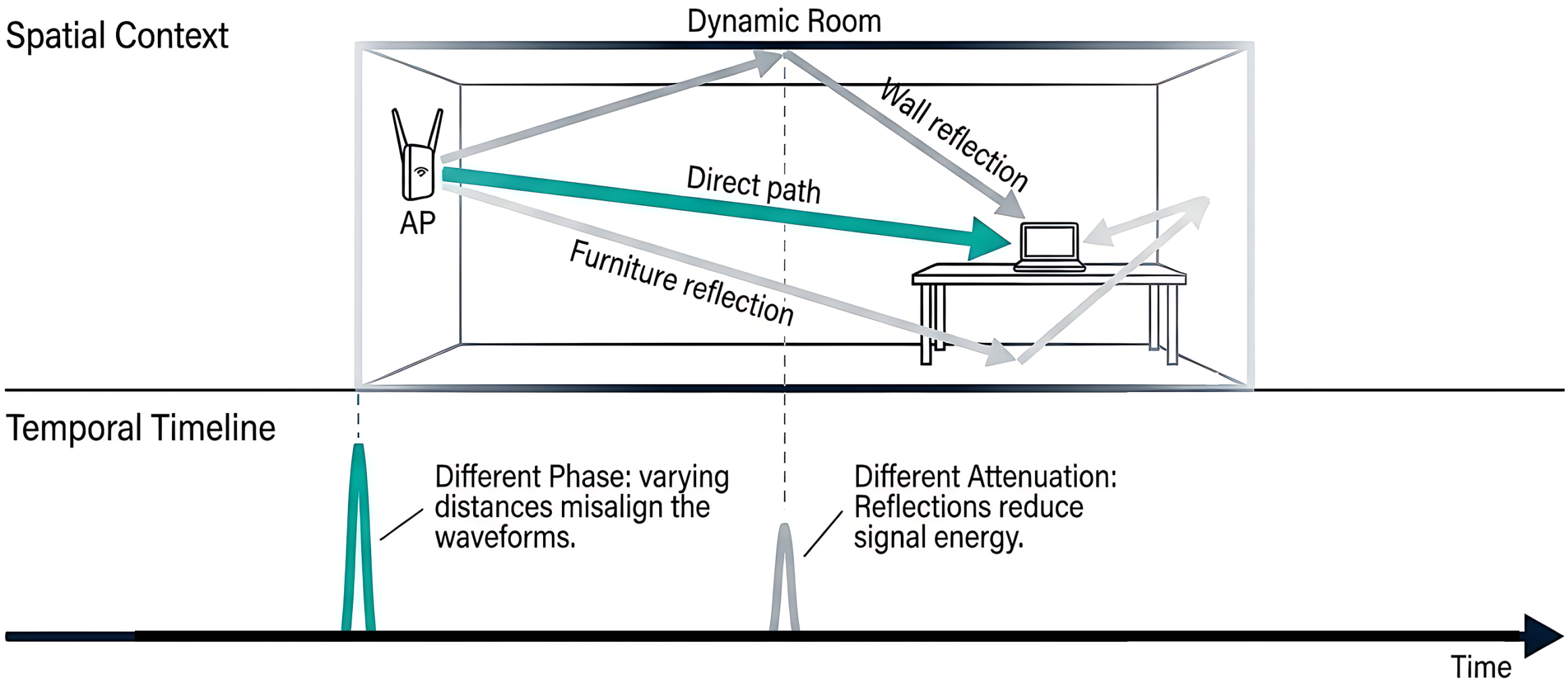
Temporal Timeline

Time

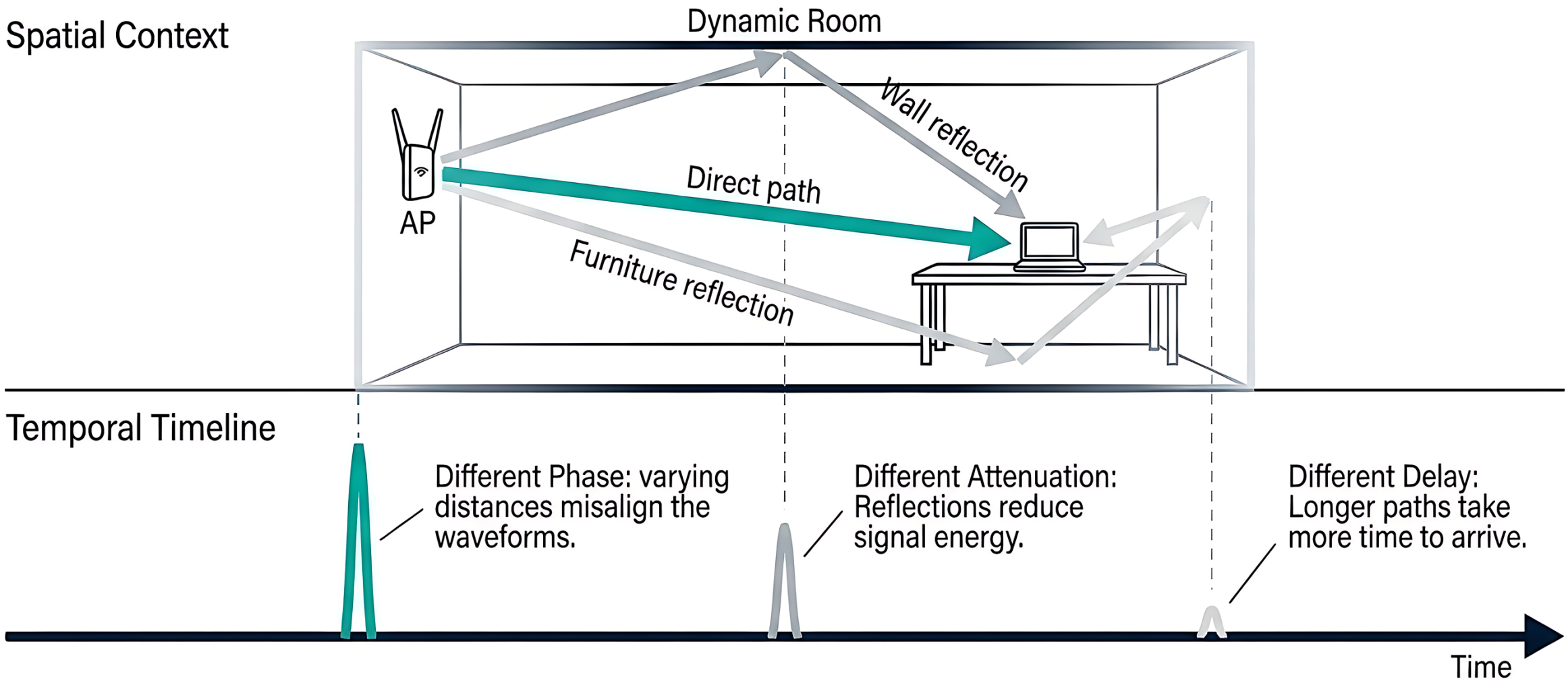
Reflected copies arrive with altered timing and strength



Reflected copies arrive with altered timing and strength

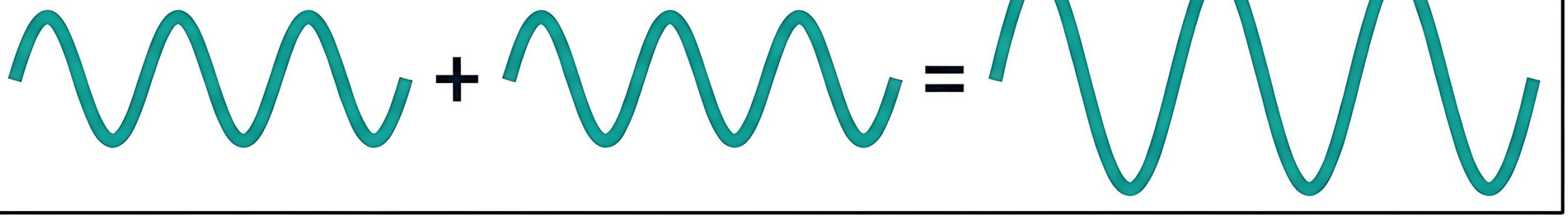


Reflected copies arrive with altered timing and strength



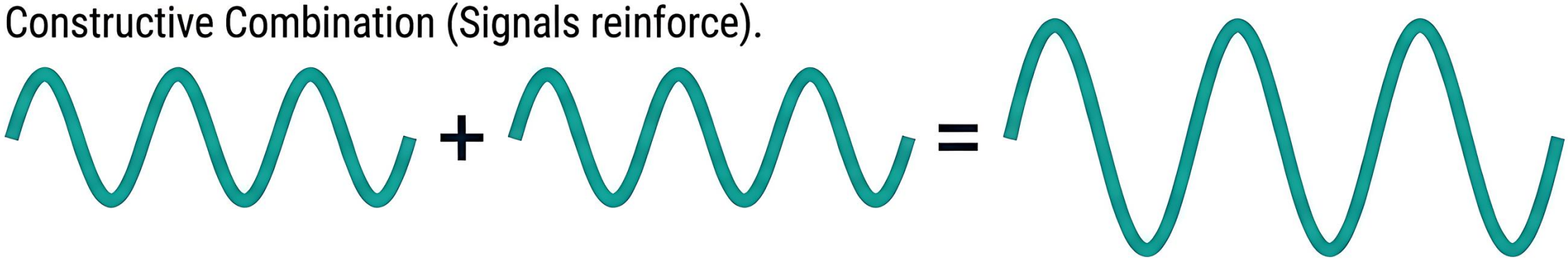
Arriving paths combine and interfere at the receiver

Constructive Combination (Signals reinforce).

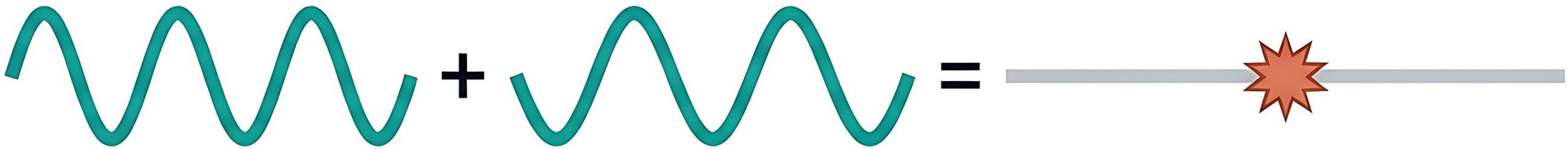


Arriving paths combine and interfere at the receiver

Constructive Combination (Signals reinforce).



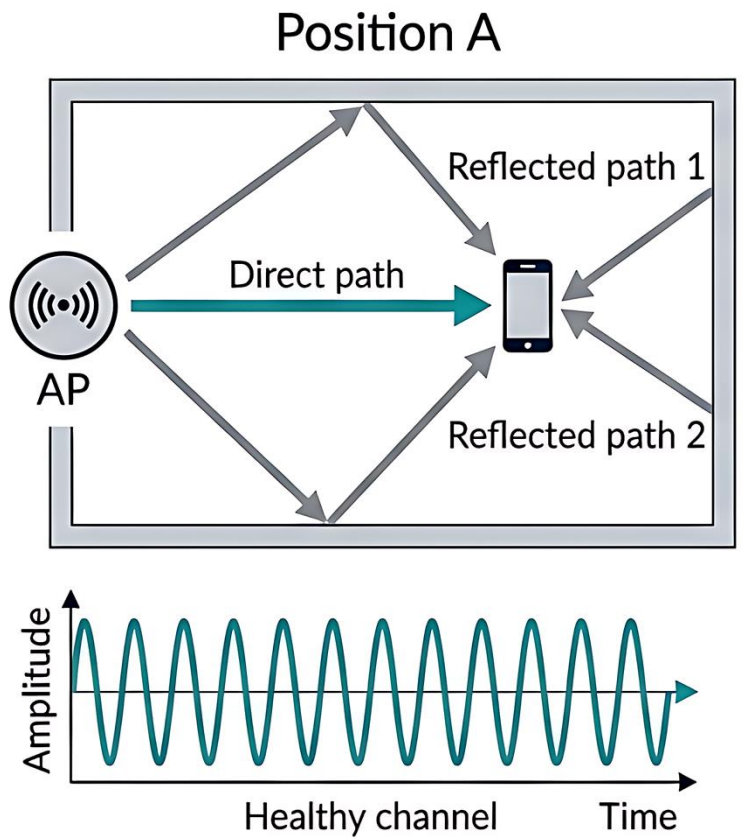
Destructive Combination (Signals cancel).



The receiver does not hear individual paths; it observes their exact sum.
The alignment of phases dictates whether the channel succeeds or fails.

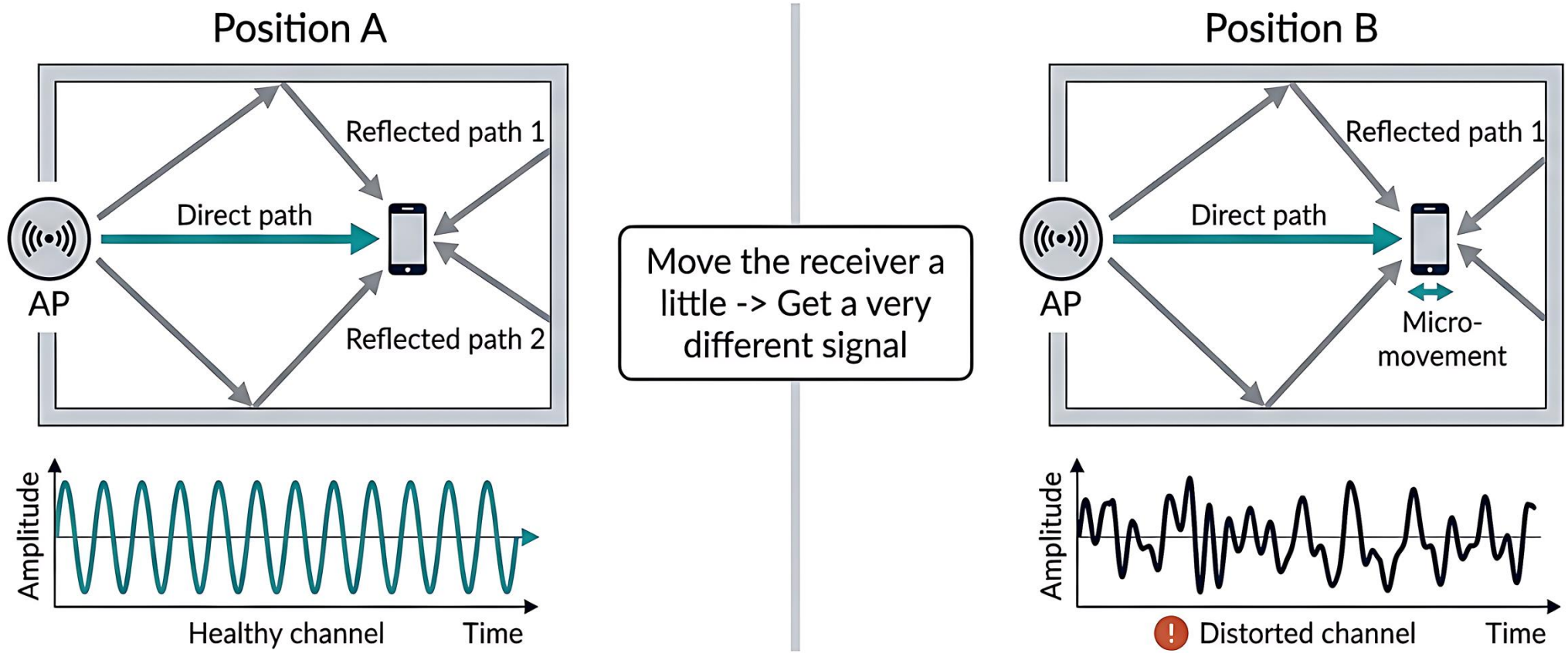
Small Movement Can Change the Signal a Lot

Multipath heavily depends on the precise geometry of the receiver.



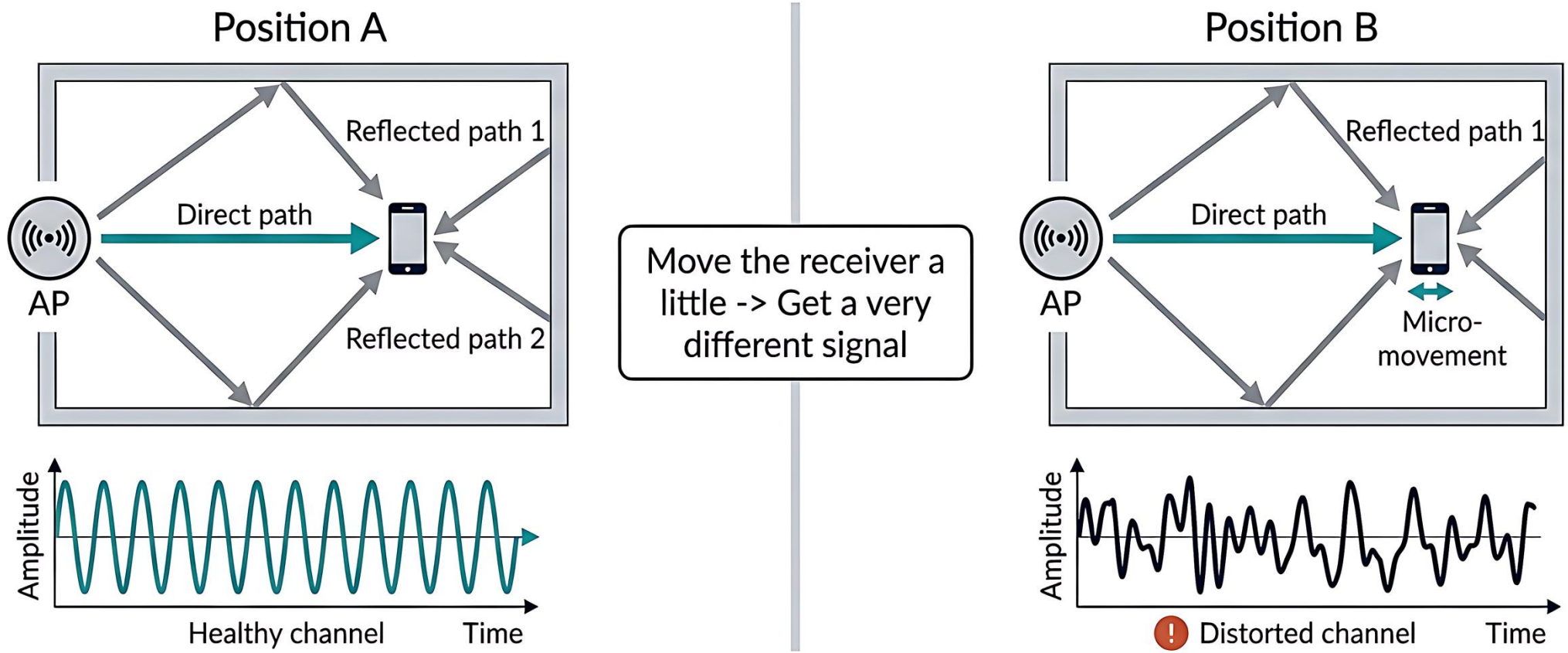
Small Movement Can Change the Signal a Lot

Multipath heavily depends on the precise geometry of the receiver.



Small Movement Can Change the Signal a Lot

Multipath heavily depends on the precise geometry of the receiver.



A small change in position alters path lengths

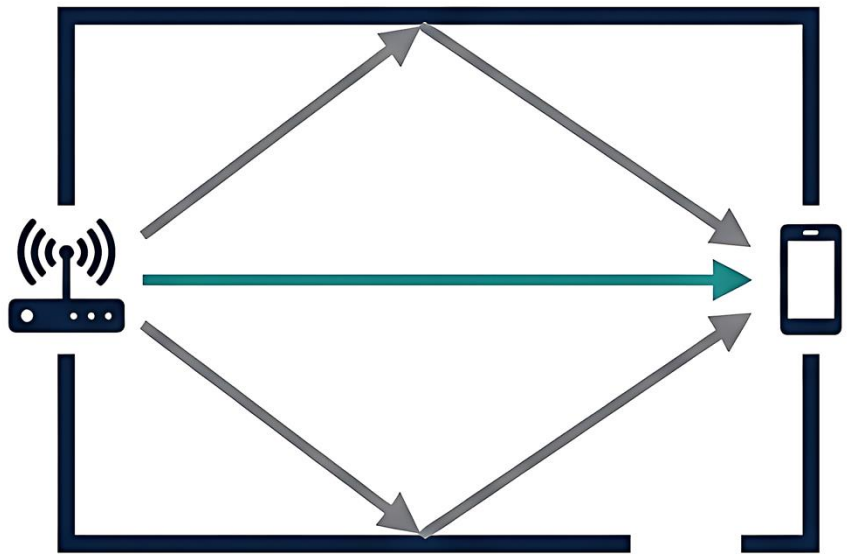
Changed path lengths alter the delays and phases

The combined signal changes significantly

The Environment Also Changes the Signal

Even if devices stay perfectly still, the channel varies over time.

Time 1

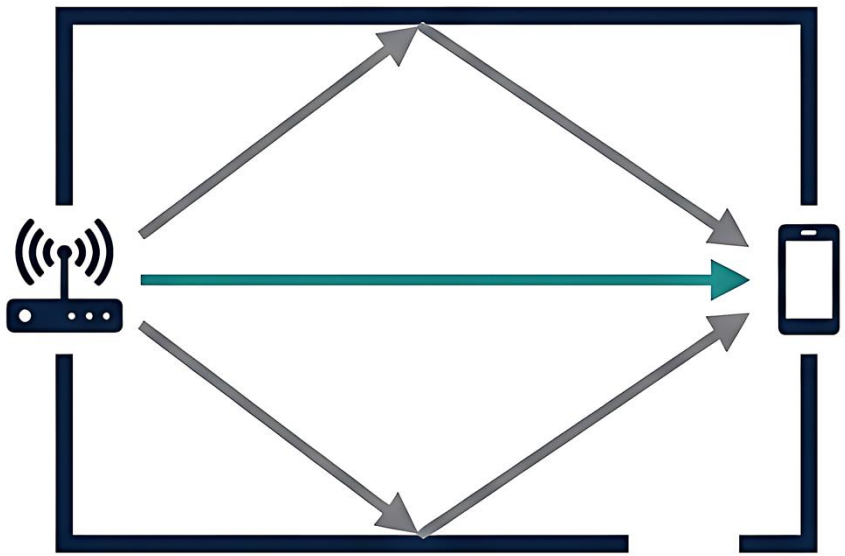


Same AP
Same Receiver

The Environment Also Changes the Signal

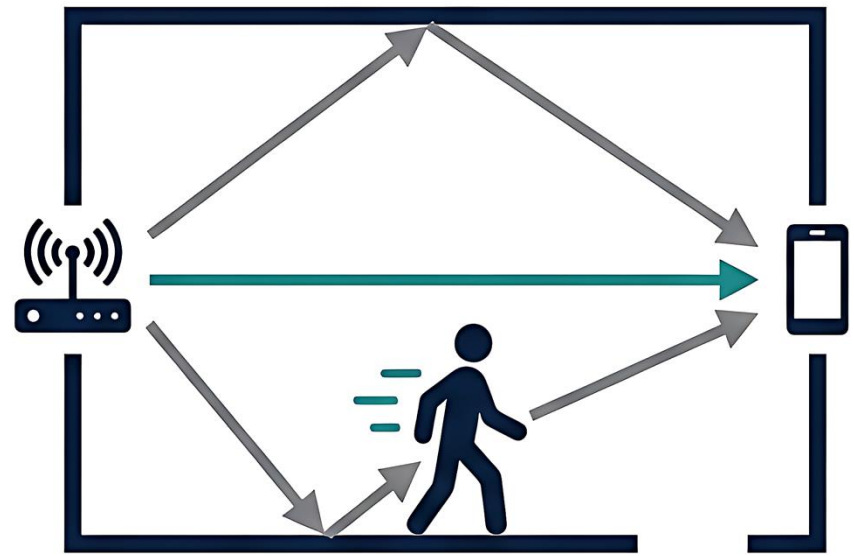
Even if devices stay perfectly still, the channel varies over time.

Time 1



Same AP
Same Receiver

Time 2



Different Environment
Different Signal

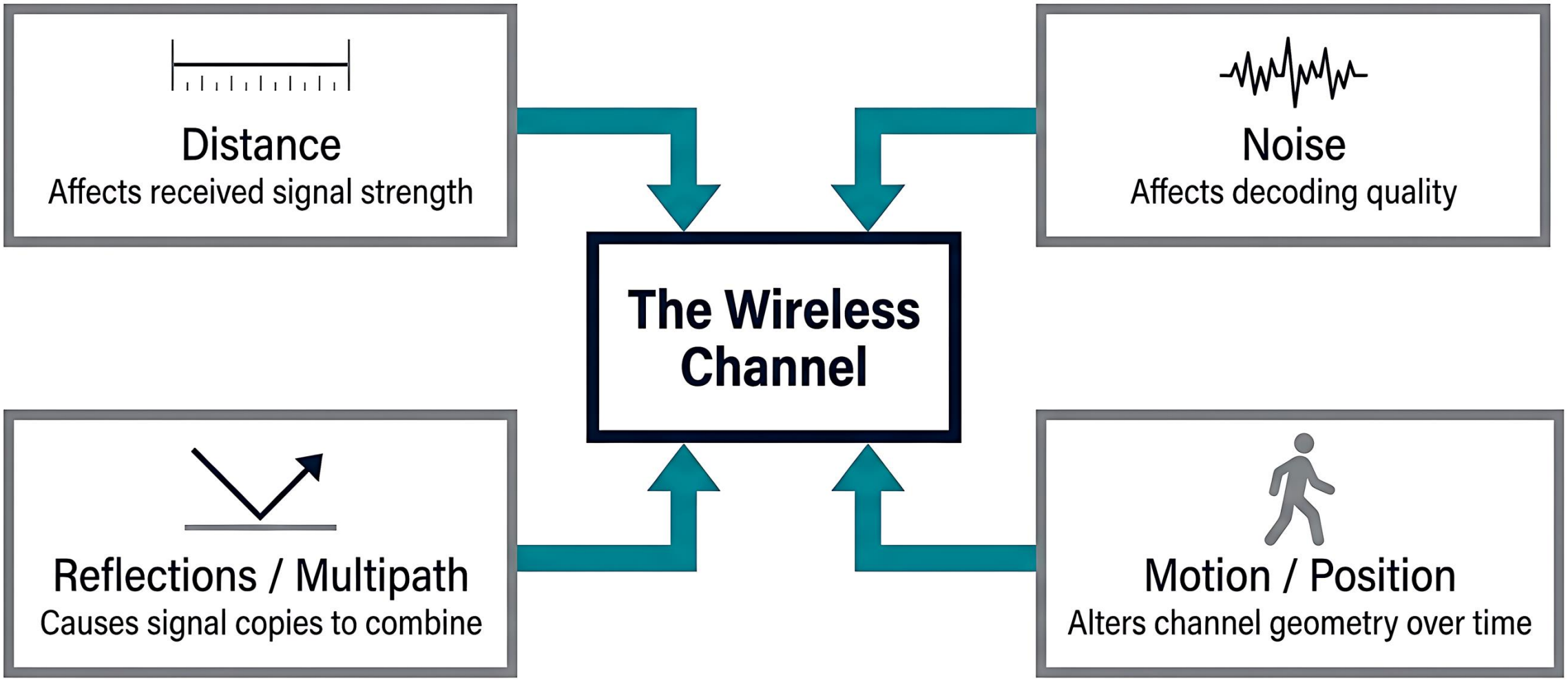
The transmitter and receiver may stay still

But objects and people moving change the reflection paths

So the wireless channel changes over time

Wireless Communication and the Physical World

Wireless channels reflect real-world geometry and dynamics.



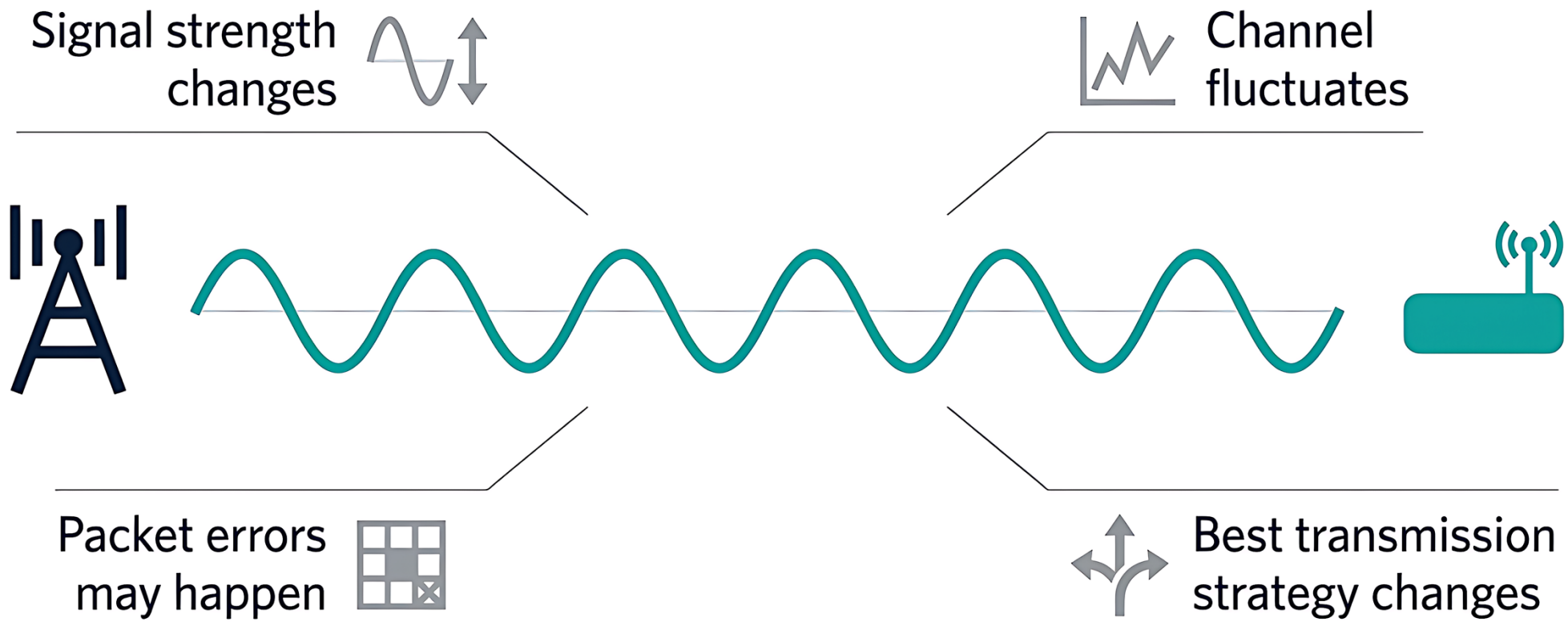
Final Takeaway

Why wireless communication is inherently dynamic.

Wireless communication is inherently dynamic because the signal travels through the real physical world.

Distance changes signal strength
Noise changes effective reception quality
Multipath causes complex signal combination
Motion significantly alters the channel over time

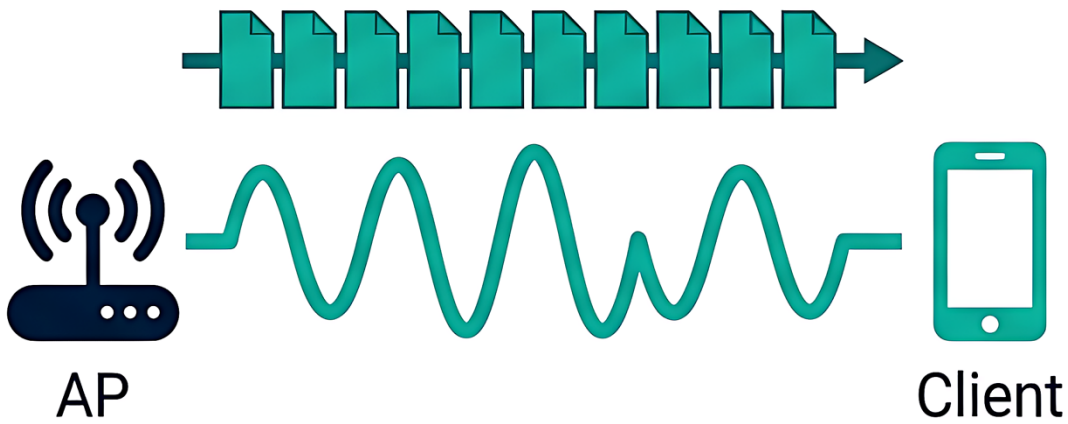
Even a Single Wireless Link Is Hard



Wireless complexity appears even before we consider multiple users.

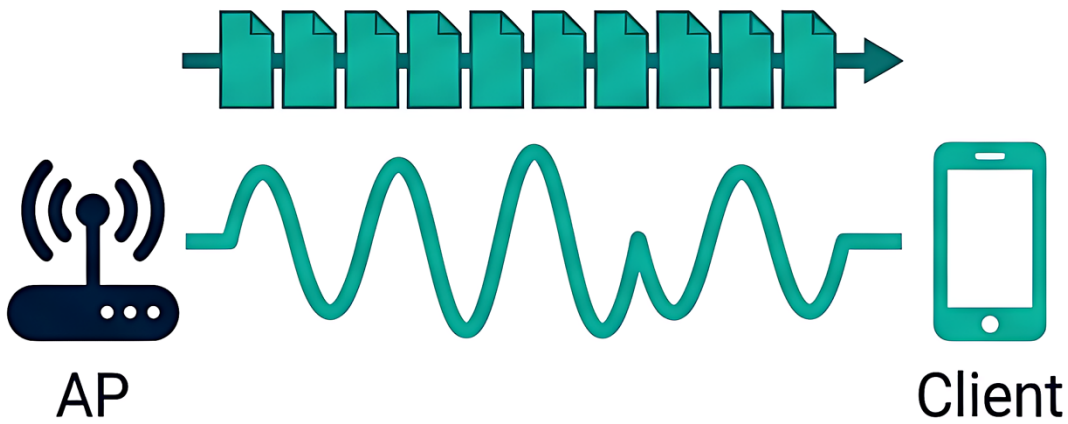
Rate Adaptation:
The Best Data Rate Changes Over Time

When the channel is good:
System uses a higher data rate.

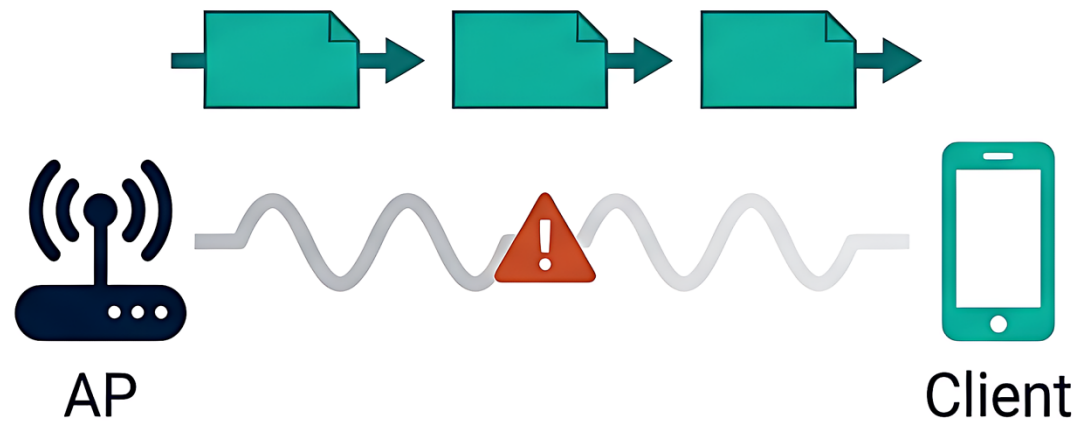


Rate Adaptation:
The Best Data Rate Changes Over Time

When the channel is good:
System uses a higher data rate.



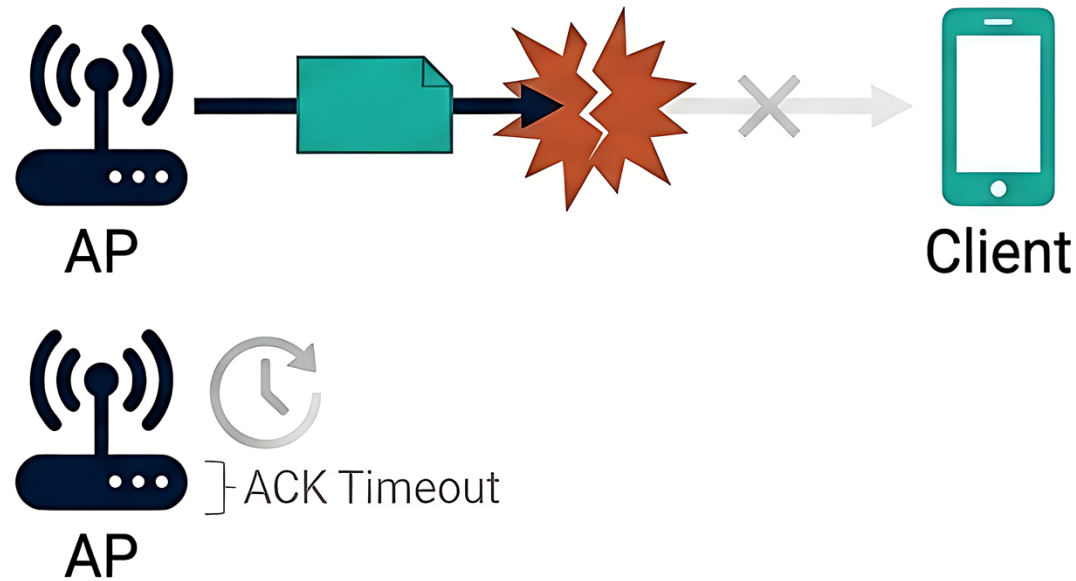
When the channel is bad:
System shifts to a lower, robust rate.



Because quality is not constant, wireless systems must adapt
their rate to current channel conditions.

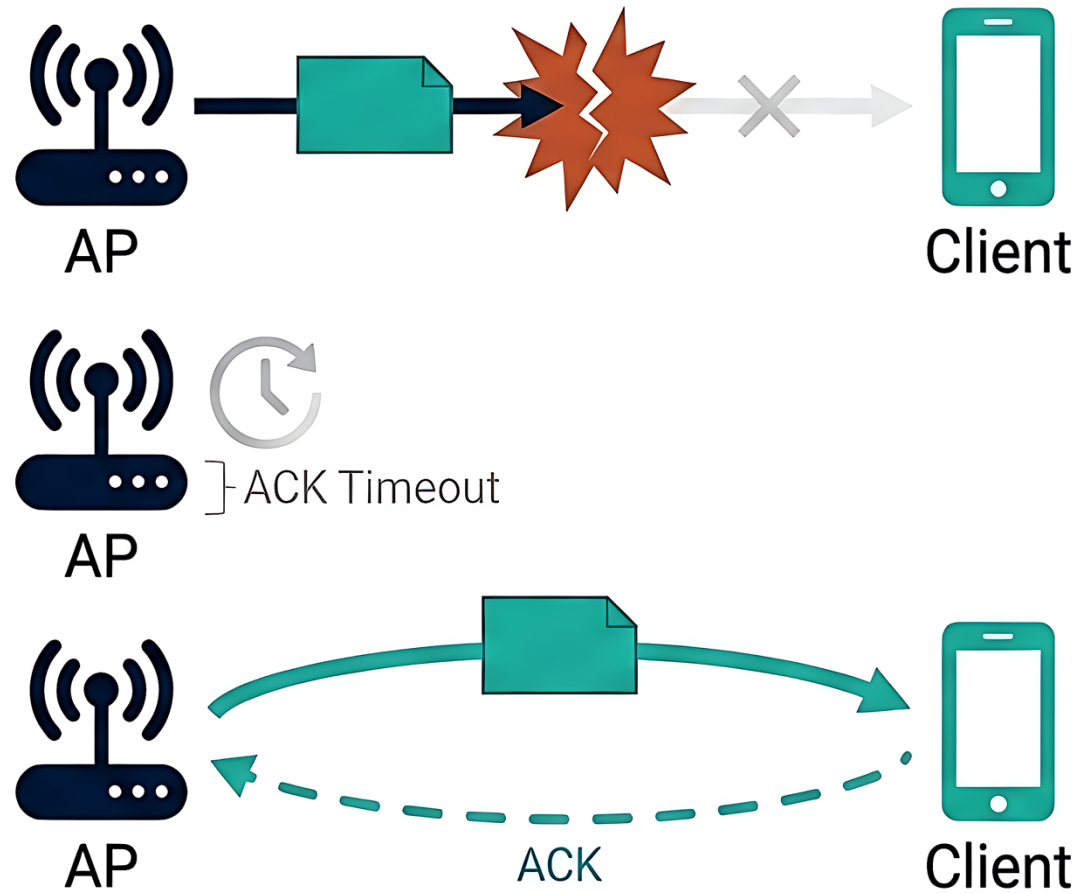
Retransmission: Packet Loss Is Common

- Packets are frequently lost due to weak signals, fading, or temporary interference.



Retransmission: Packet Loss Is Common

- Packets are frequently lost due to weak signals, fading, or temporary interference.
- Systems rely on link-layer recovery: ACKs and active retransmissions.



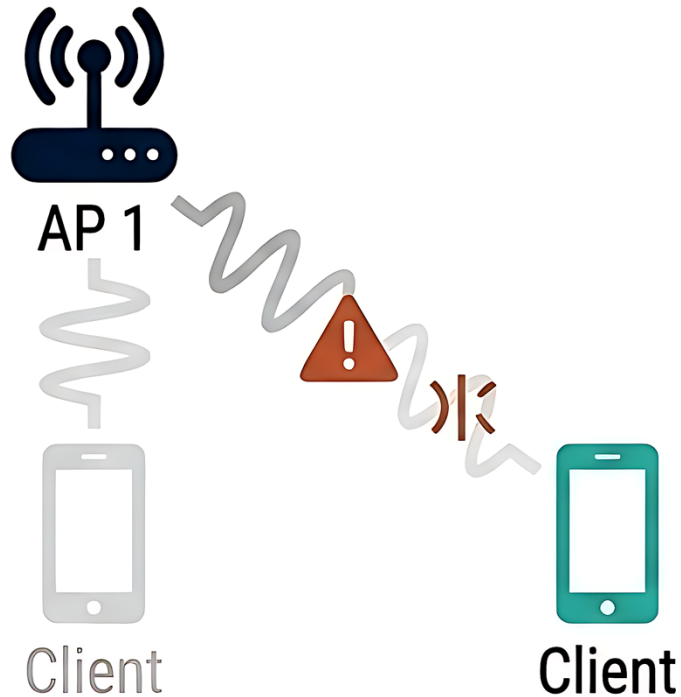
A wireless link often needs active recovery, not just best-effort delivery.

Mobility Can Trigger Roaming and Handover

1. User moves

Mobility Can Trigger Roaming and Handover

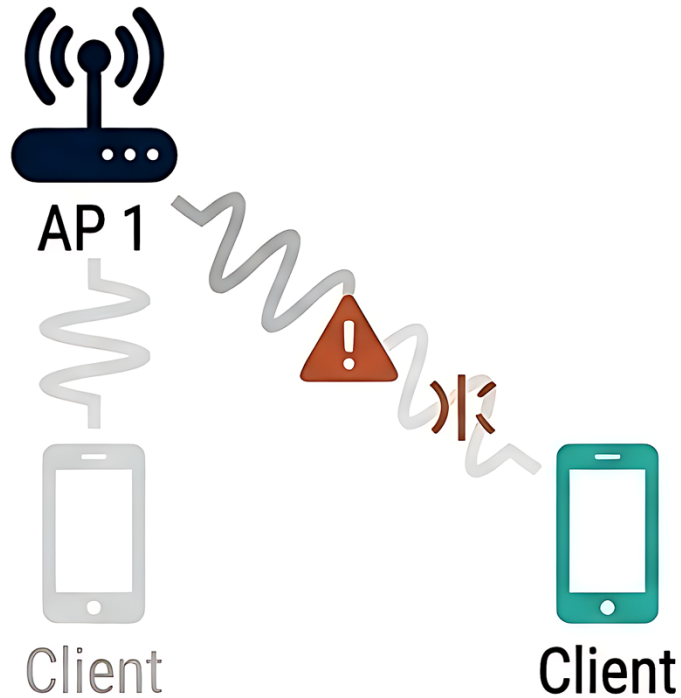
1. User moves



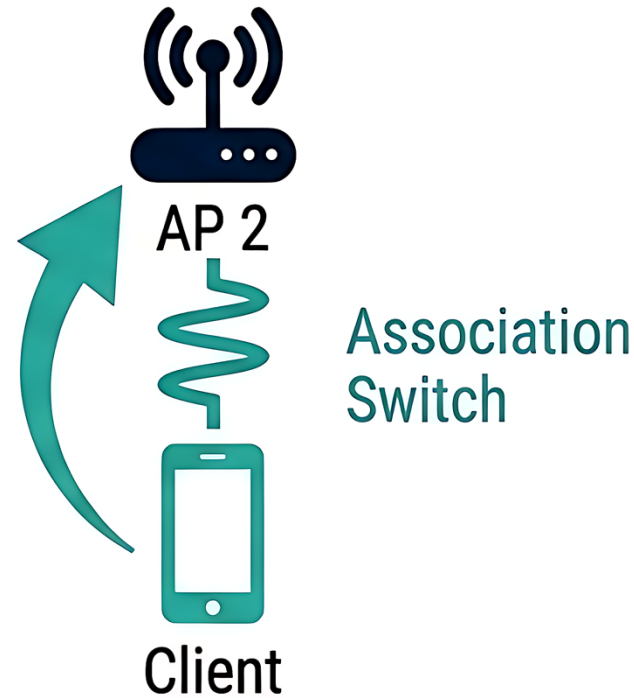
2. Current AP becomes weak

Mobility Can Trigger Roaming and Handover

1. User moves

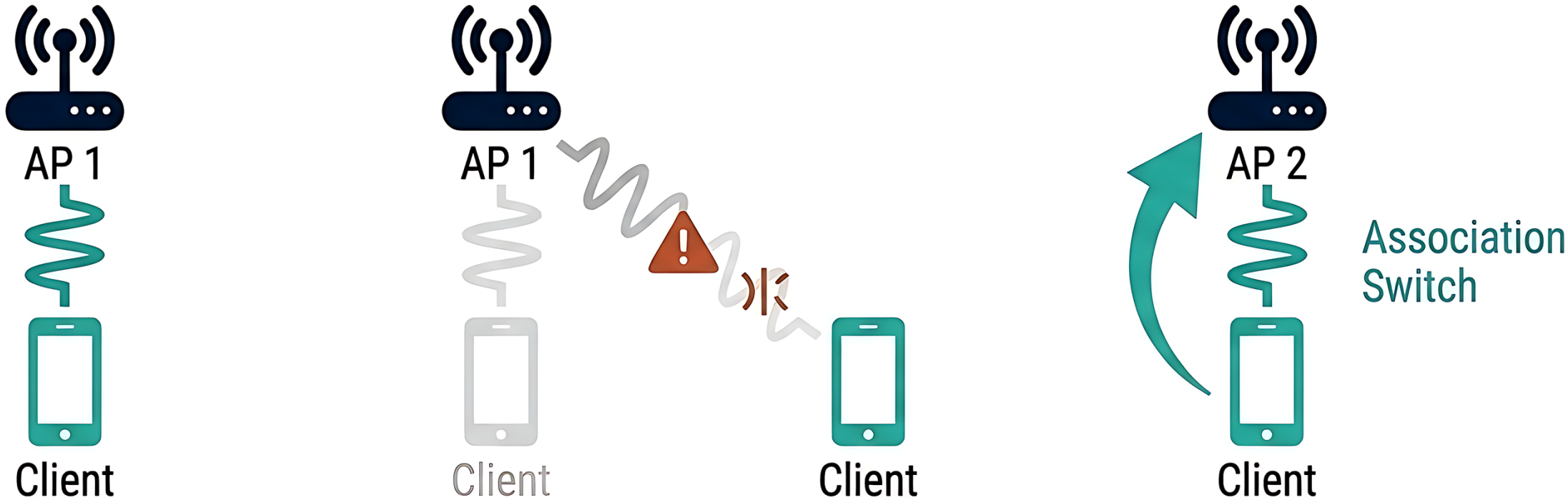


2. Current AP becomes weak



3. Device switches to a better nearby AP

Mobility Can Trigger Roaming and Handover



1. User moves

2. Current AP becomes weak

3. Device switches to a better nearby AP

Communication must continue: mobility changes the best attachment point, not just signal strength.

Maintaining One Wireless Link Requires Continuous Adaptation

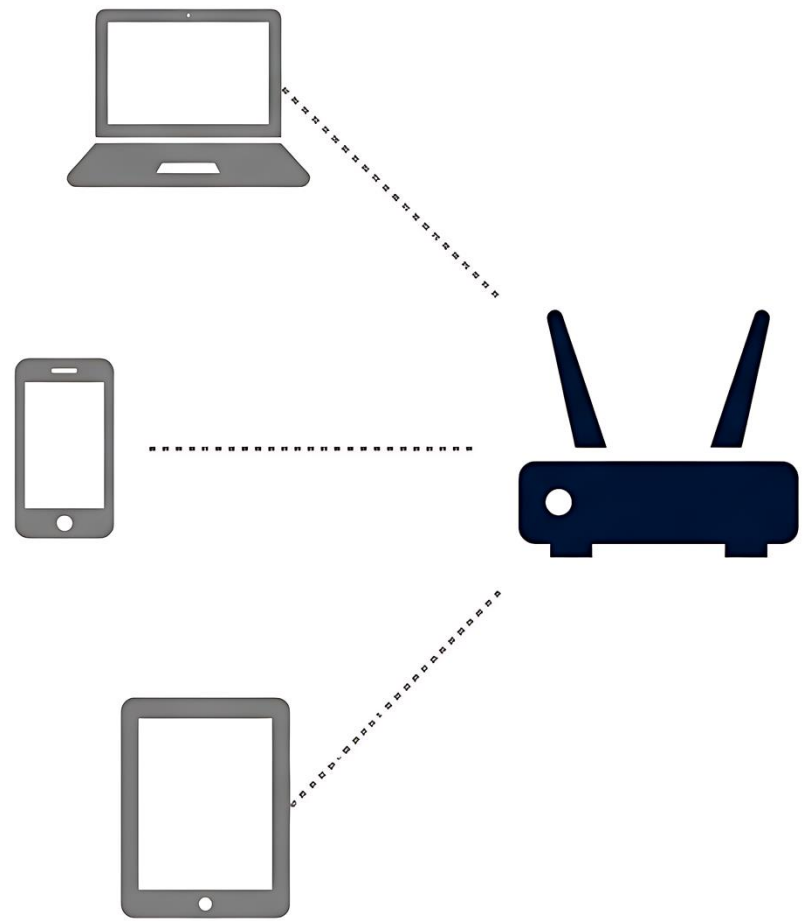
System Challenge	Required Adaptation
Fluctuating Channel Quality	Track quality & adapt data rate 
Common Packet Loss	Retransmit lost packets 
User Mobility	Switch AP association 

A single wireless link is already a dynamic control problem.

From Wireless Links to Wireless MAC

Wireless links are difficult because of:

- Path loss
- Multipath
- Fading
- Mobility
- Interference

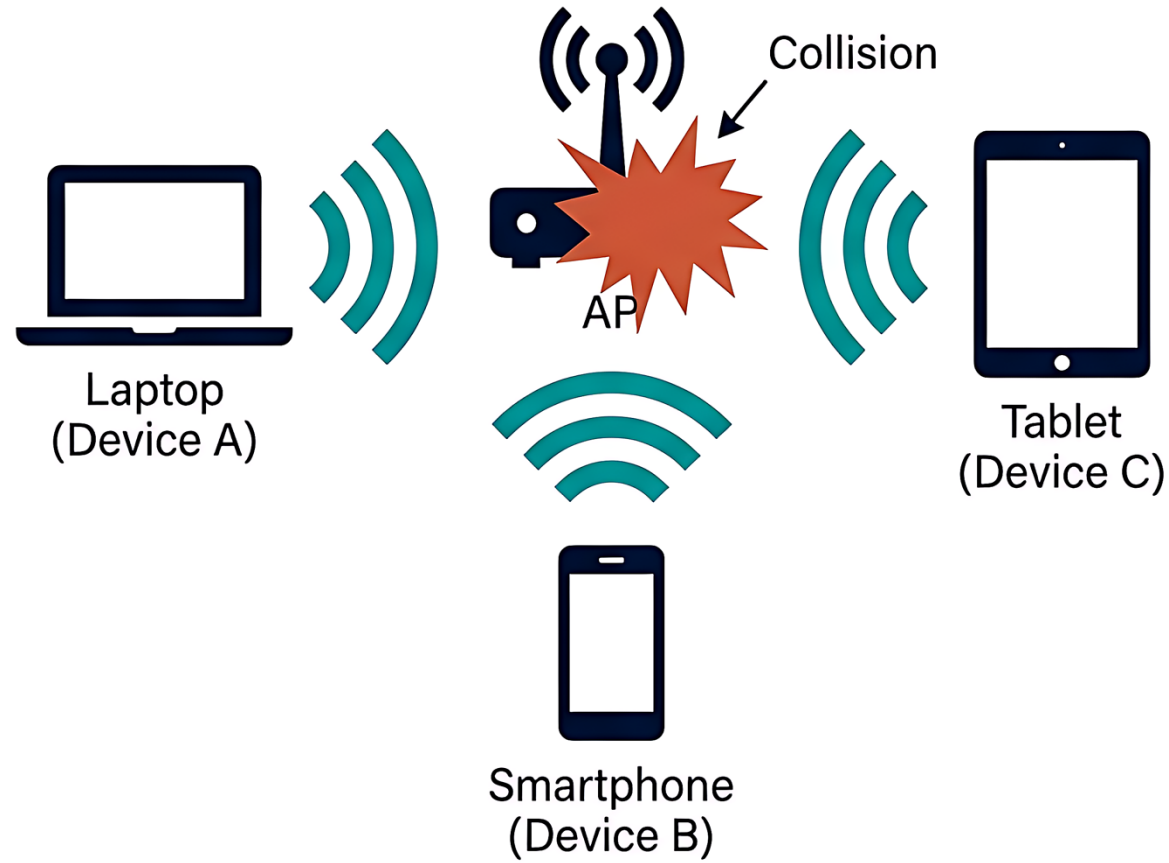


When many devices share the same wireless channel, who gets to transmit?

The Core MAC Question: Who Transmits When?

The MAC layer must answer:

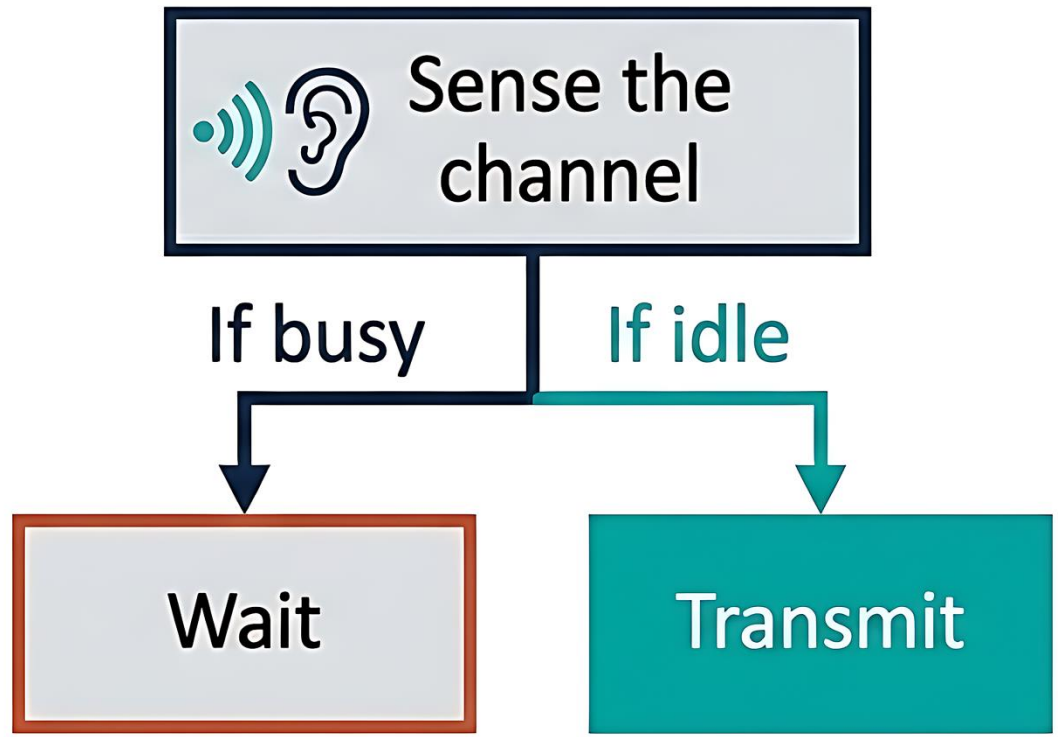
- When should a device transmit?
- When should it wait?
- How can devices avoid transmitting at the same time?
- What should happen after a failed transmission?



A Natural Starting Point: CSMA

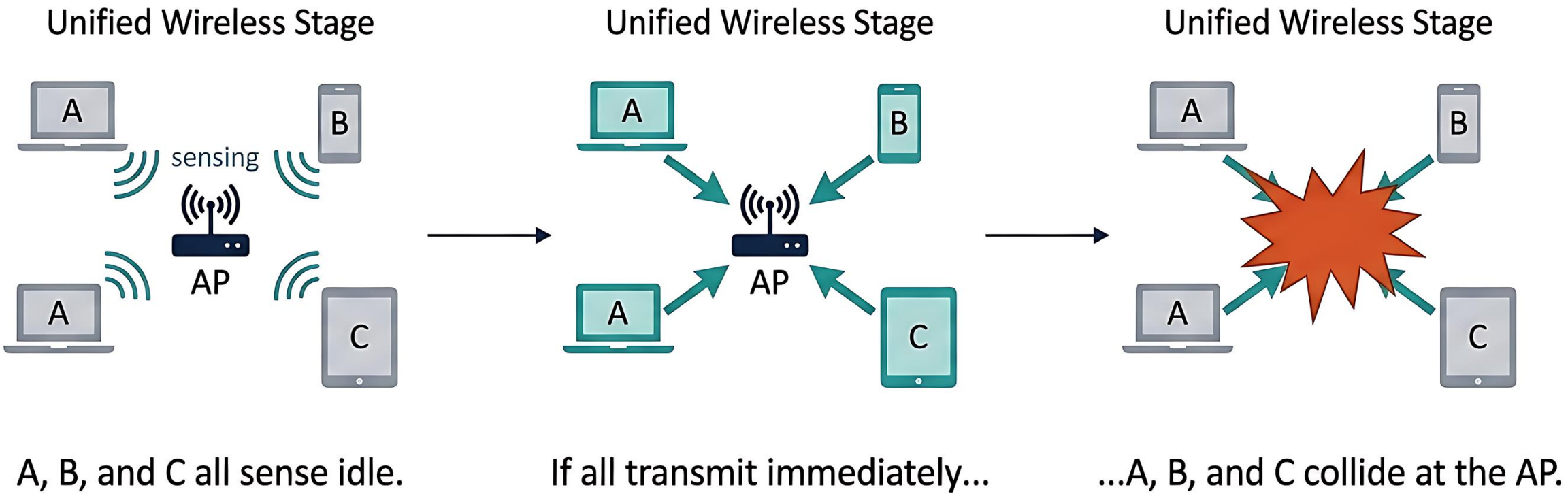
CSMA: Carrier Sense Multiple Access

Basic idea:
Listen before talking.



CSMA tries to reduce collisions by checking whether the medium is busy before sending.

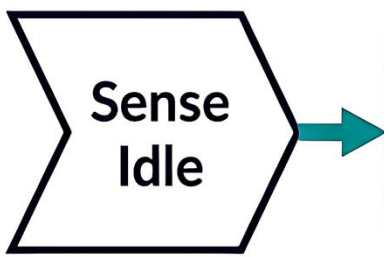
Collision is Common in Wireless: Plain CSMA doesn't work



In wireless, "idle" does not mean "only I will transmit."

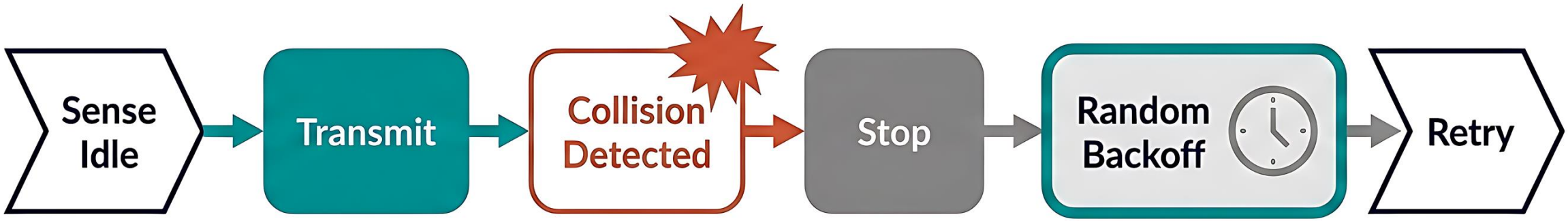
CSMA/CD: Transmit First, Detect Collision Later

CSMA/CD: Carrier Sense Multiple Access with Collision Detection.



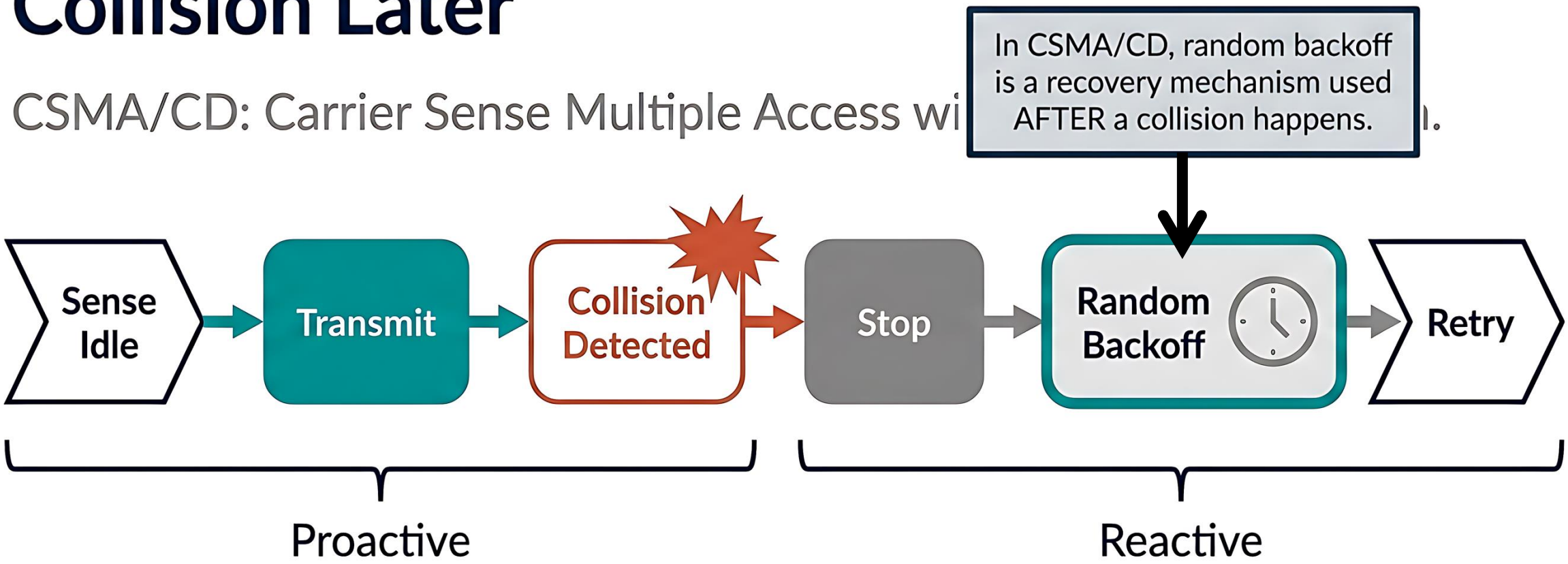
CSMA/CD: Transmit First, Detect Collision Later

CSMA/CD: Carrier Sense Multiple Access with Collision Detection.



CSMA/CD: Transmit First, Detect Collision Later

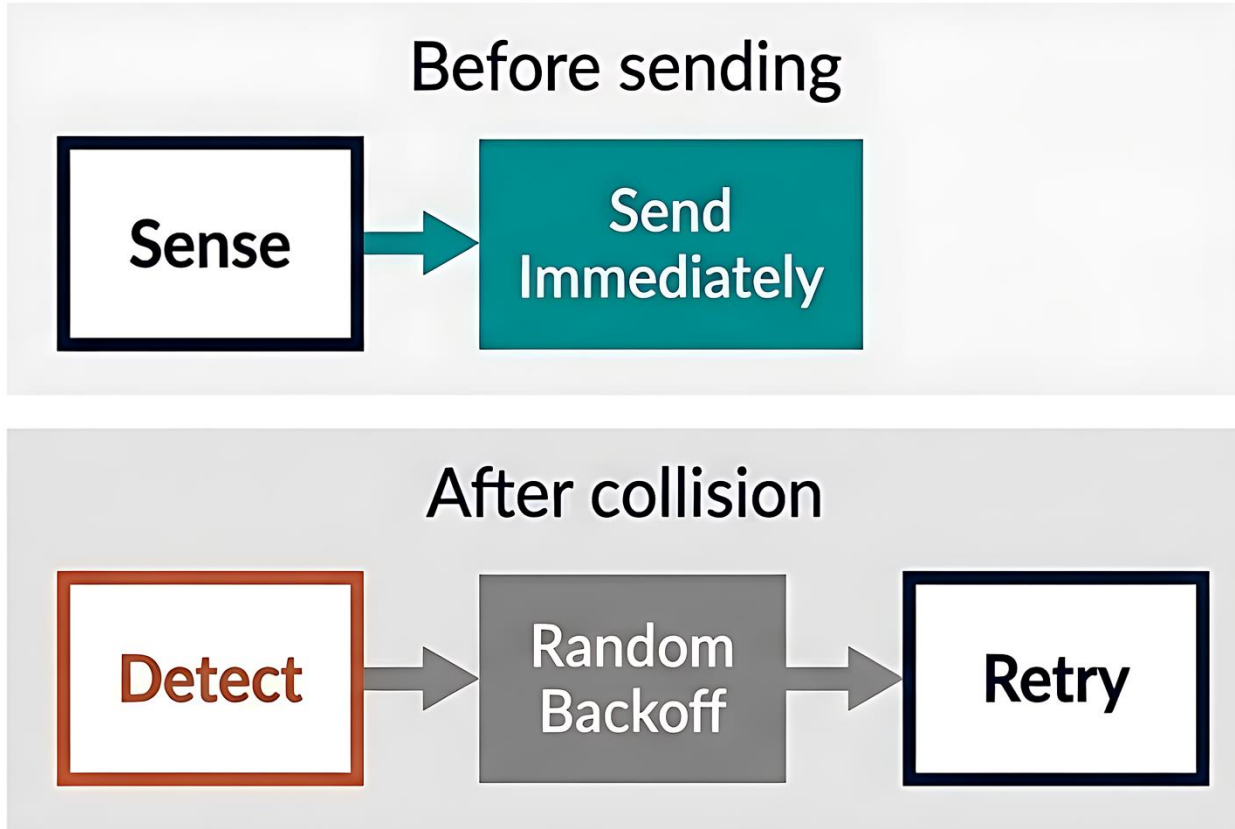
CSMA/CD: Carrier Sense Multiple Access wi l.



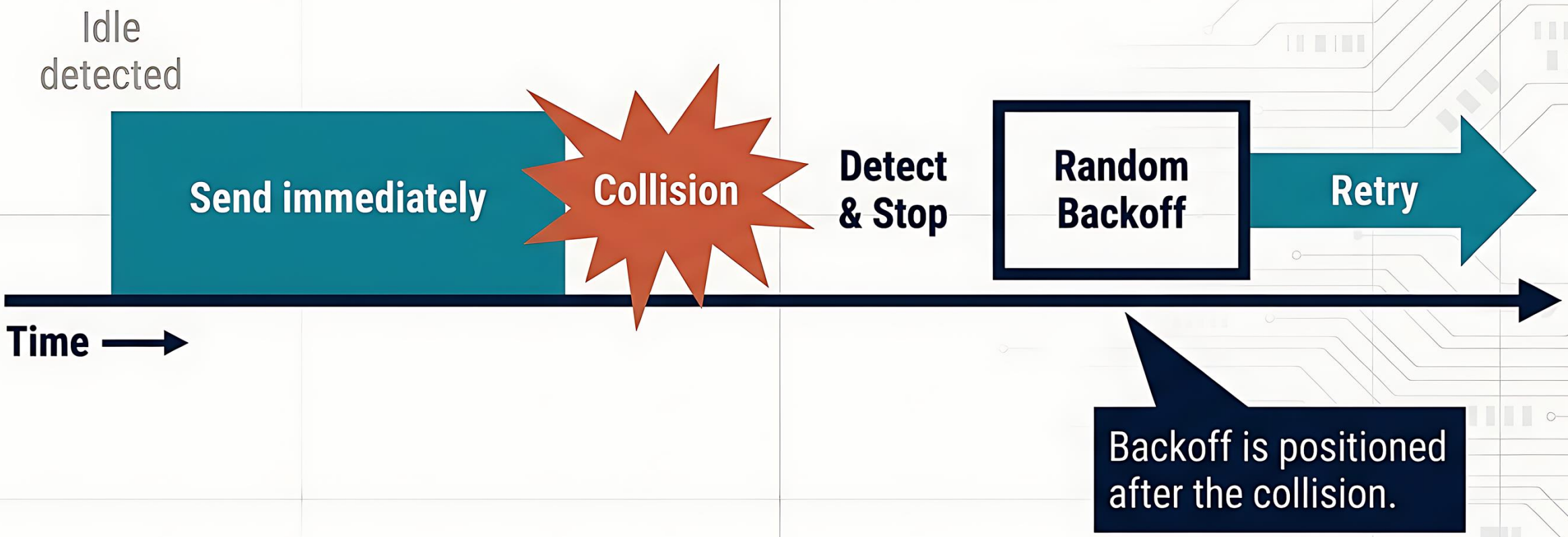
CSMA/CD Philosophy: Send First, Recover Later

CSMA/CD assumes:

- ✔ Collision detection is feasible
- ✔ The sender can notice a collision
- ✔ The sender can stop quickly
- ✔ Random backoff can resolve the retry

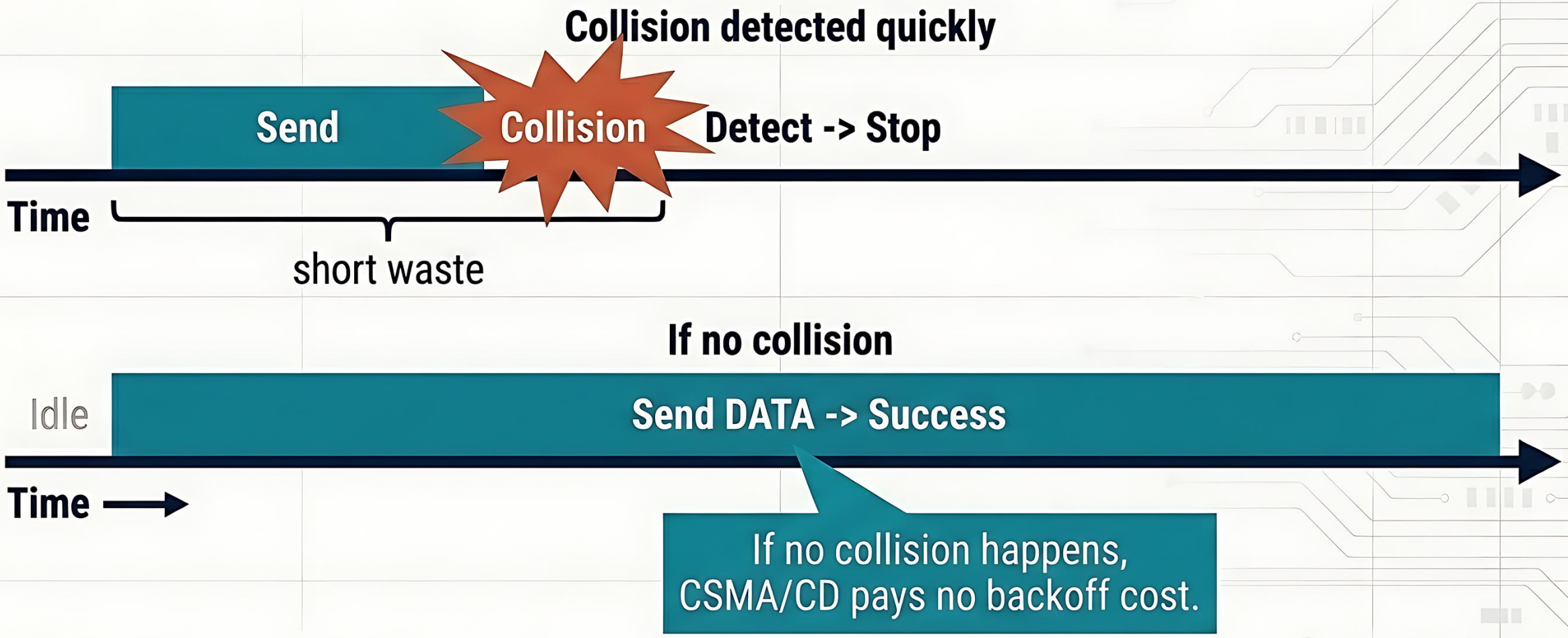


CSMA/CD Relies on Sending First and Recovering Later



In CSMA/CD, random backoff is a reactive recovery mechanism.

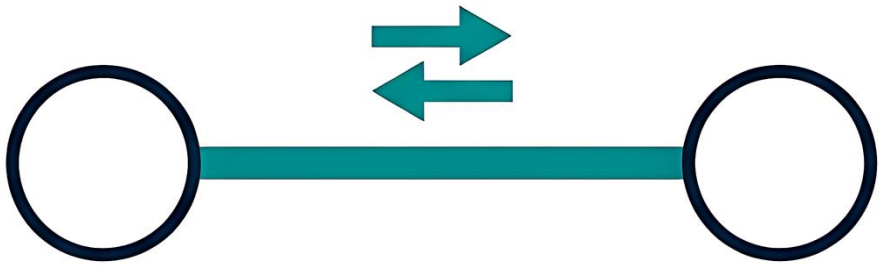
Why the Send-First Strategy Works for CSMA/CD



CSMA/CD avoids unnecessary waiting when collision detection is available.

Can We Use CSMA/CD in Wireless Networks?

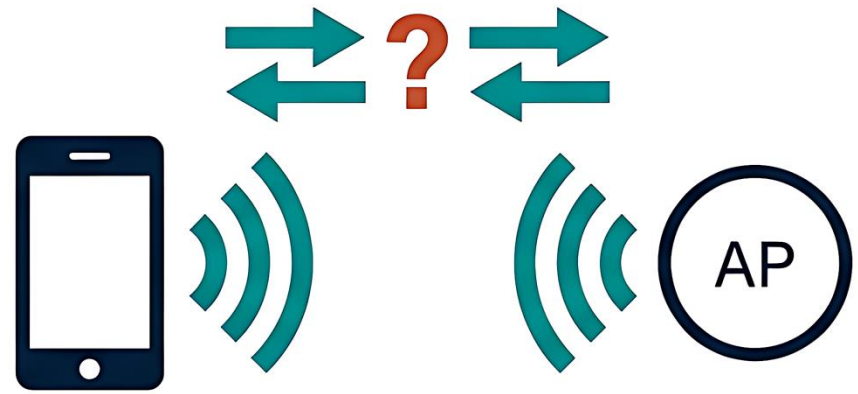
Wired Ethernet



- Transmit immediately when idle

- Detect collision if it happens
- Stop and retry

Wireless Networks



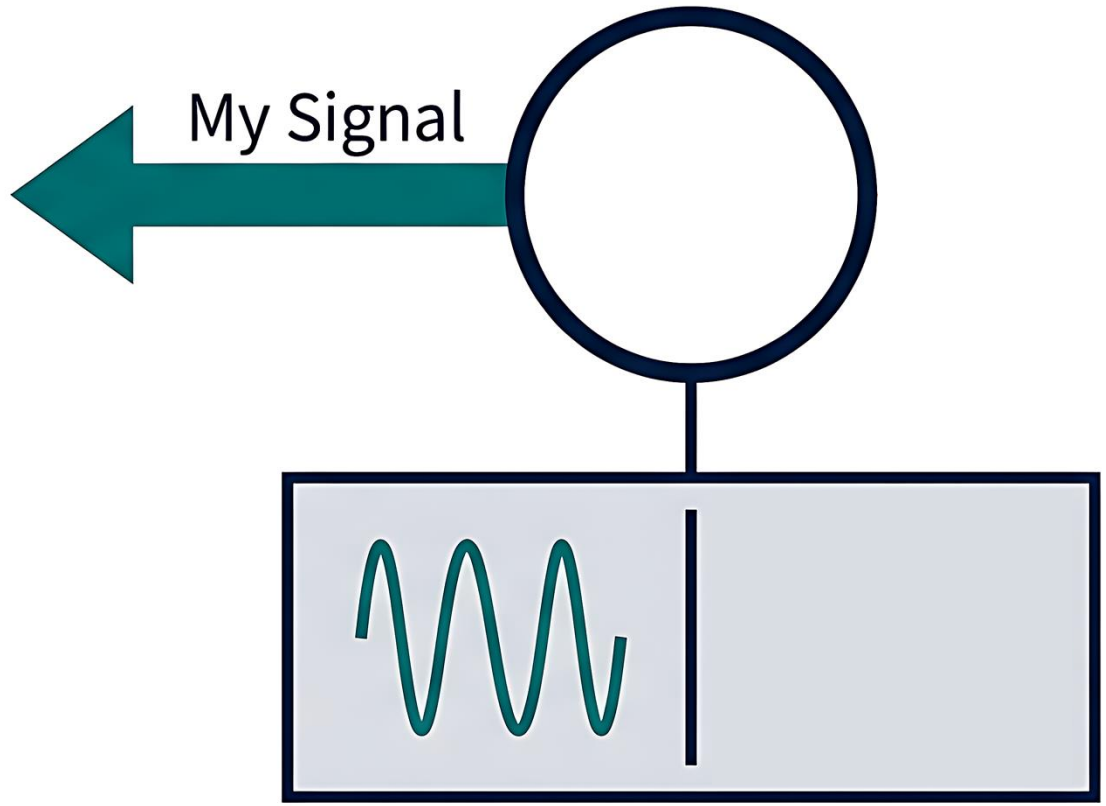
- Can we transmit and listen at the same time?

Can a wireless node detect a collision while transmitting?

What Does Collision Detection Require?

To detect a collision, a node must:

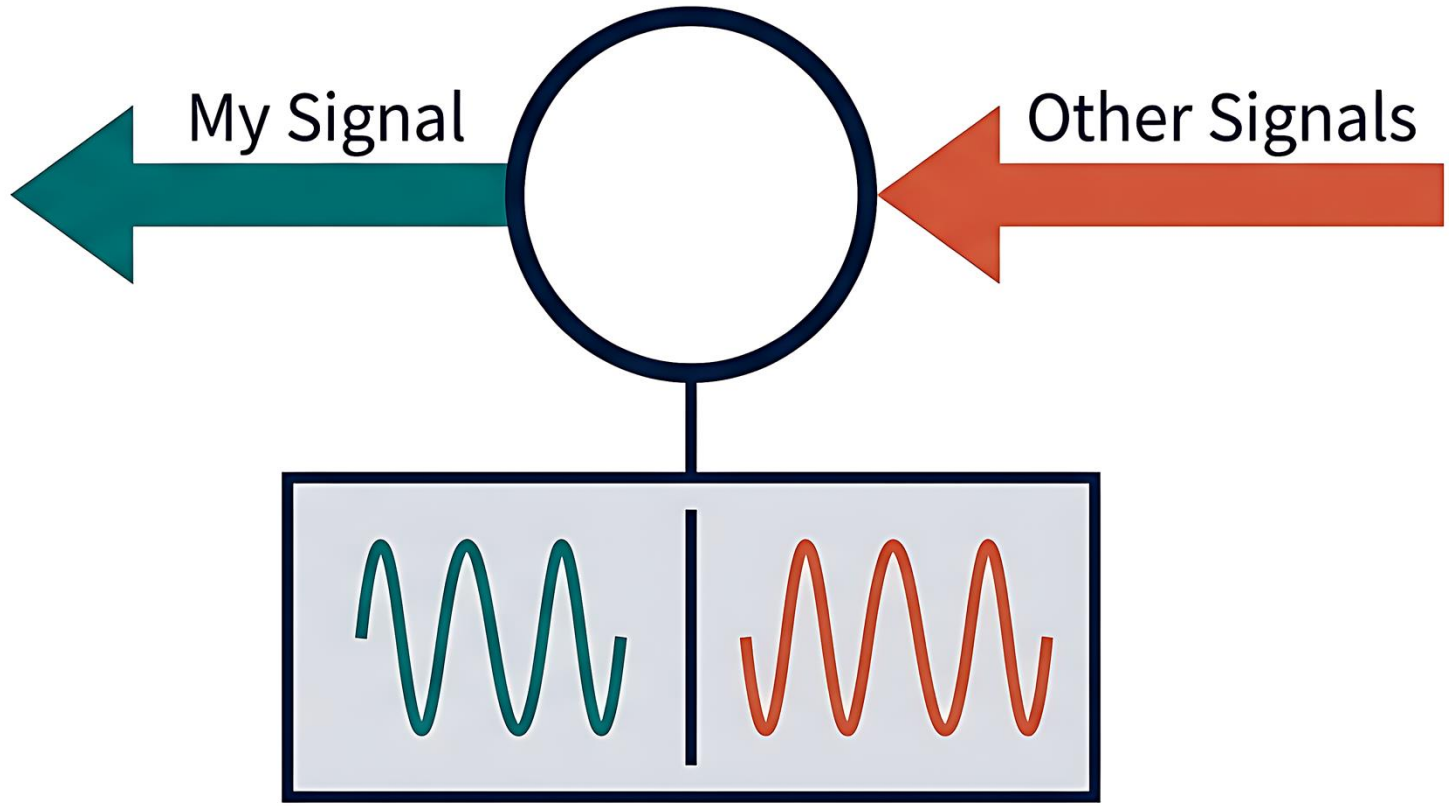
- Transmit its own signal.



What Does Collision Detection Require?

To detect a collision, a node must:

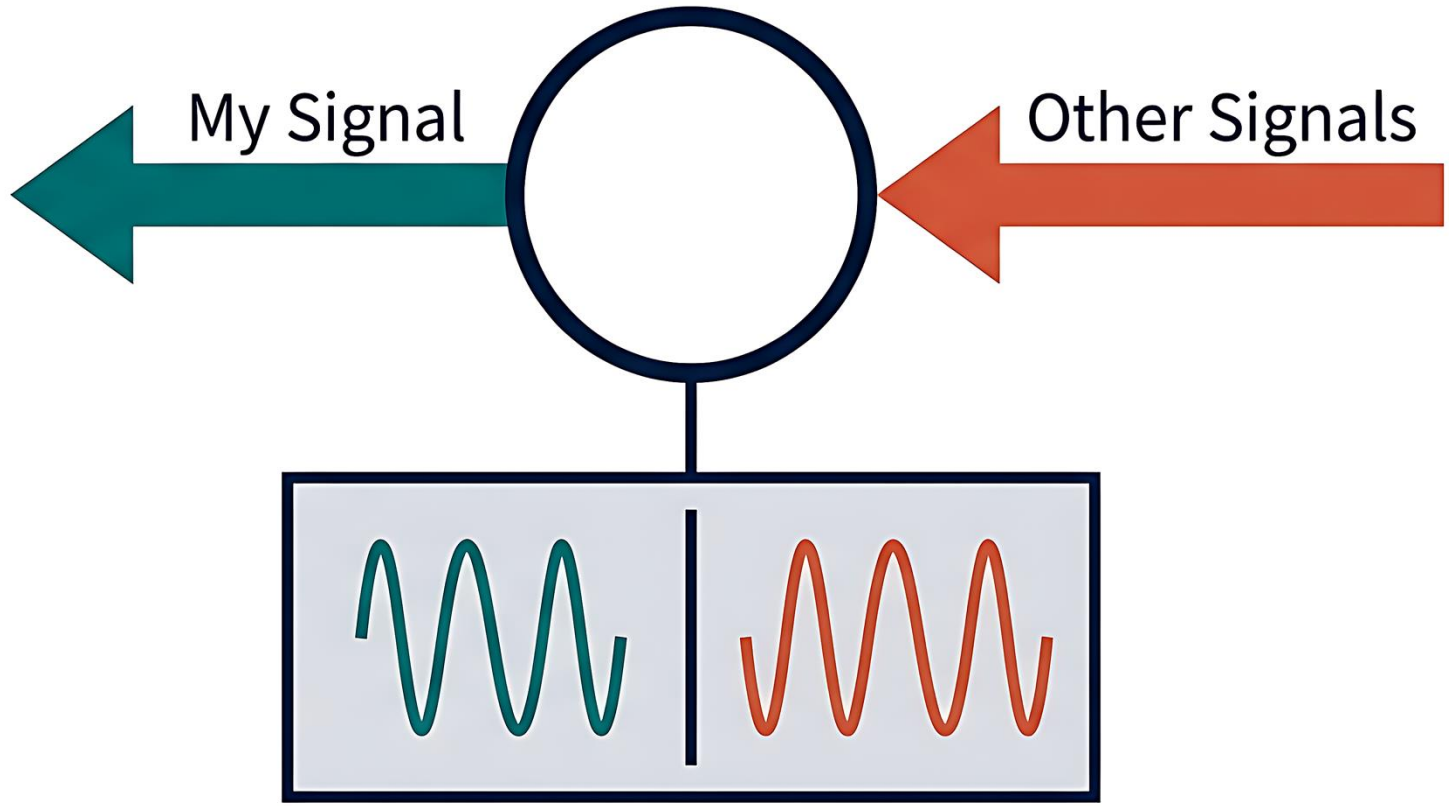
- Transmit its own signal.
- Simultaneously receive signals from others.



What Does Collision Detection Require?

To detect a collision, a node must:

- Transmit its own signal.
- Simultaneously receive signals from others.
- **Distinguish: my signal vs other signals.**



The node must reliably hear other signals while transmitting.

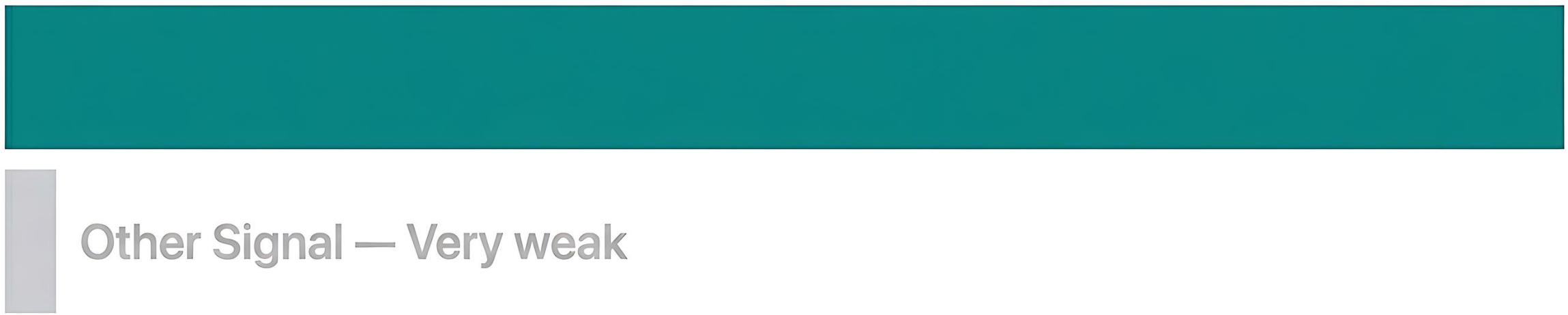
The Core Problem: Your Own Signal Is Much Stronger

Transmitted power is exponentially greater than received power.

My Transmission — VERY STRONG

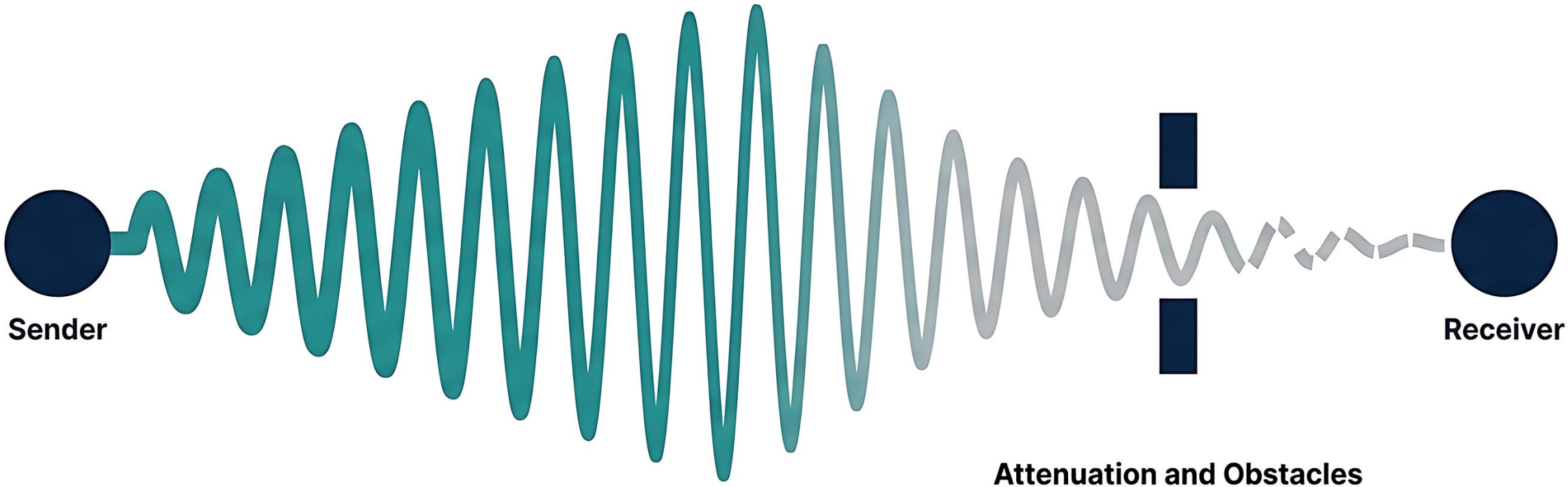
The Core Problem: Your Own Signal Is Much Stronger

Transmitted power is exponentially greater than received power.



Your own signal overwhelms incoming signals at the antenna.

Why Is the Received Signal Much Weaker?



Propagation Loss: Power spreads out exponentially with distance.

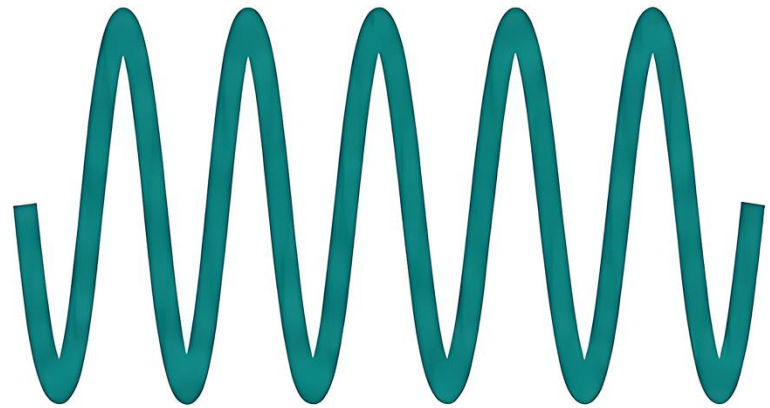
Attenuation and Obstacles

Environmental Attenuation: Obstacles and space absorb and degrade the signal strength significantly before it ever reaches the receiver.

Why This Makes Collision Detection Difficult

During transmission:
- Sender’s own signal dominates

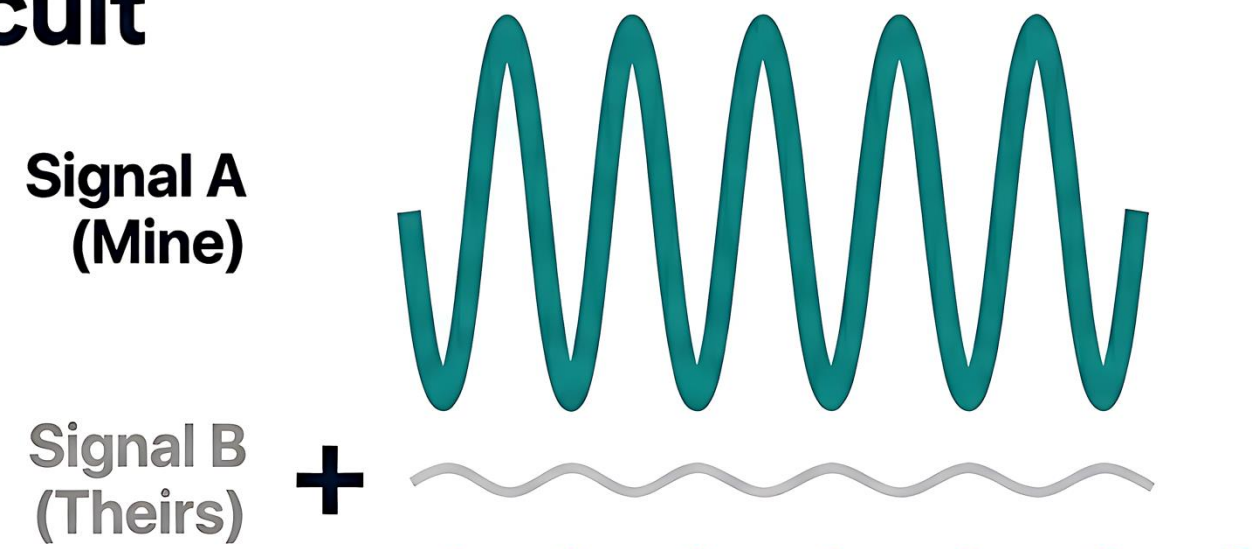
Signal A (Mine)



Why This Makes Collision Detection Difficult

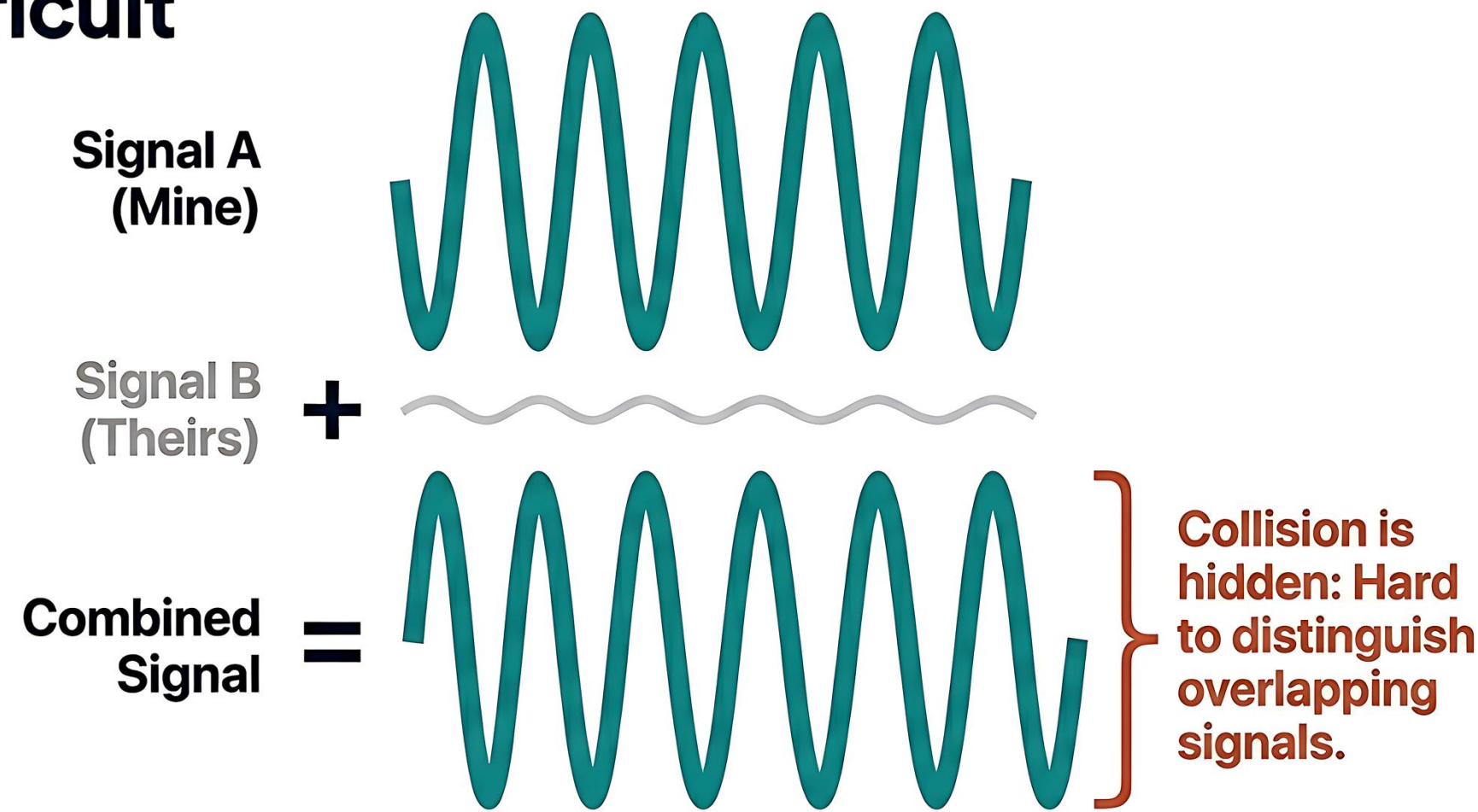
During transmission:

- Sender's own signal dominates
- Incoming signals are too weak to detect



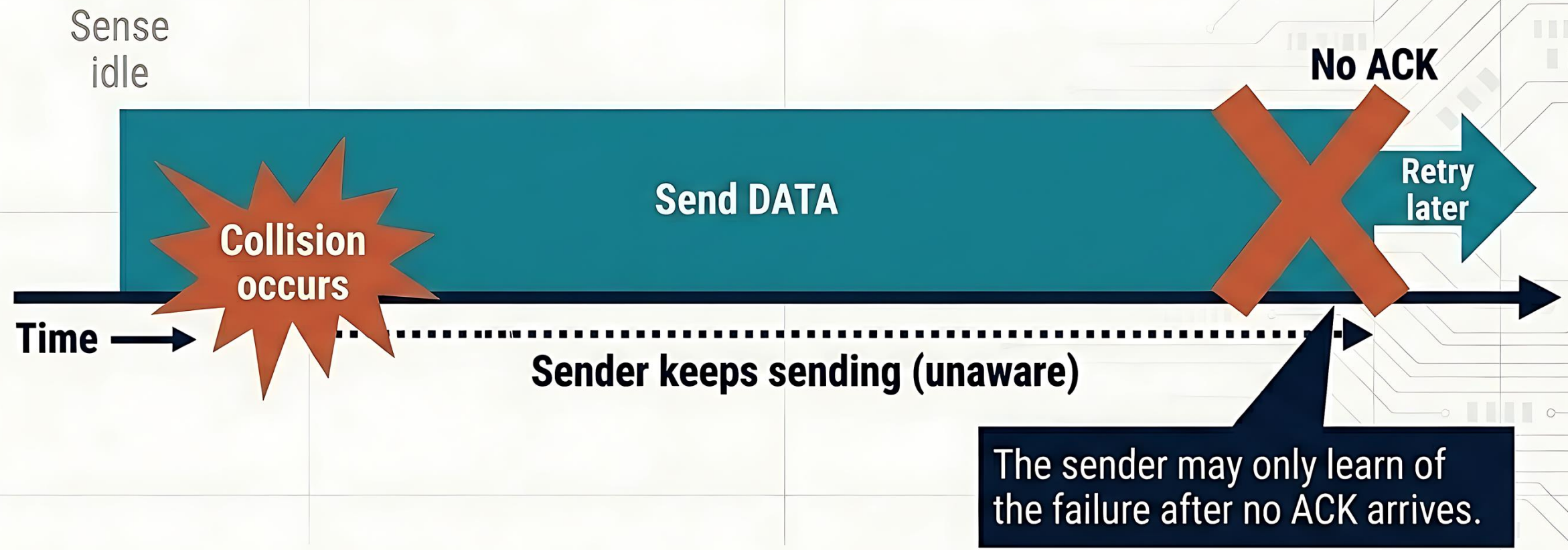
Why This Makes Collision Detection Difficult

During transmission:
- Sender's own signal dominates
- Incoming signals are too weak to detect
- Hard to tell if another node is transmitting



The sender cannot reliably detect a collision while transmitting.

Unreliable Detection Makes Collisions Highly Expensive



Without reliable detection, collision recovery is slower and vastly more costly.

Wireless collision detection is unreliable

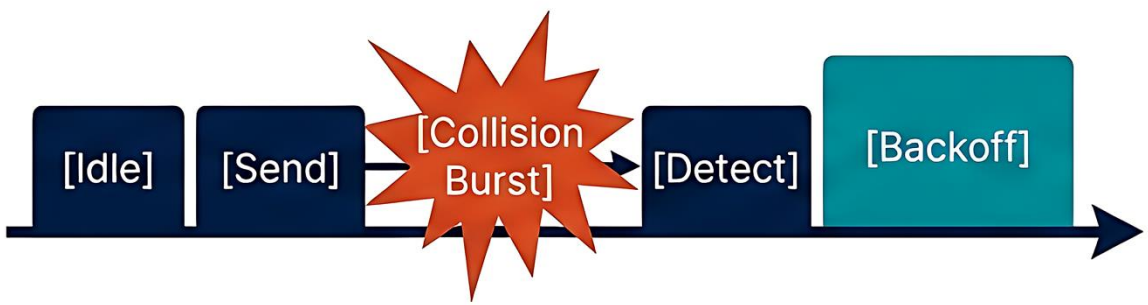
Cannot rely on “send first, detect later”

Need a different MAC strategy

The physical limitation changes the MAC design strategy.

CSMA/CD Philosophy:

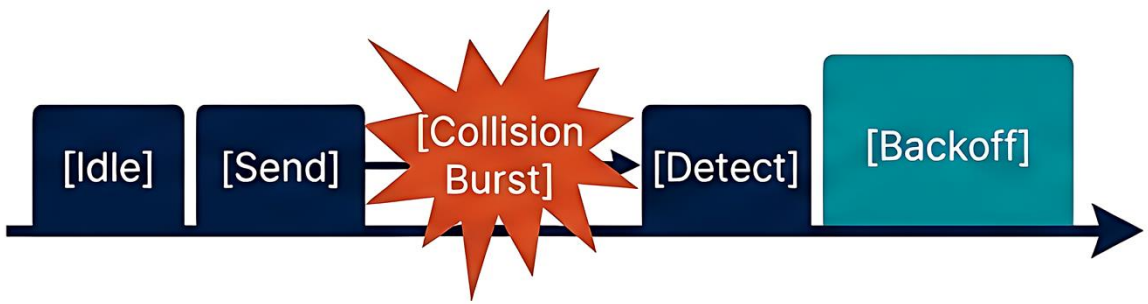
Send first. If collision happens,
detect it and recover.



Reactive

CSMA/CD Philosophy:

Send first. If collision happens, detect it and recover.



Reactive

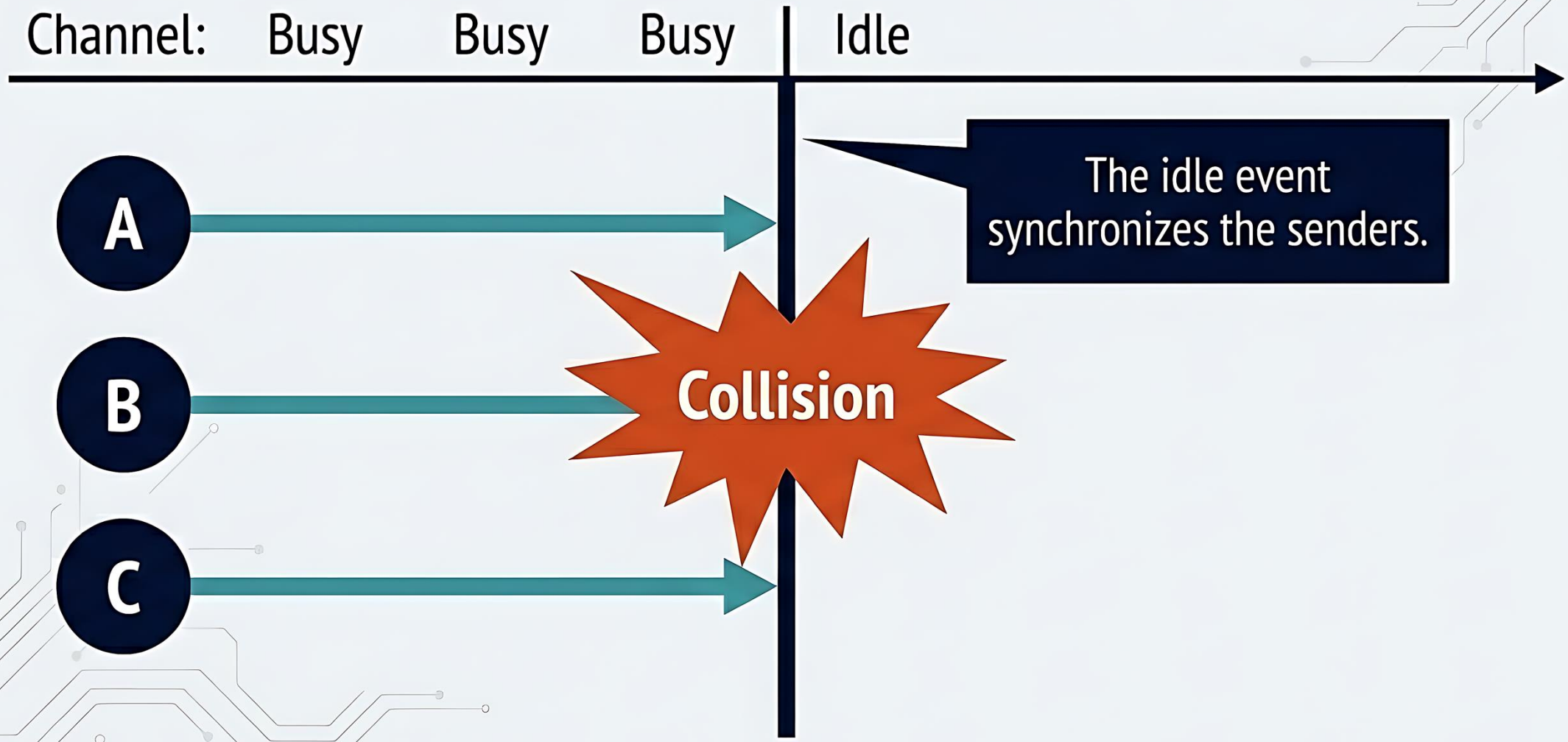
Same tool, moved earlier.

CSMA/CA Philosophy:

Since collision is hard to detect, reduce the chance before sending.

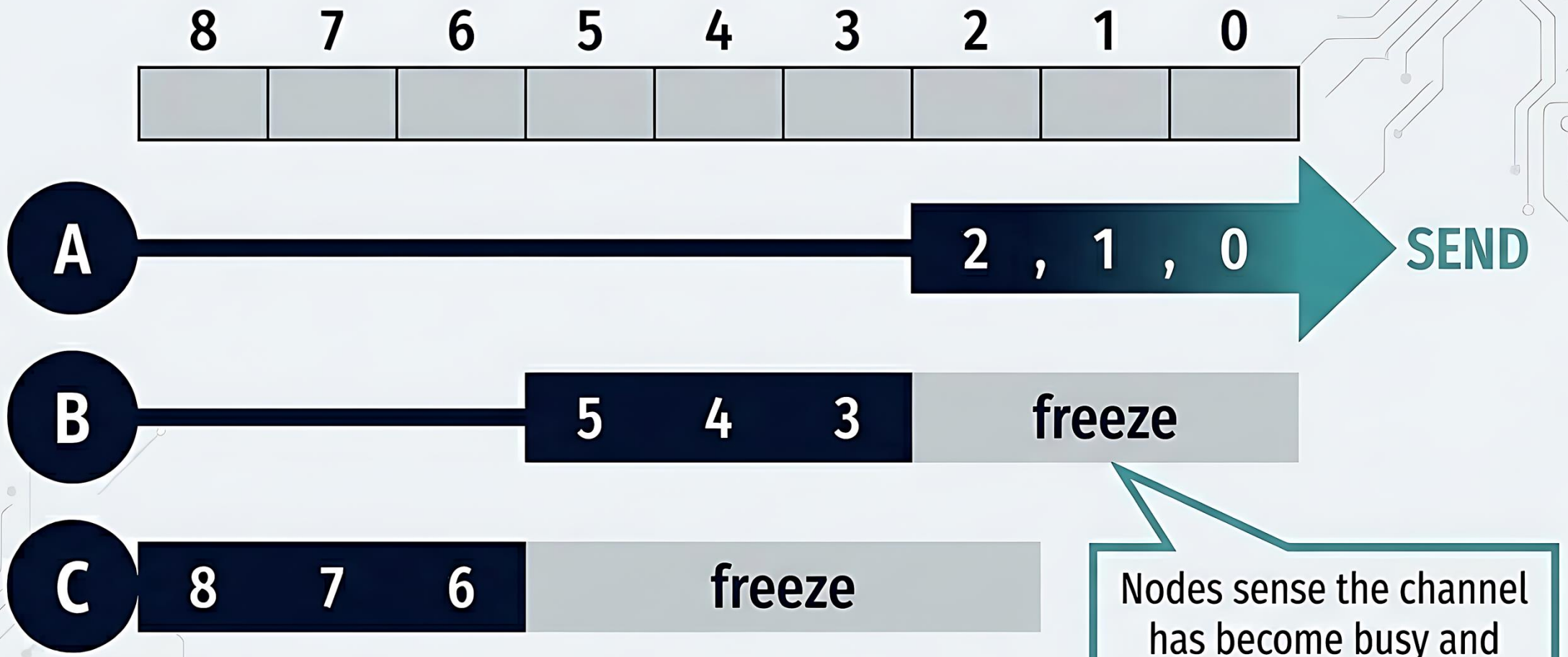
Proactive

How an Idle Channel Synchronizes Competitors



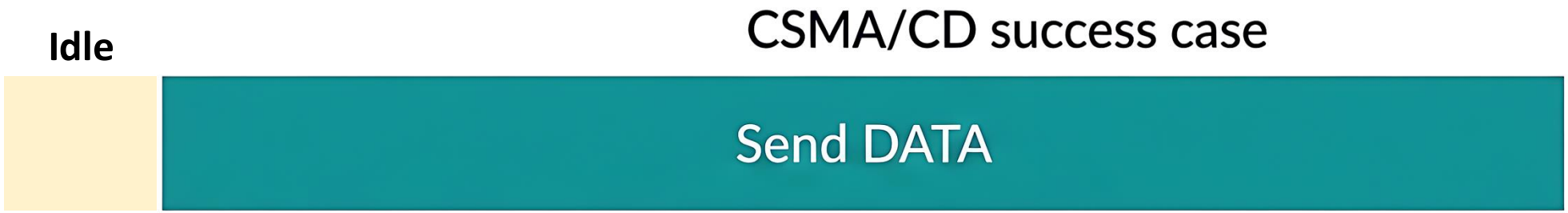
Without pre-backoff, the idle channel triggers many competing senders at once.

Random Backoff Breaks Synchronization

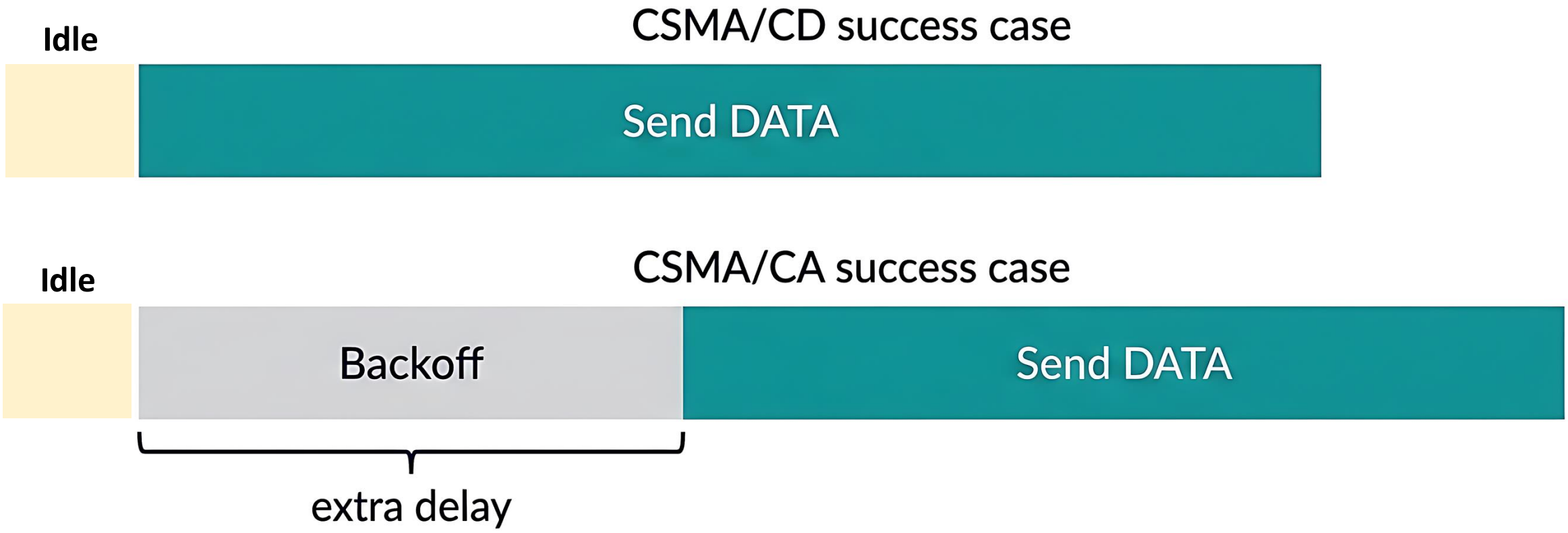


Random waiting desynchronizes competing nodes and spreads attempts over time.

The Tradeoff of Extra Waiting Before Transmission

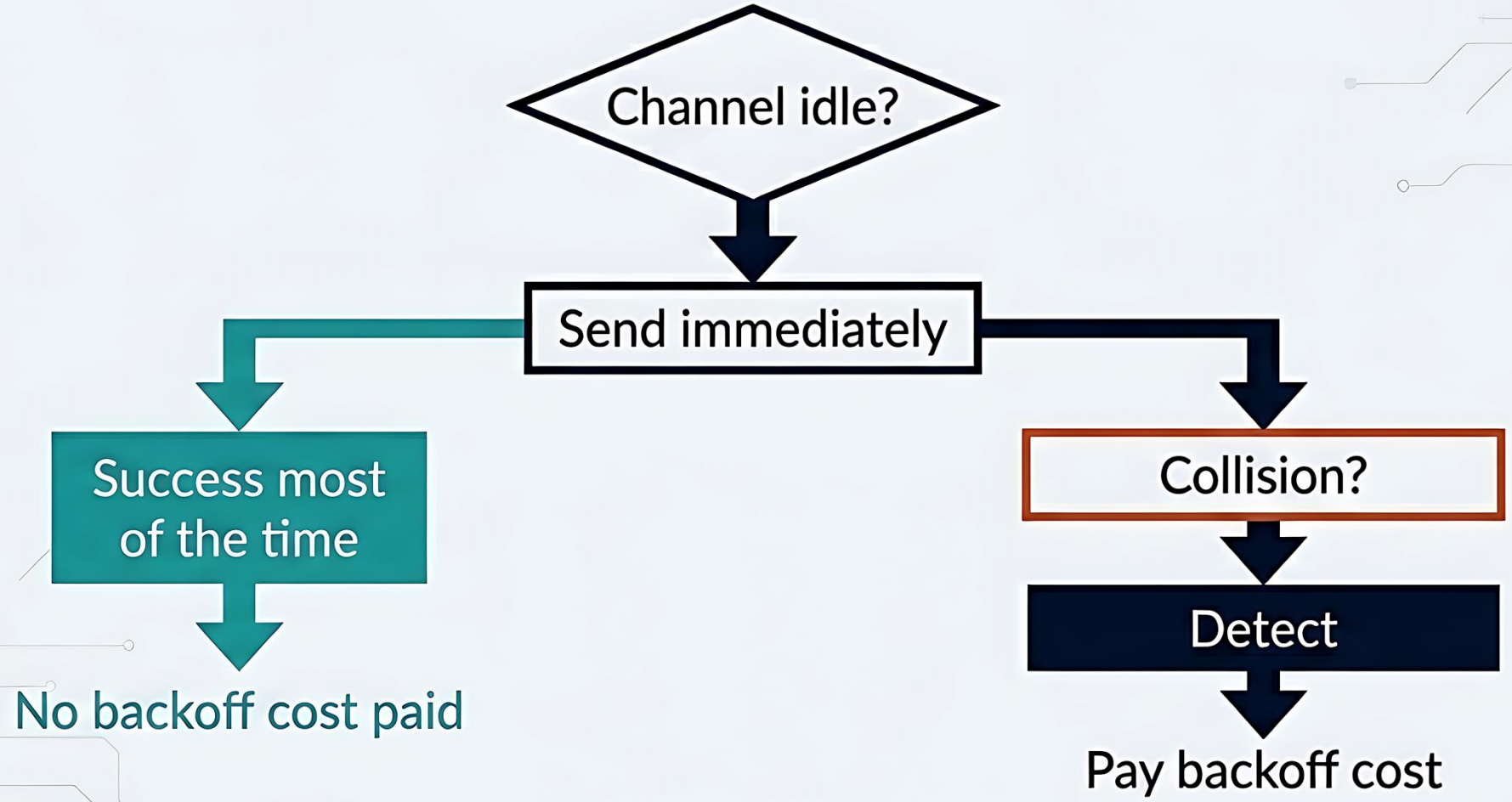


The Tradeoff of Extra Waiting Before Transmission



Pre-backoff reduces collisions but undeniably increases per-transmission delay.

Why CSMA/CD Avoids Proactive Backoff

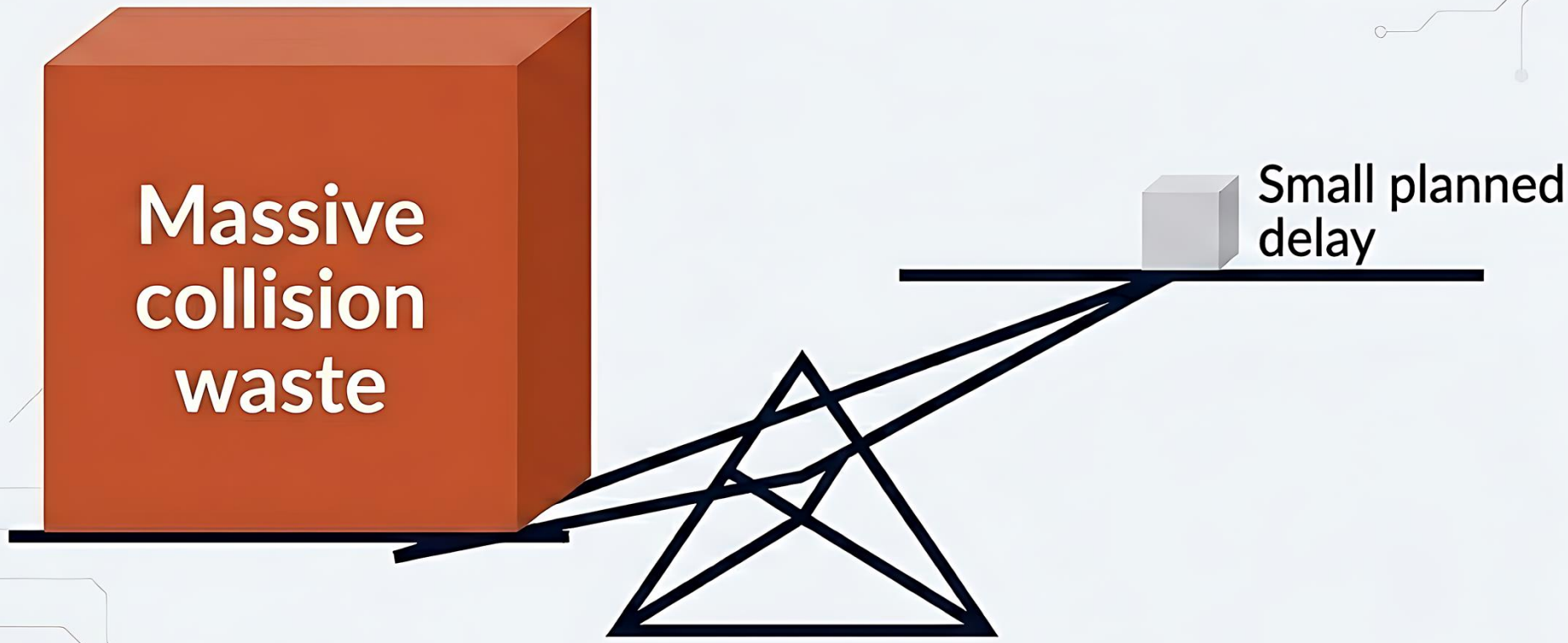


CSMA/CD is designed to keep the fast path fast because collision detection is reliable in wired networks.

Why CSMA/CA Gladly Accepts the Extra Waiting

Send immediately -> higher risk
-> Possible full-frame waste

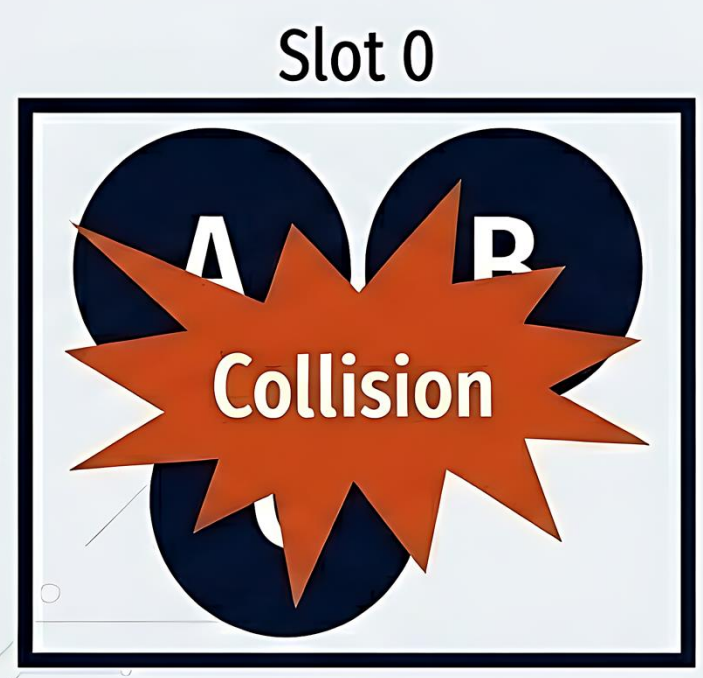
Random backoff first -> lower risk
-> Small waiting cost



CSMA/CA trades a small planned delay for vastly fewer costly failures.

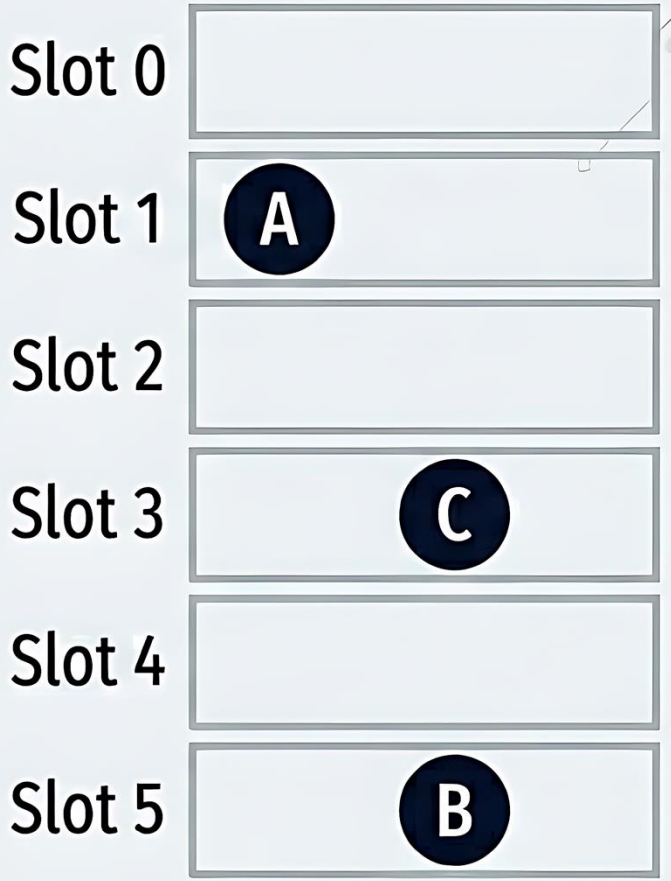
Randomness Reduces Collision Probability

Without backoff



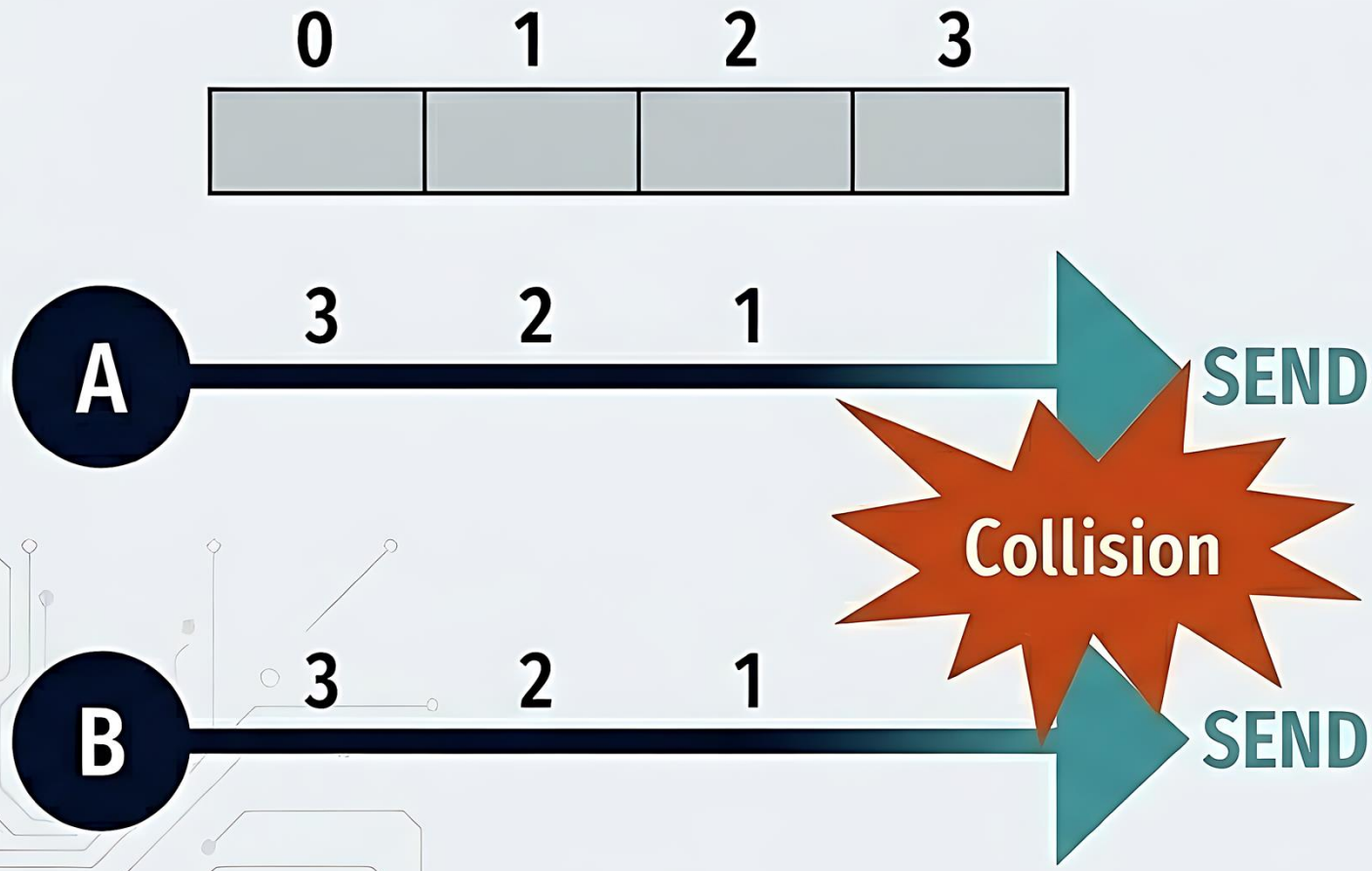
Randomness spreads choices across time.

With backoff



More possible slots means less overlap and lower collision probability.

Collision Avoidance Cannot Eliminate Collisions Completely

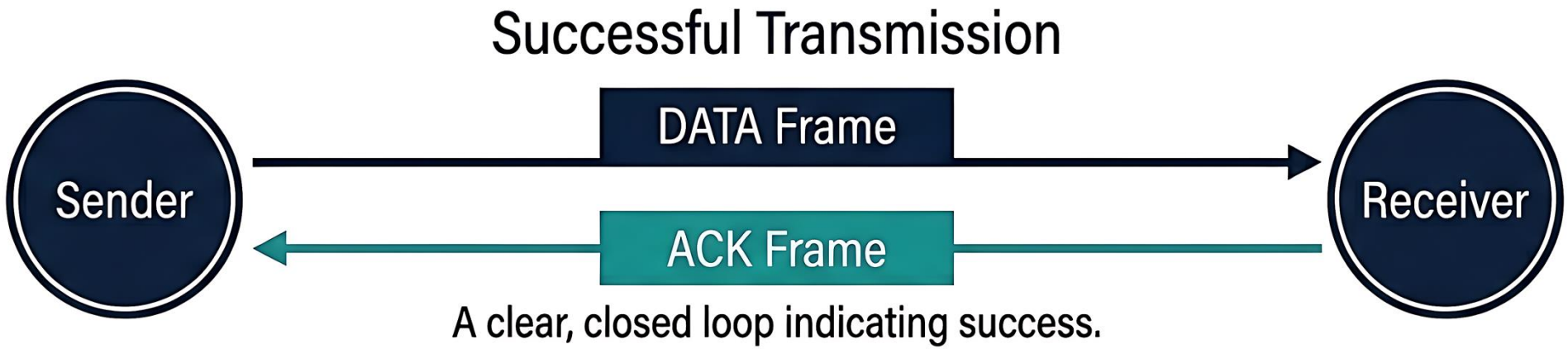


- Two nodes independently choosing the same backoff slot.
- **Hidden terminals** that cannot hear each other deferring.
- **Interference** corrupting the frame.
- Lost ACKs.

Avoidance is probabilistic.

How Do We Know the Frame Succeeded?

Because senders cannot reliably detect collisions mid-flight, Wi-Fi relies on receiver feedback.

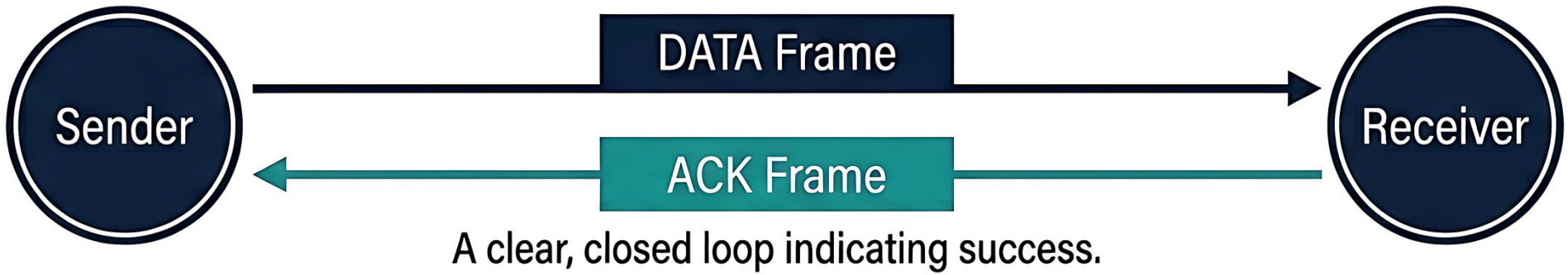


A clear, closed loop indicating success.

How Do We Know the Frame Succeeded?

Because senders cannot reliably detect collisions mid-flight, Wi-Fi relies on receiver feedback.

Successful Transmission



A clear, closed loop indicating success.

Failed Transmission

(No ACK)

Sender assumes failure and prepares to retry.

In CSMA/CA, failure is inferred from missing ACKs.

Dimension	CSMA/CD	CSMA/CA
When idle	Send immediately	Random backoff first
Backoff position	After collision	Before transmission
Backoff purpose	Recovery	Prevention
Design style	Reactive	Proactive
Waiting cost	Paid after collision	Paid before attempts
Collision strategy	Detect and recover	Avoid before sending

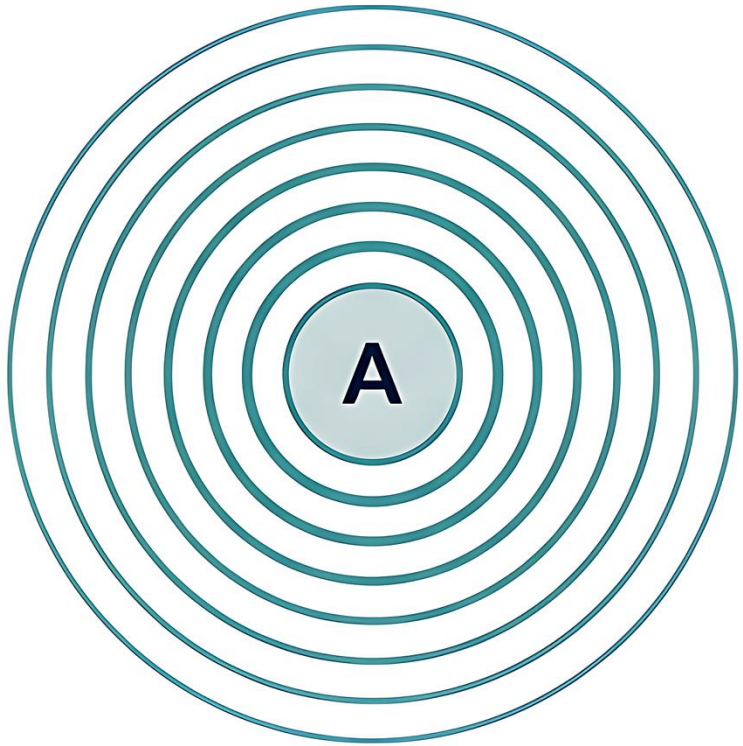
VISUAL LEGEND

CSMA/CD: [Idle] → [Send] → [Collision] → [Detect] → [Backoff] → [Retry]

CSMA/CA: [Idle] → [Backoff] → [Send] → [ACK]

Carrier Sensing Is Local

At Sender A

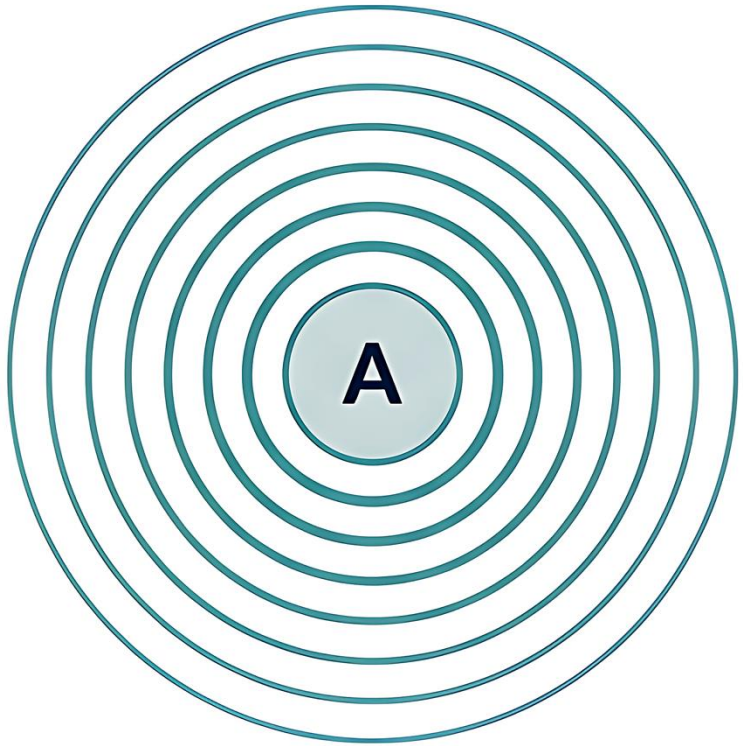


Channel looks idle.

A sender can only sense the channel near itself.

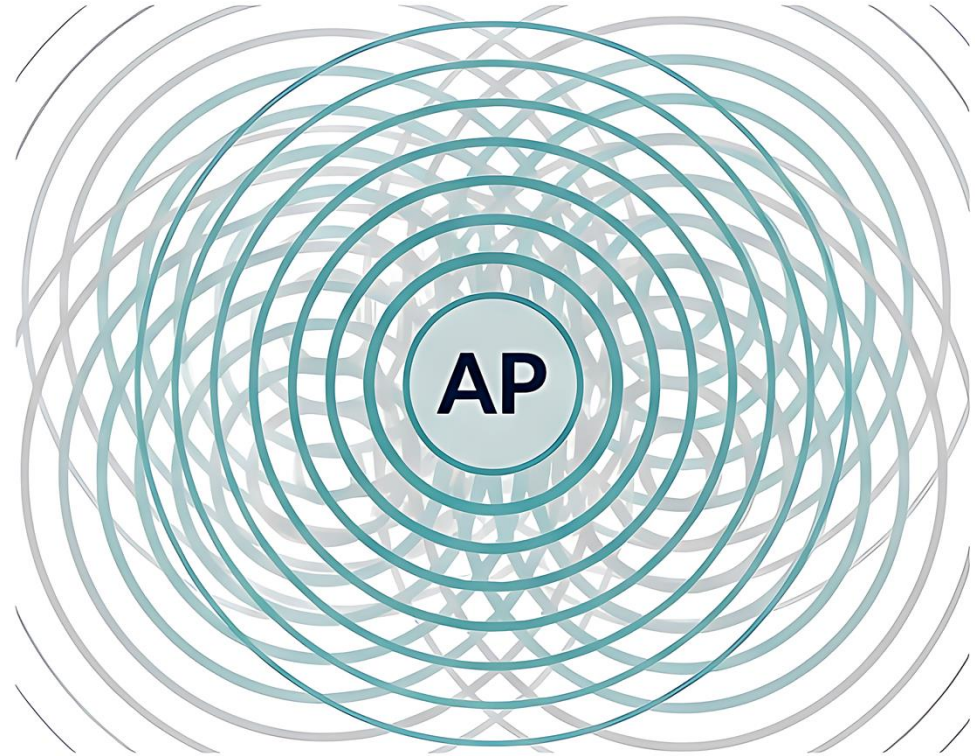
Carrier Sensing Is Local

At Sender A



Channel looks idle.
A sender can only sense the channel near itself.

At AP

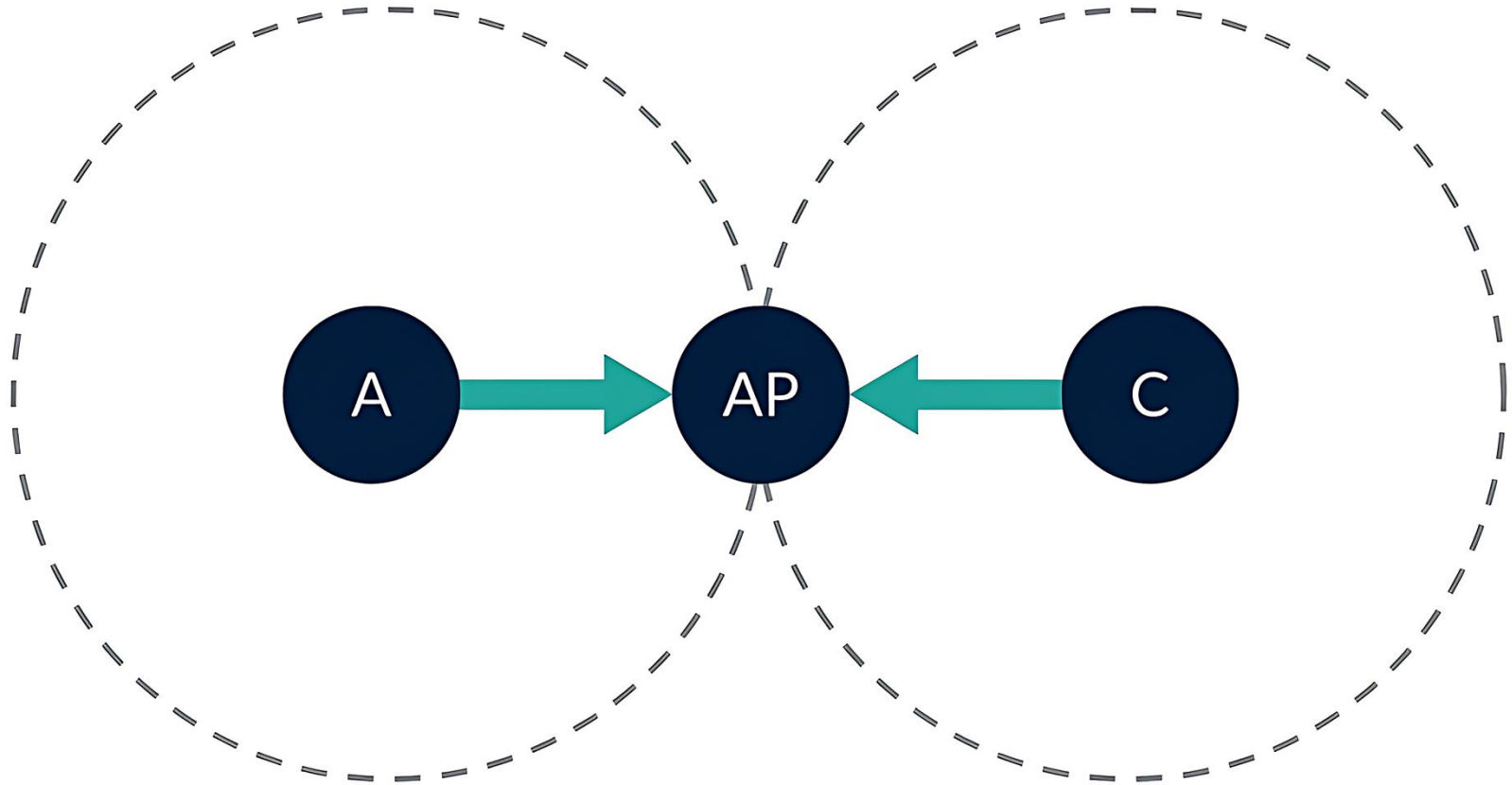


Will my transmission
interfere at the receiver?

Carrier sensing is local, but collisions happen at the receiver.

The Hidden Terminal Problem

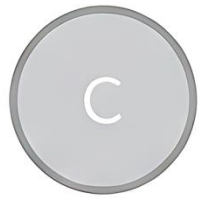
- A wants to send to AP
- C wants to send to AP
- A cannot hear C, and C cannot hear A



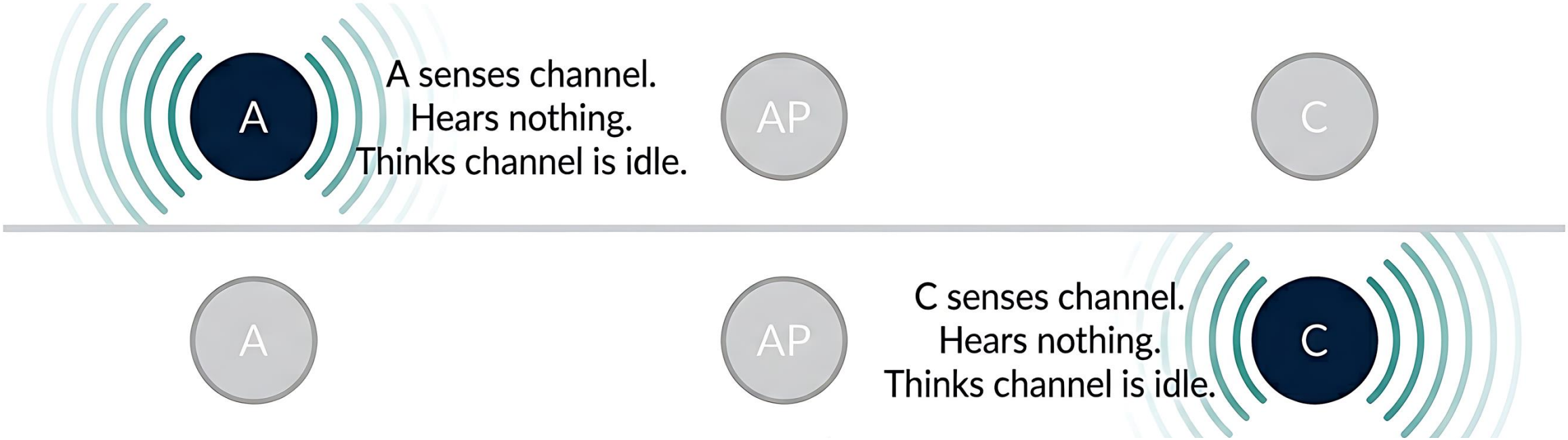
A and C are hidden from each other, but not from the AP.

How the Collision Happens

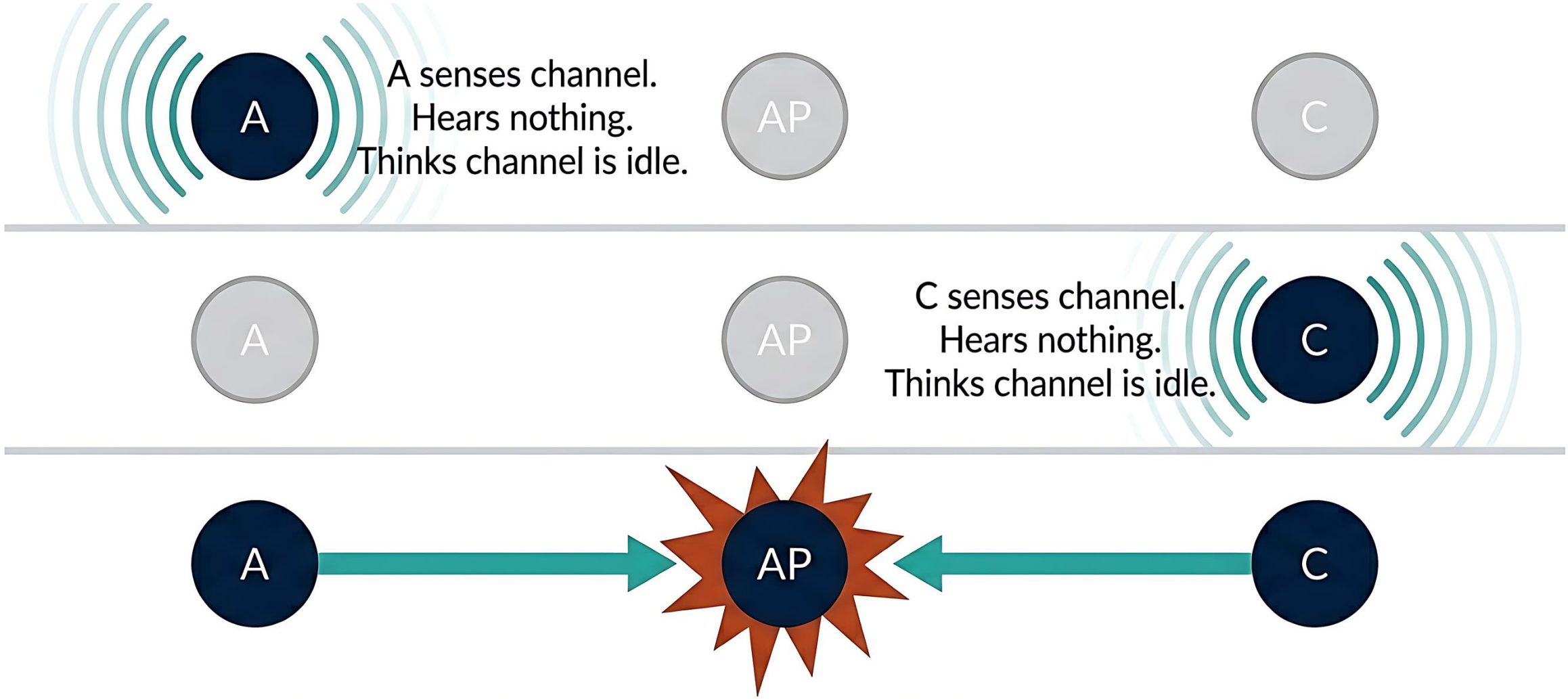
A senses channel.
Hears nothing.
Thinks channel is idle.



How the Collision Happens



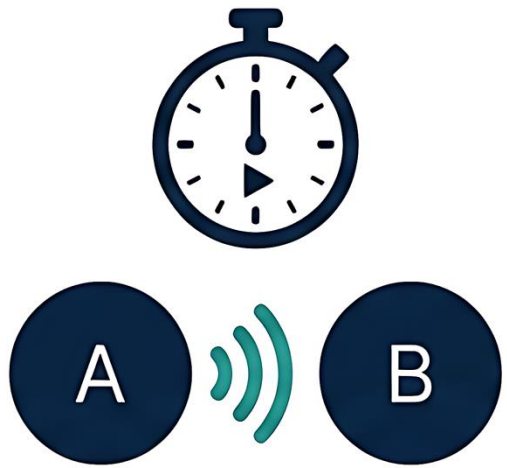
How the Collision Happens



Both senders make reasonable local decisions, but the receiver sees a collision.

Why CSMA/CA Cannot Fully Fix This

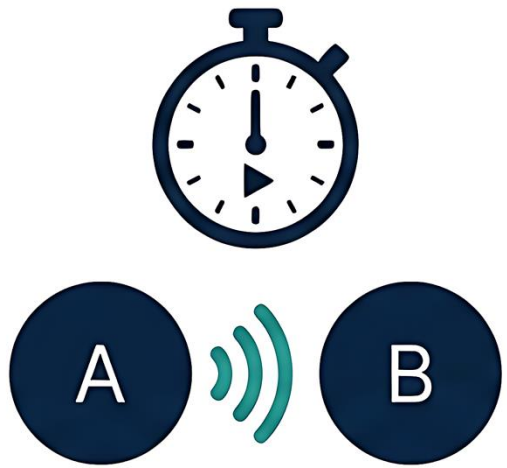
Random backoff reduces risk, but cannot fix missing information.



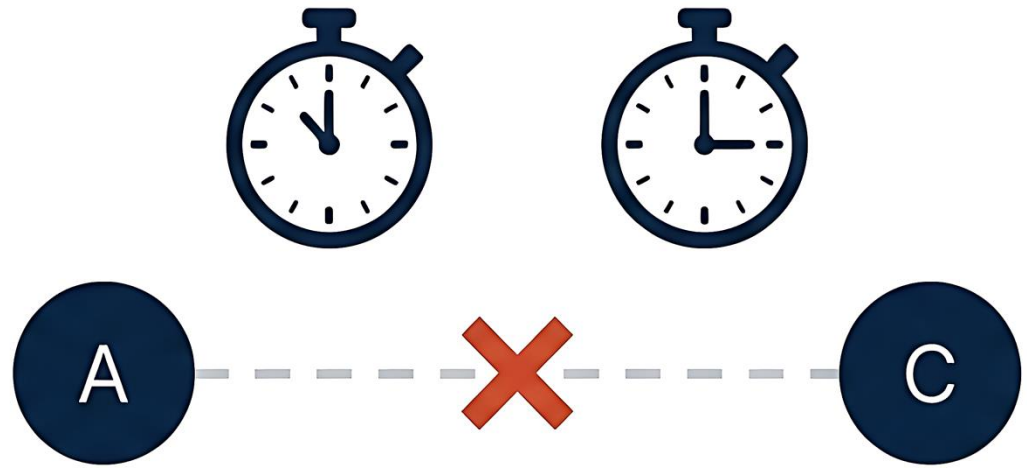
A hears B → Backoff effectively staggers transmissions.

Why CSMA/CA Cannot Fully Fix This

Random backoff reduces risk, but cannot fix missing information.



A hears B → Backoff effectively staggers transmissions.

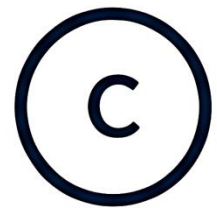
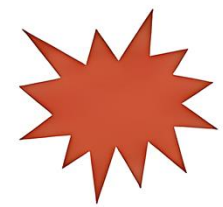


A cannot hear C → Backoff cannot coordinate invisible competitors.

Hidden terminals cannot coordinate through carrier sensing because they do not know they are competing.

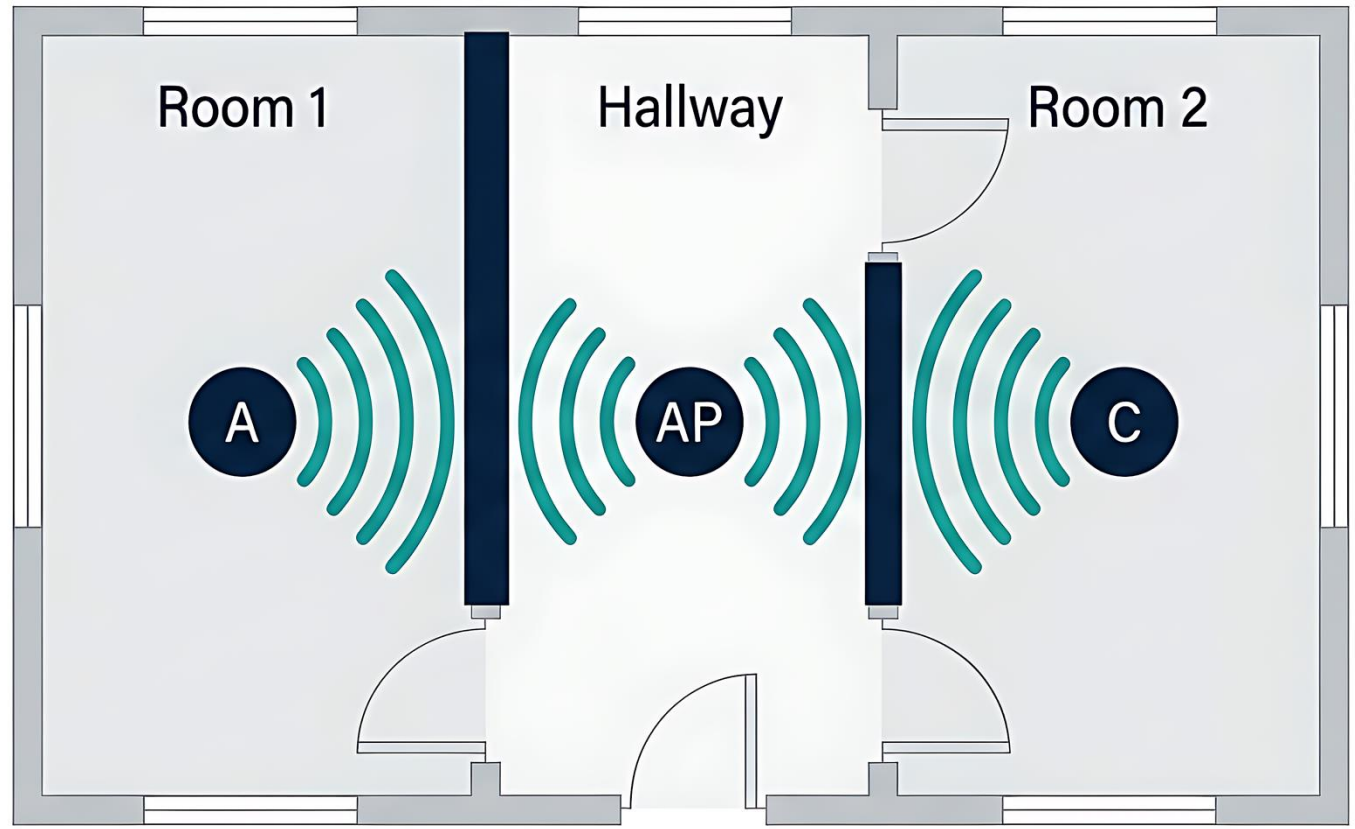
Sender View ≠ Receiver View

Wireless interference is fundamentally receiver-dependent.

Node A	Node C	Access Point
		
“I do not hear C. The channel is idle.”	“I do not hear A. The channel is idle.”	“I hear both A and C. The frames collide.”
 **Idle**	 **Idle**	 **Collision**

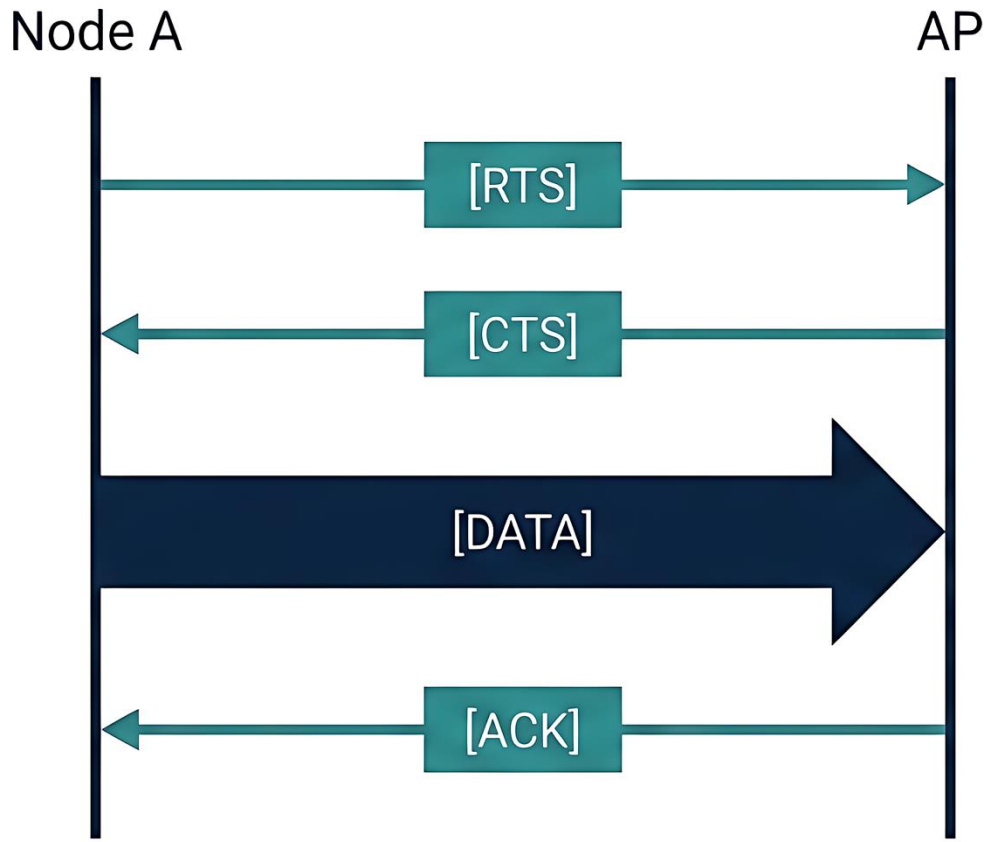
Why Hidden Terminals Are Common in Wireless

- Walls or physical obstacles
- Long distances
- Signal attenuation / fading
- Uneven wireless coverage
- Differing transmit powers



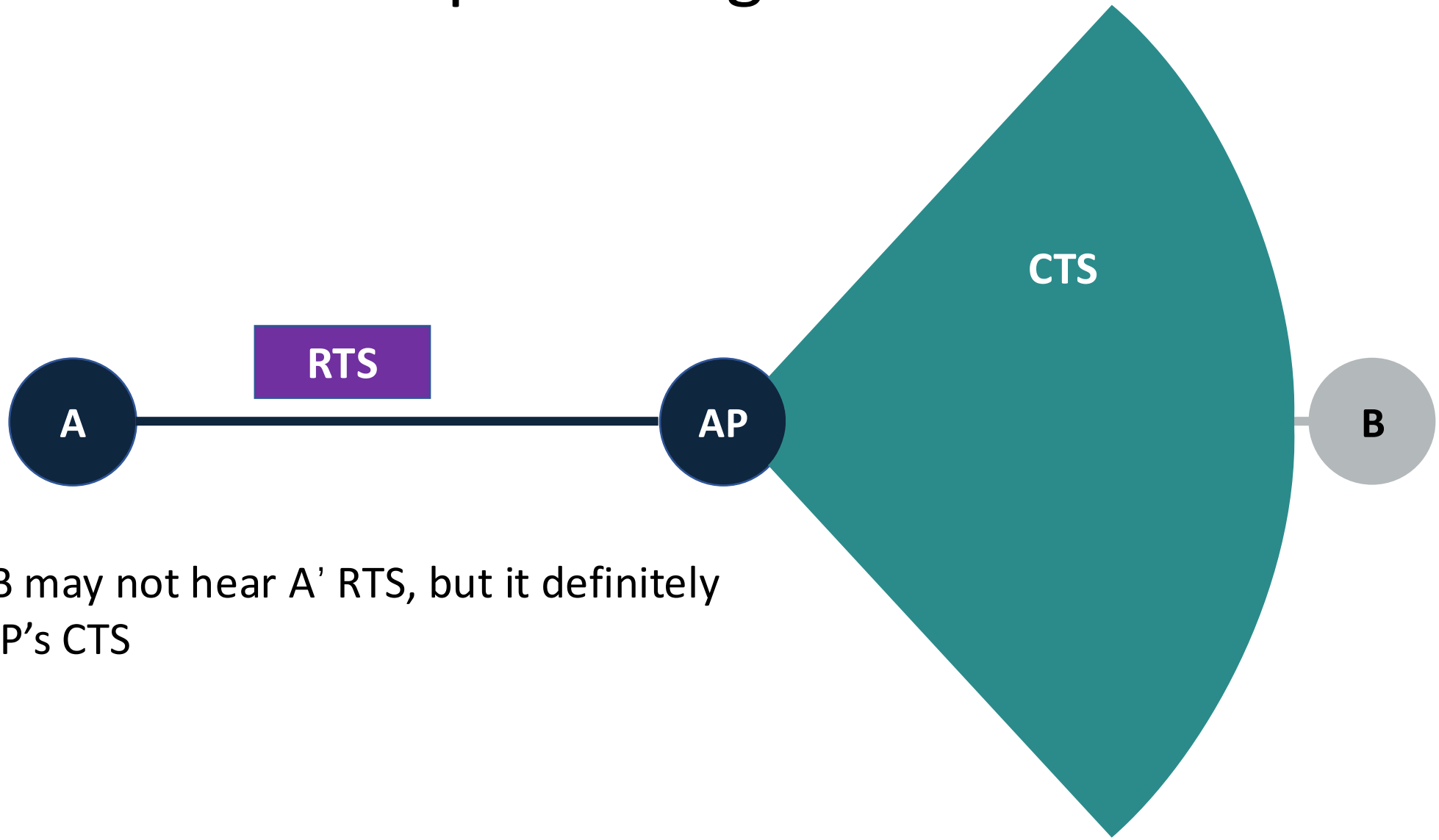
RTS/CTS: Coordinating Around the Receiver

Let the receiver help reserve the medium using short control frames.



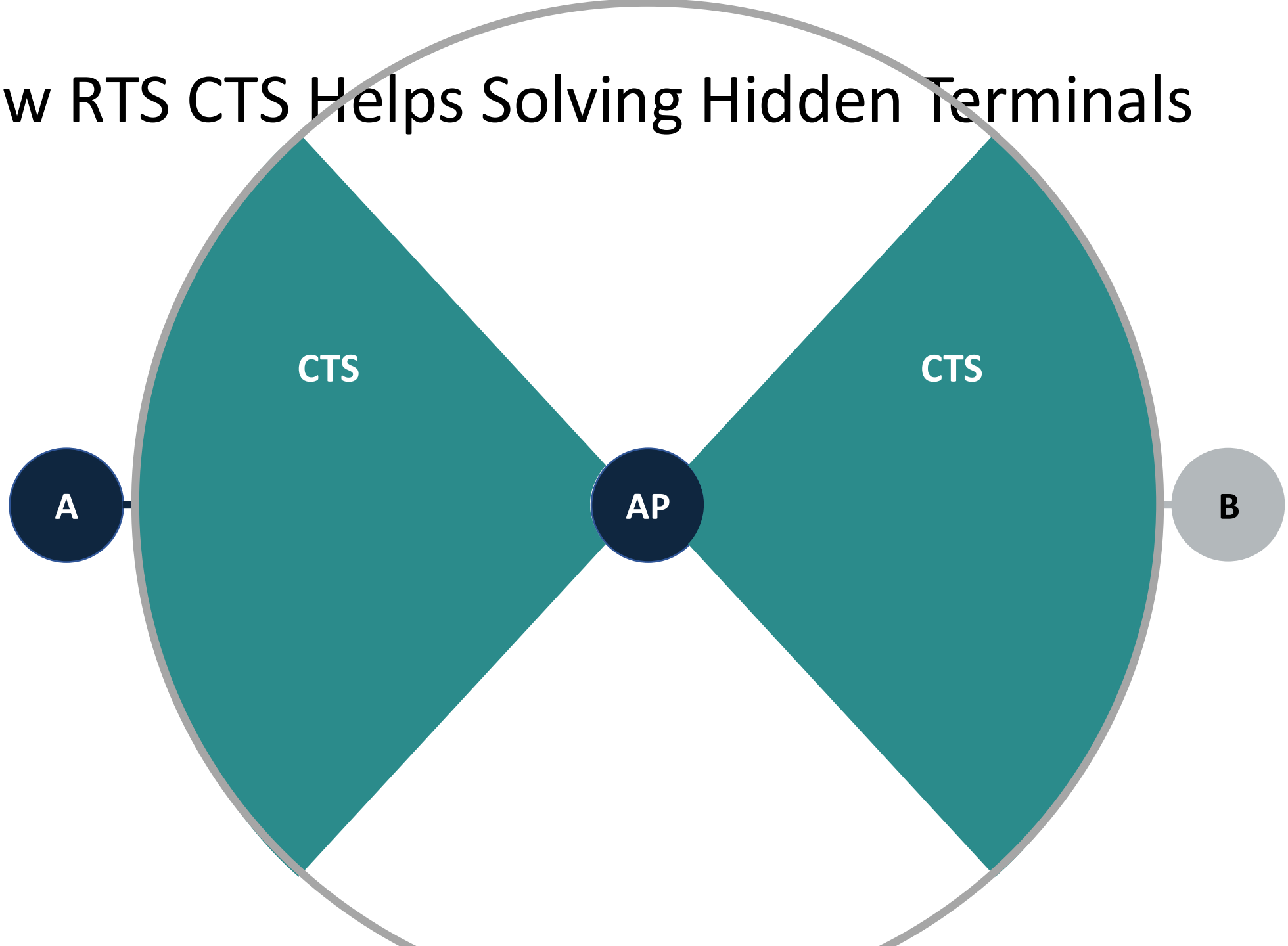
RTS/CTS shifts coordination from the blind sender toward the all-seeing receiver.

How RTS CTS Helps Solving Hidden Terminals

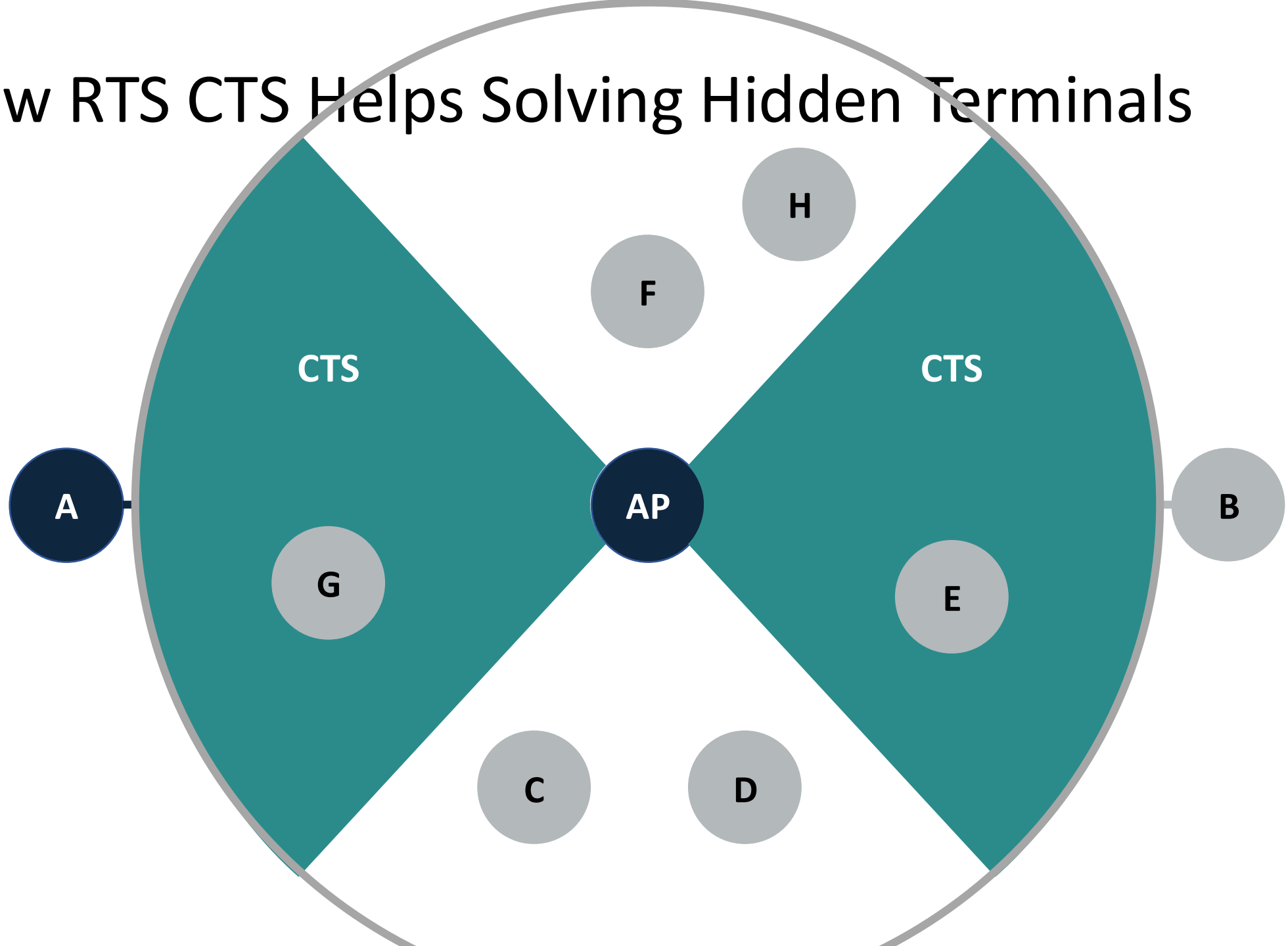


Node B may not hear A' RTS, but it definitely hear AP's CTS

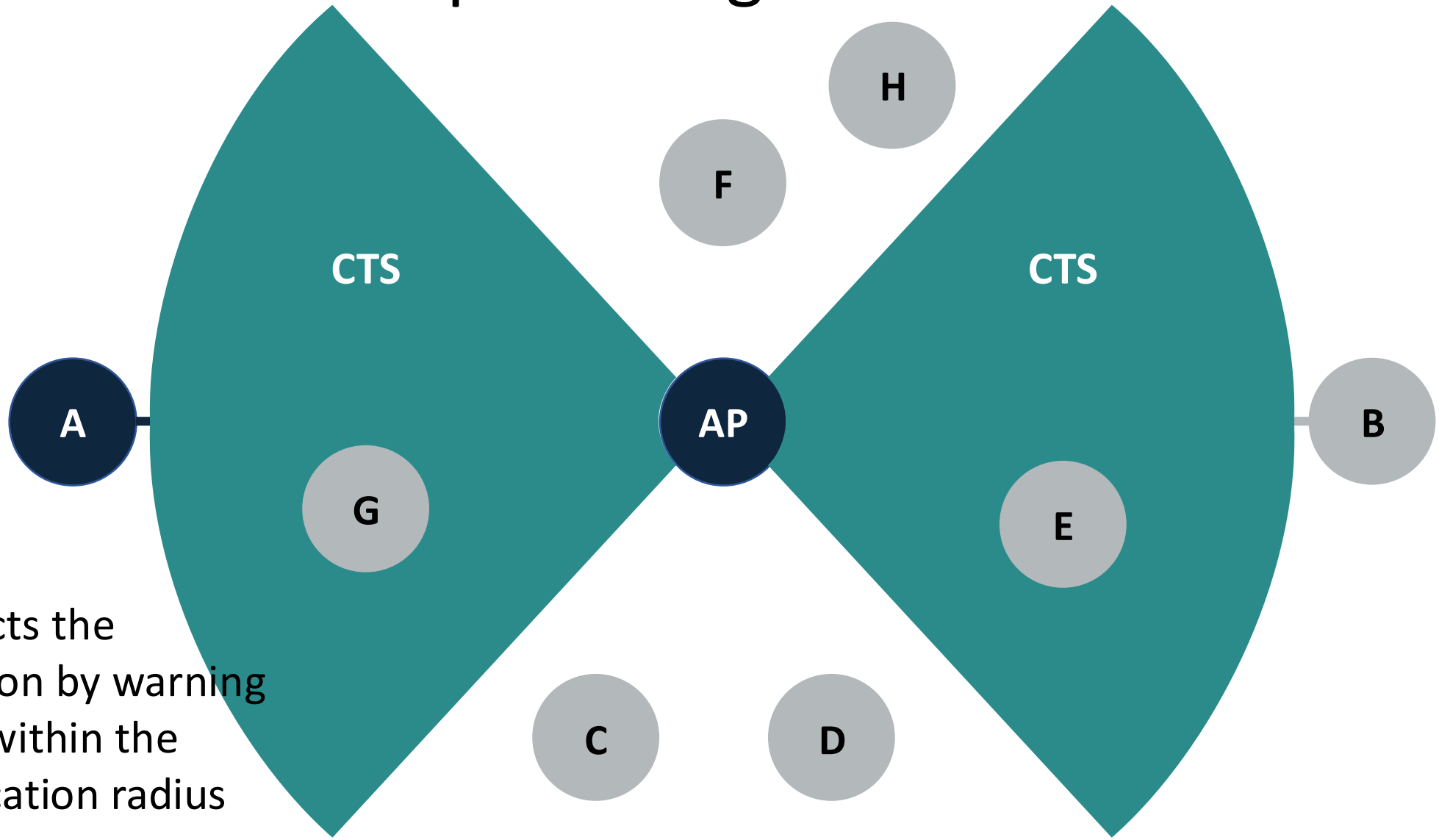
How RTS CTS Helps Solving Hidden Terminals



How RTS CTS Helps Solving Hidden Terminals

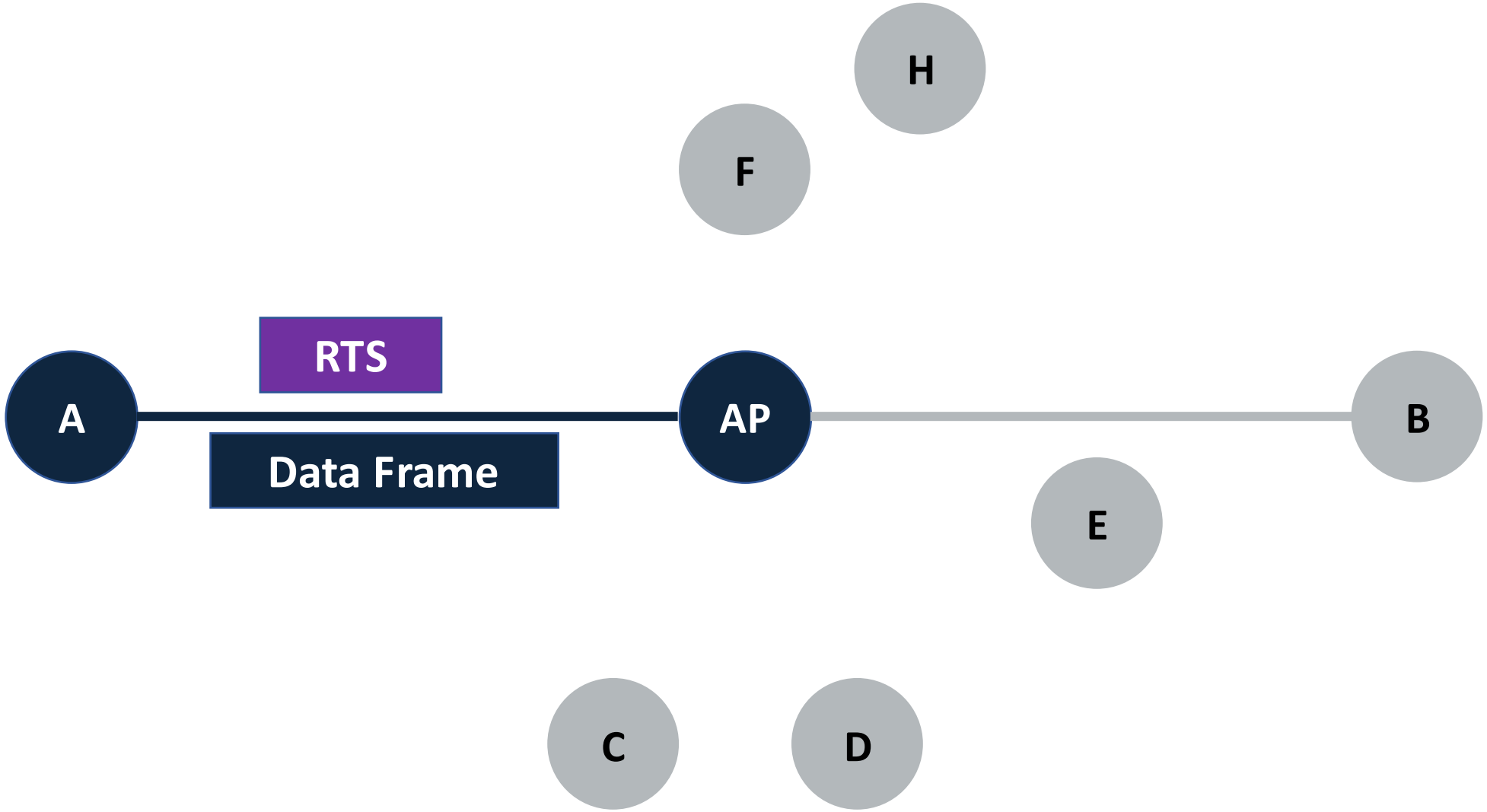


How RTS CTS Helps Solving Hidden Terminals



CTS protects the transmission by warning all nodes within the communication radius

How RTS CTS Helps Solving Hidden Terminals



Summary and Tradeoff

RTS/CTS reduces collisions, but adds upfront overhead.

Without RTS/CTS

Lower overhead, but vulnerable to hidden terminals.

With RTS/CTS

Higher upfront airtime cost, but protects the data payload.

Hidden terminals show why wireless MAC is hard: nodes make local decisions, but collisions happen at receivers.