802.11ax
High Efficiency WLANs

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Legacy 802.11 Standards

Early Wi-Fi standards: 802.11a/b/g

802.11b	802.11a	802.11g
1999	1999	2003
2.4 GHz	5 GHz	2.4 + 5 GHz
Up to 11 Mbps	Up to 54 Mbps	Up to 54 Mbps
DSSS modulation	OFDM modulation	DSSS + OFDM

Trade-offs between range, speed, and frequency bands

802.11n – Precursor to Modern Wi-Fi

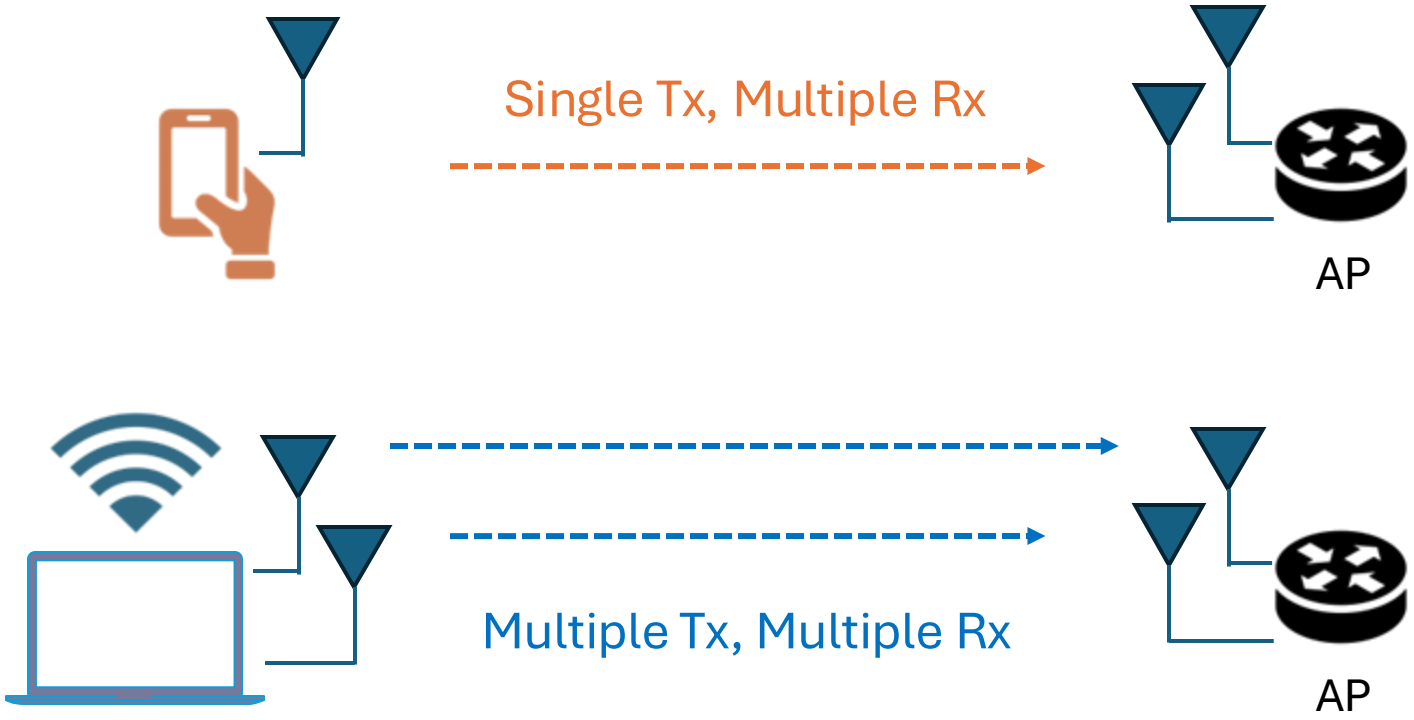
Introduced MIMO (Multiple input, Multiple output)

Dual-band operation on 2.4 GHz and 5 GHz

Theoretical max of 600 Mbps

MIMO

Multiplies the capacity of a link using multiple Tx and Rx antennas



802.11ac – The Bridge to Wi-Fi 6

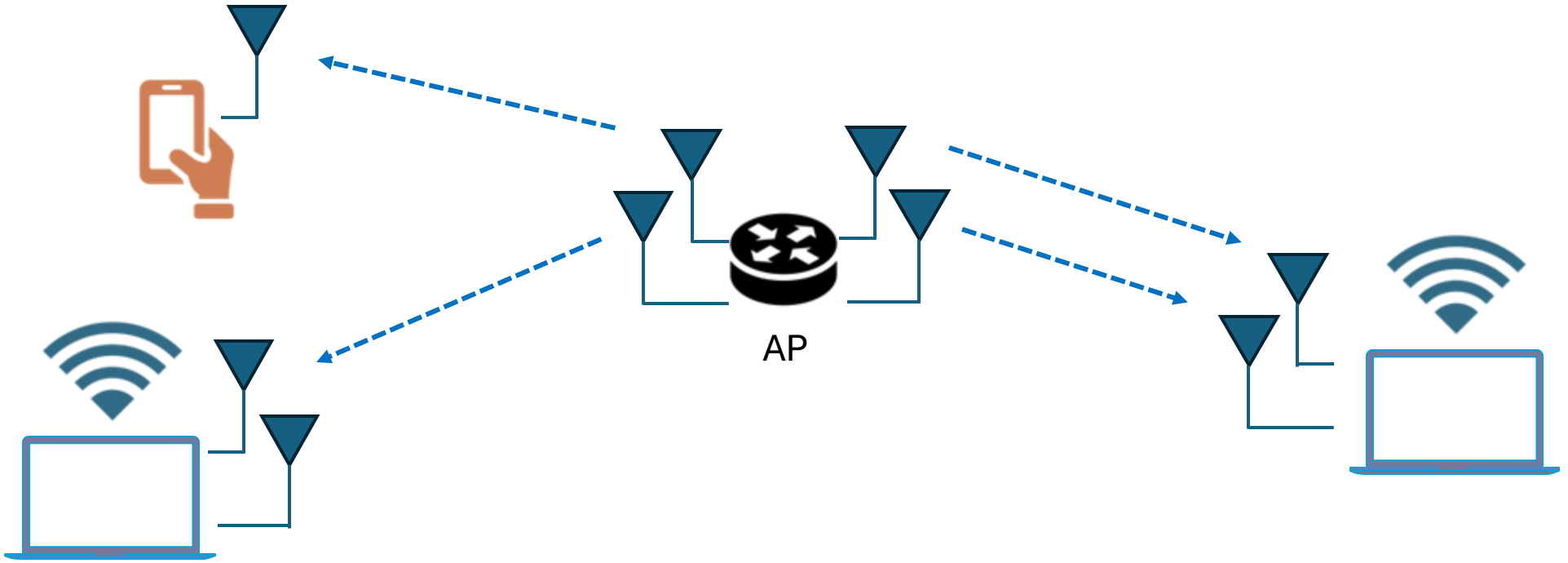
Increased data rates to 3.5 Gbps

Operates only in the 5 GHz band

DL MU-MIMO: Router transmits to multiple clients

Downlink MU-MIMO

AP transmits separate spatial streams to multiple clients at once



DL MU-MIMO Constraints

- ✗ Only worked with up to 4 client devices
- ✗ Clients still need to take turns when transmitting
- ✗ Requires Channel State Information feedback from clients (management traffic overhead)
- ✗ No uplink synchronization

Limitations of Legacy Standards

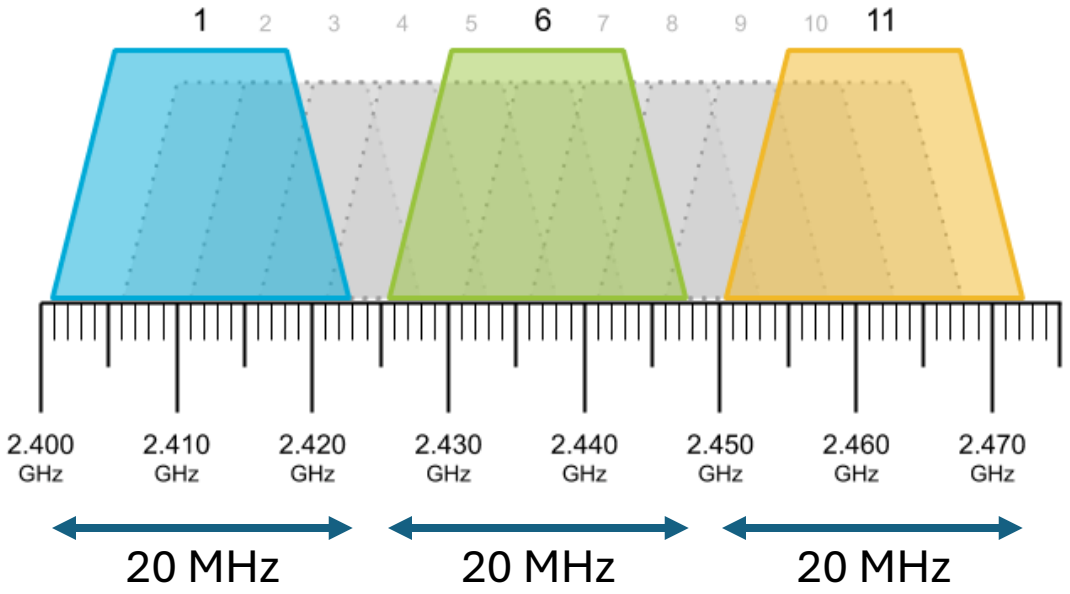
- Multiuser scheduling only worked on the downlink
- Dense areas suffered from low throughput, interference
- High MAC layer overhead for short frames
- Power consumption vs. Higher data rates
- QoS for time-sensitive apps needed improvement

802.11ax – Wi-Fi Today

But first, a little more background

802.11 Channel Bands

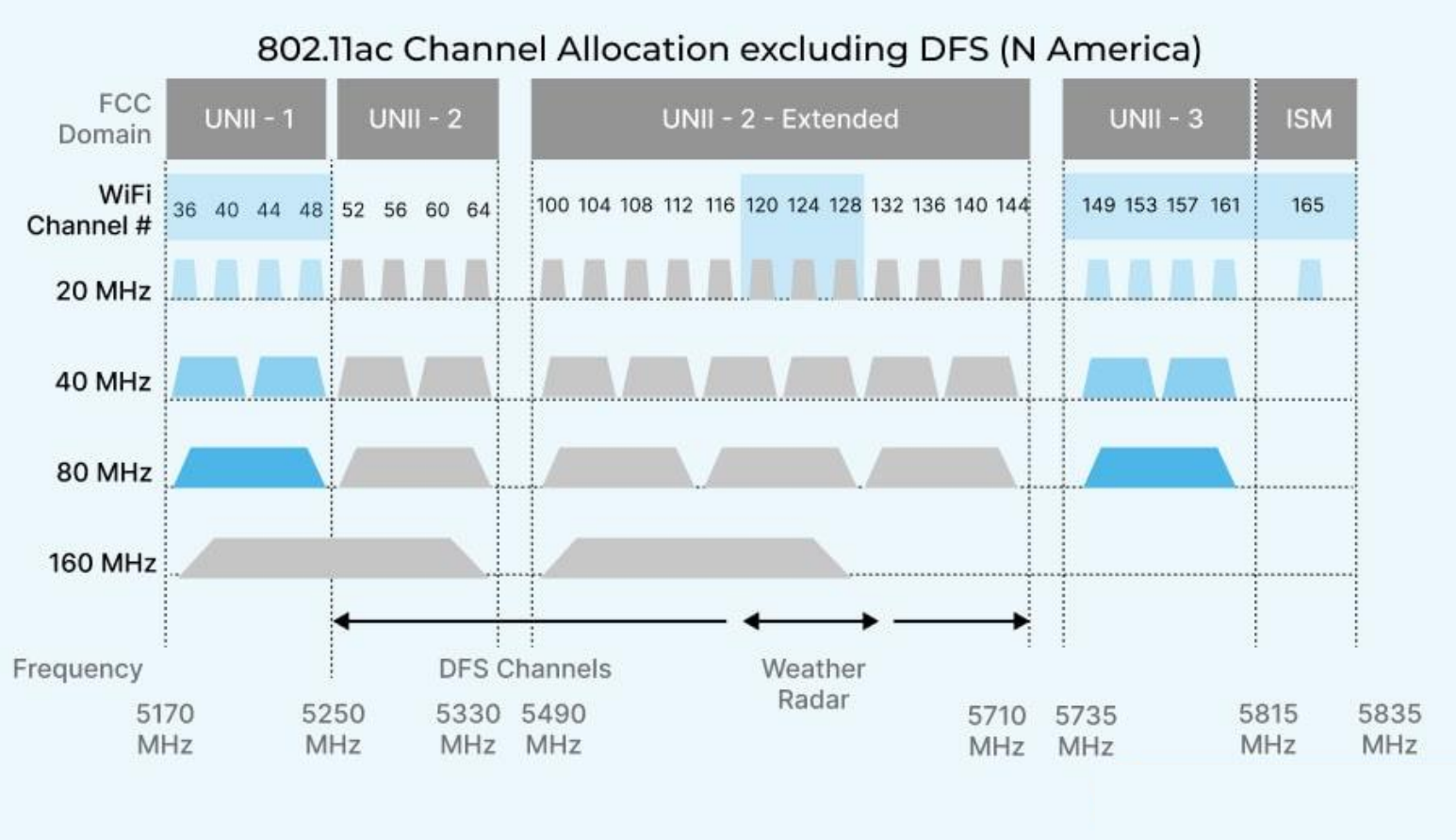
2.4 GHz band



APs and devices on the 2.4 GHz band should operate on these channels to reduce interference

802.11 Channel Bands

5 GHz band



Wi-Fi 5 uses fixed bandwidth, but not all devices need it

https://homeowner.com/connectivity/wifi-channel-width

802.11ax: High Efficiency WLANs

High Efficiency (HE) operation on both uplink and downlink

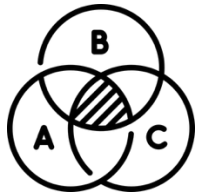
- OFDMA: Divides subcarriers into Resource Units (RUs)
- Difference from MU-MIMO: divide bandwidth instead of different spatial streams
- Uplink OFDMA enables multiuser access without requiring an entire channel for each user

Key Features of 802.11ax

Speed improvement of up to 9.6 Gbps

Channel Capacity improvements

- OFDMA
- 160 MHz channels



Efficiency improvements

- BSS Coloring
- Target Wake Time

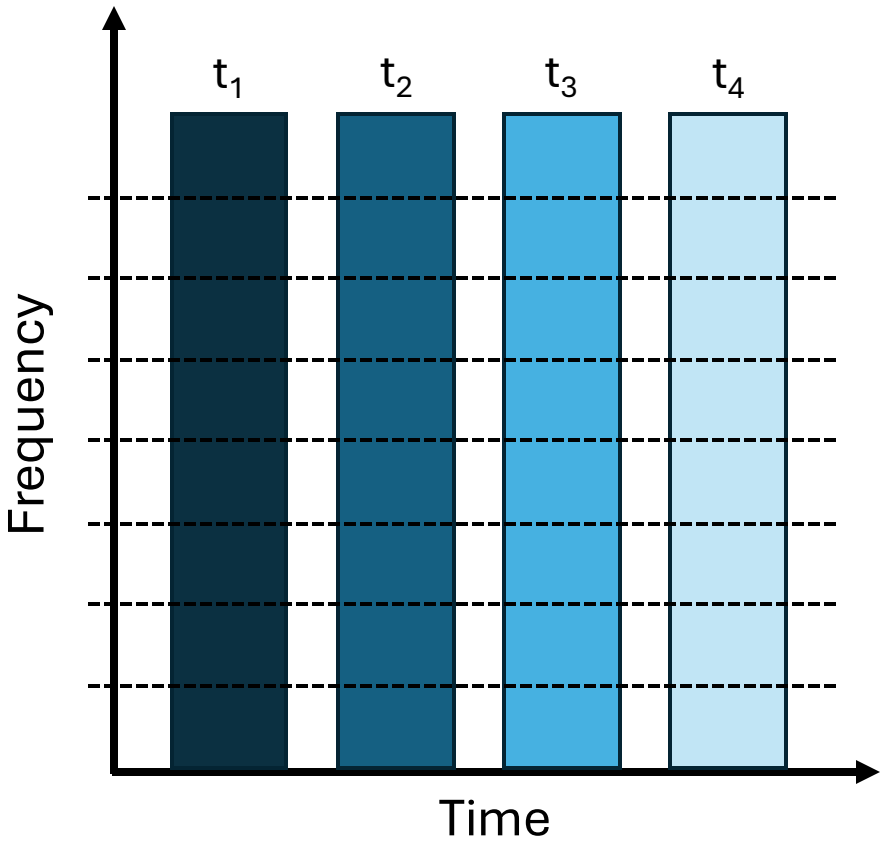
OFDMA

- **O**rthogonal **F**requency **D**ivision **M**ultiple **A**ccess
- Splits subcarriers (frequencies) into groups of bandwidths
- Shares the channel among multiple devices simultaneously

OFDM vs. ODFMA

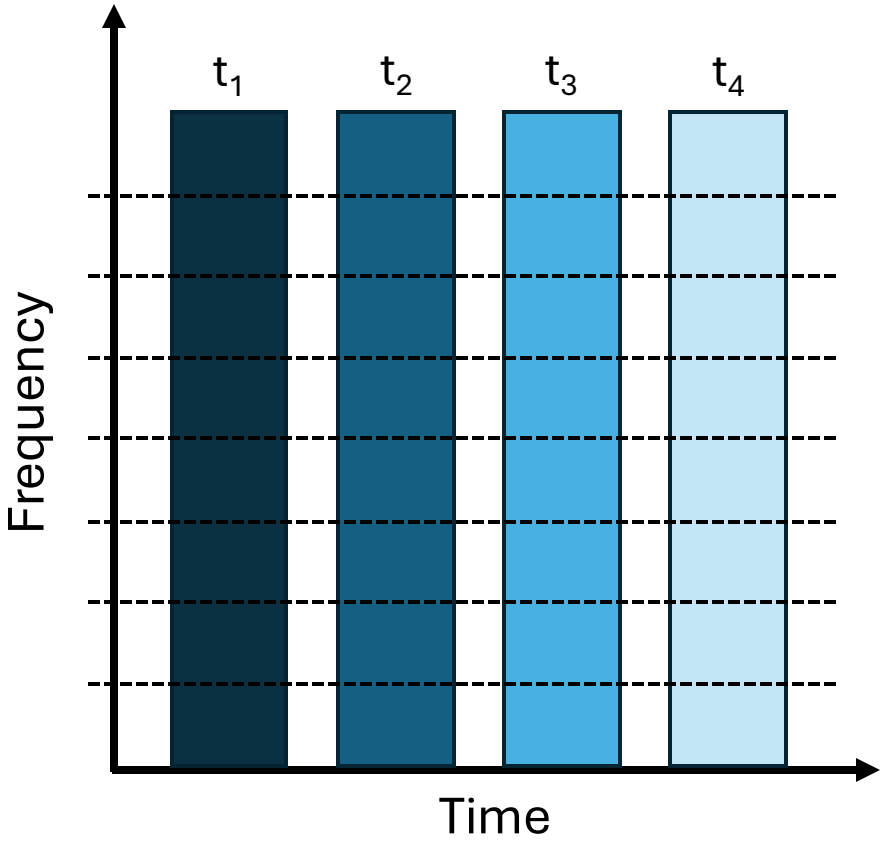
	OFDM **Orthogonal Frequency Division Multiplexing**	**OFDMA** **Orthogonal Frequency Division Multiple Access**
Resource Granularity	All subcarriers act as one block for one STA	Subcarriers are partitioned into groups **(RUs)**, allocated per STA
Efficiency	Idle airtime if a user has little data (wasted channel use)	Better efficiency, multiple small packets from different users fit in parallel
Latency	Higher, because users wait for their turn to use the full channel	Lower, since multiple users can transmit in the same time slot
Uplink Support	One STA per transmission, collisions possible without coordination	AP coordinates STAs via **Trigger frames**, synchronized uplink transmissions
Design Influence on Traffic patterns	Good for high-throughput single-user streams	Good for mixed traffic with many small packets

OFDM (Previous generations)



Previous standards have clients use the **entire channel** to transmit data

OFDM (Previous generations)



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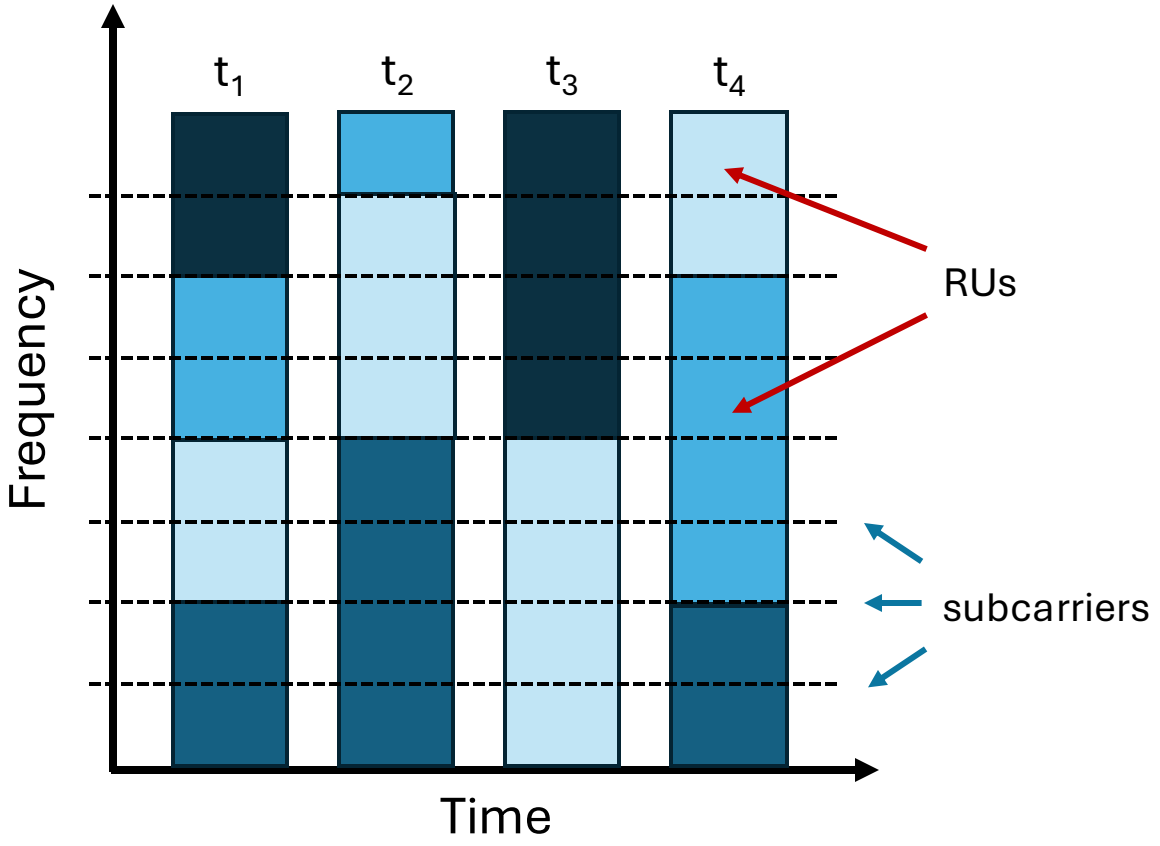
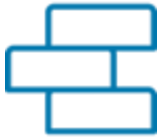
OFDMA (Wi-Fi 6)



OFDMA configures traffic for **multiple user packets per time segment**, increasing spectrum efficiency

Resource Units

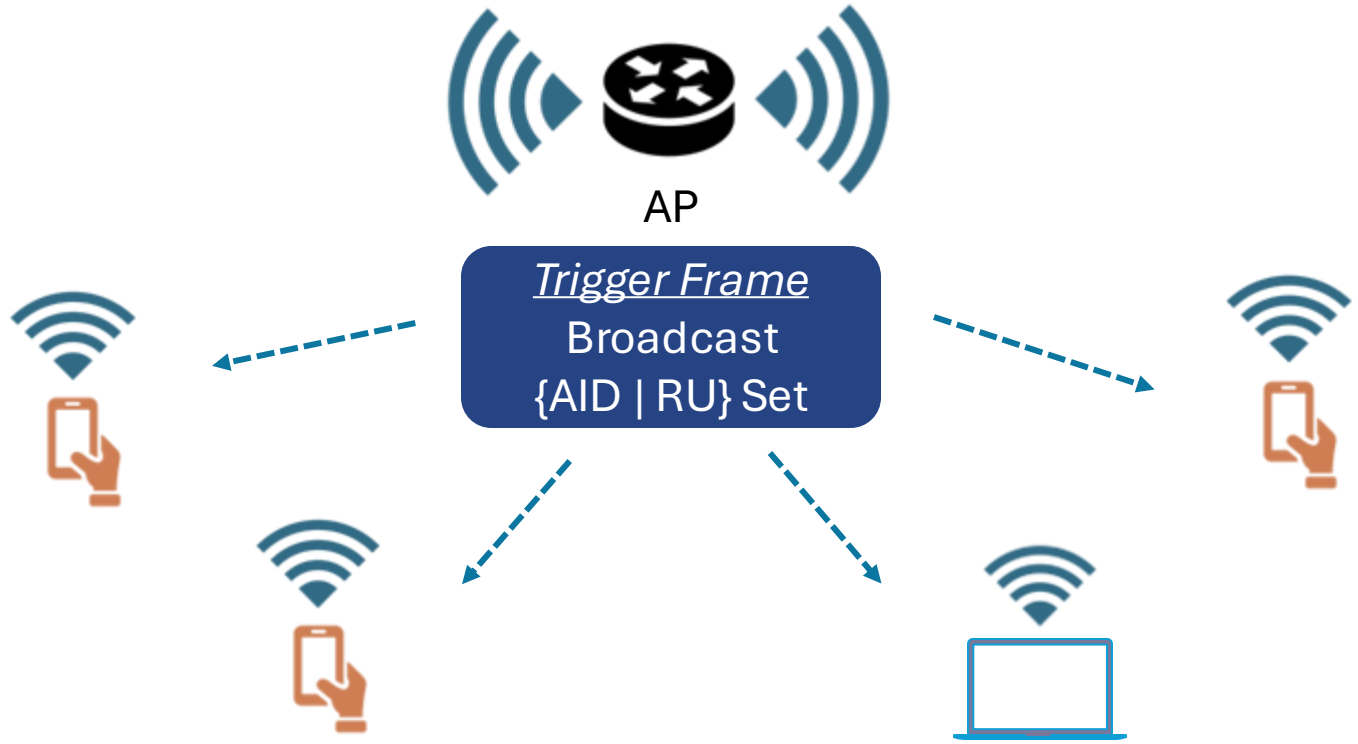


RUs are the allocation blocks of bandwidth in OFDMA

Vary in size depending on channel width

Adjacent subcarriers (*tones*) are grouped together into a resource unit (*RU*)

Assigning Bandwidths to Devices



RUs are allocated by the AP, determined by traffic demand

Trigger Frames define the RUs that devices can use

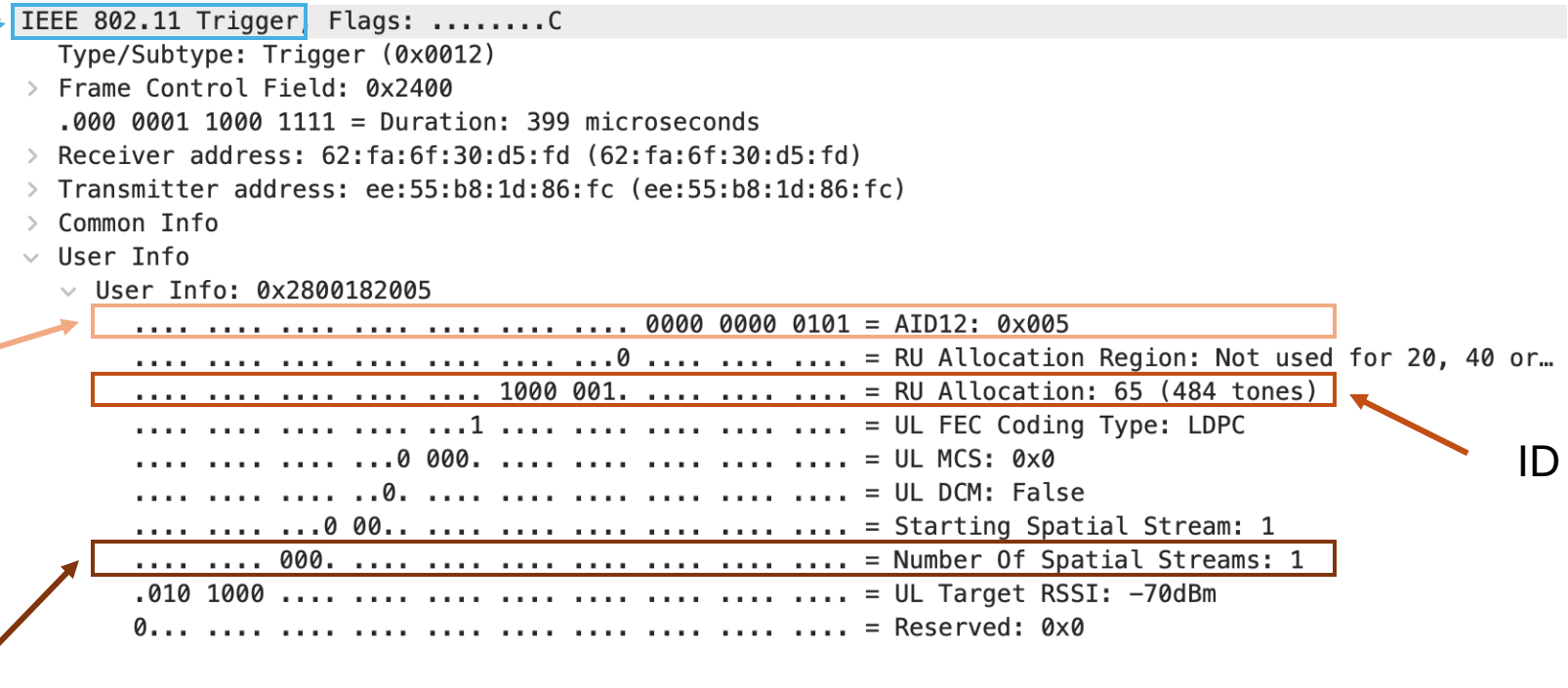
Assigning Bandwidths to Devices

Trigger Frame

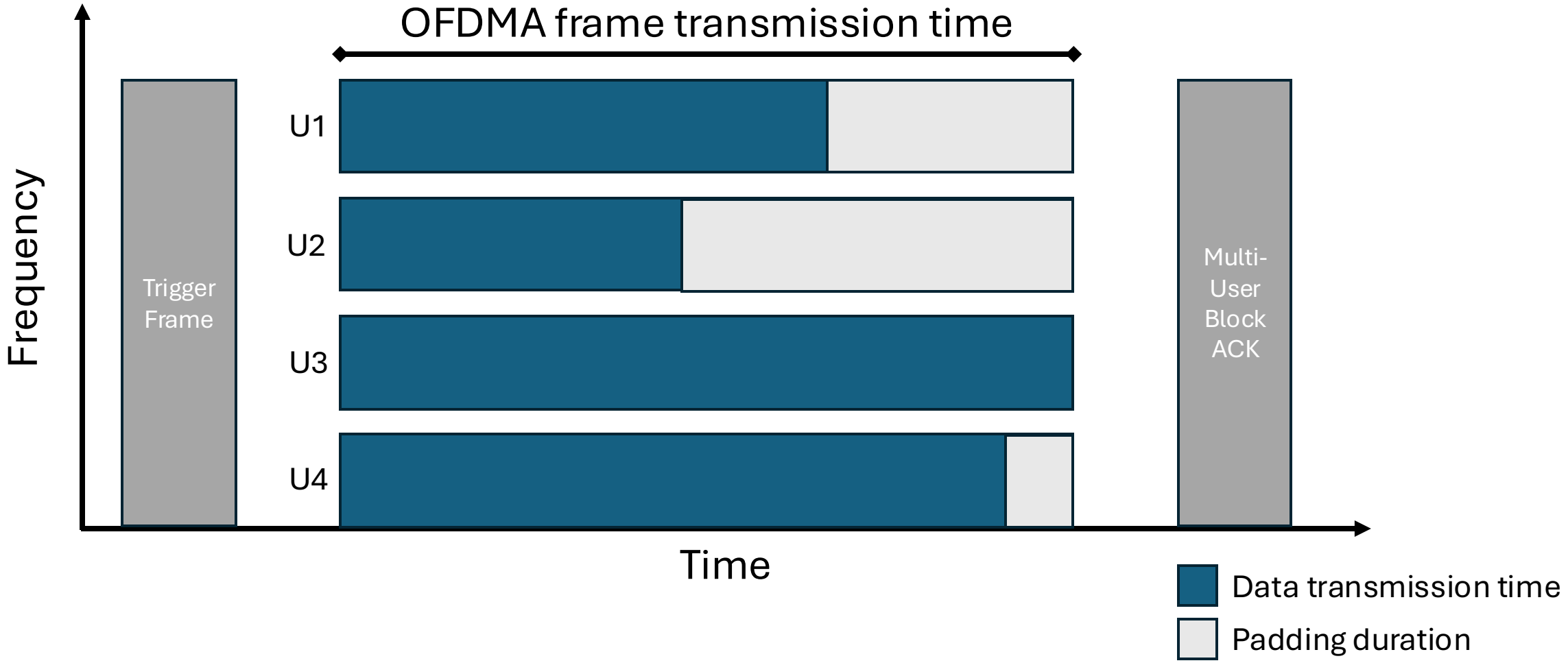
AID: Association ID of Client

Spatial streams assigned to use (Number of antennas needed)

ID of RU with tones



Transmission Time Utilization

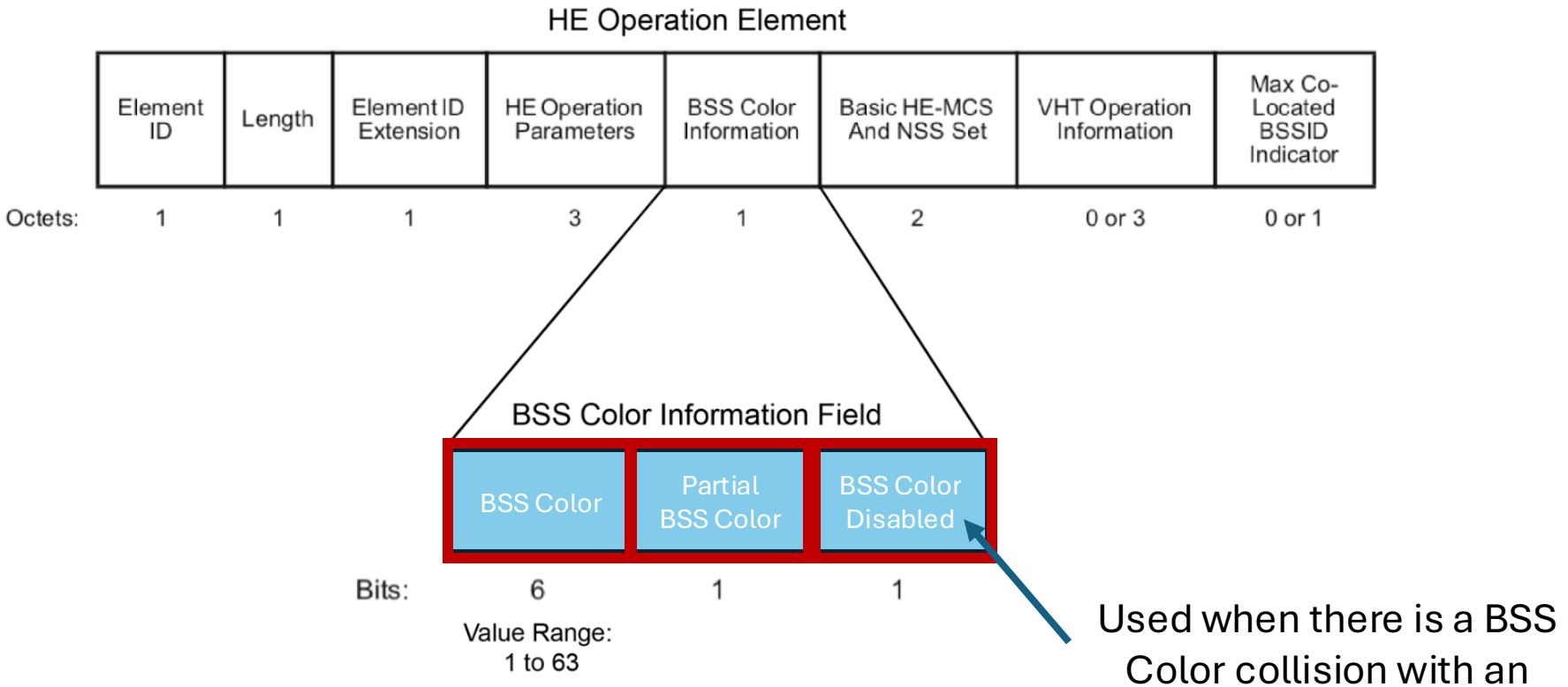


BSS Coloring

Reduces interference from nearby APs

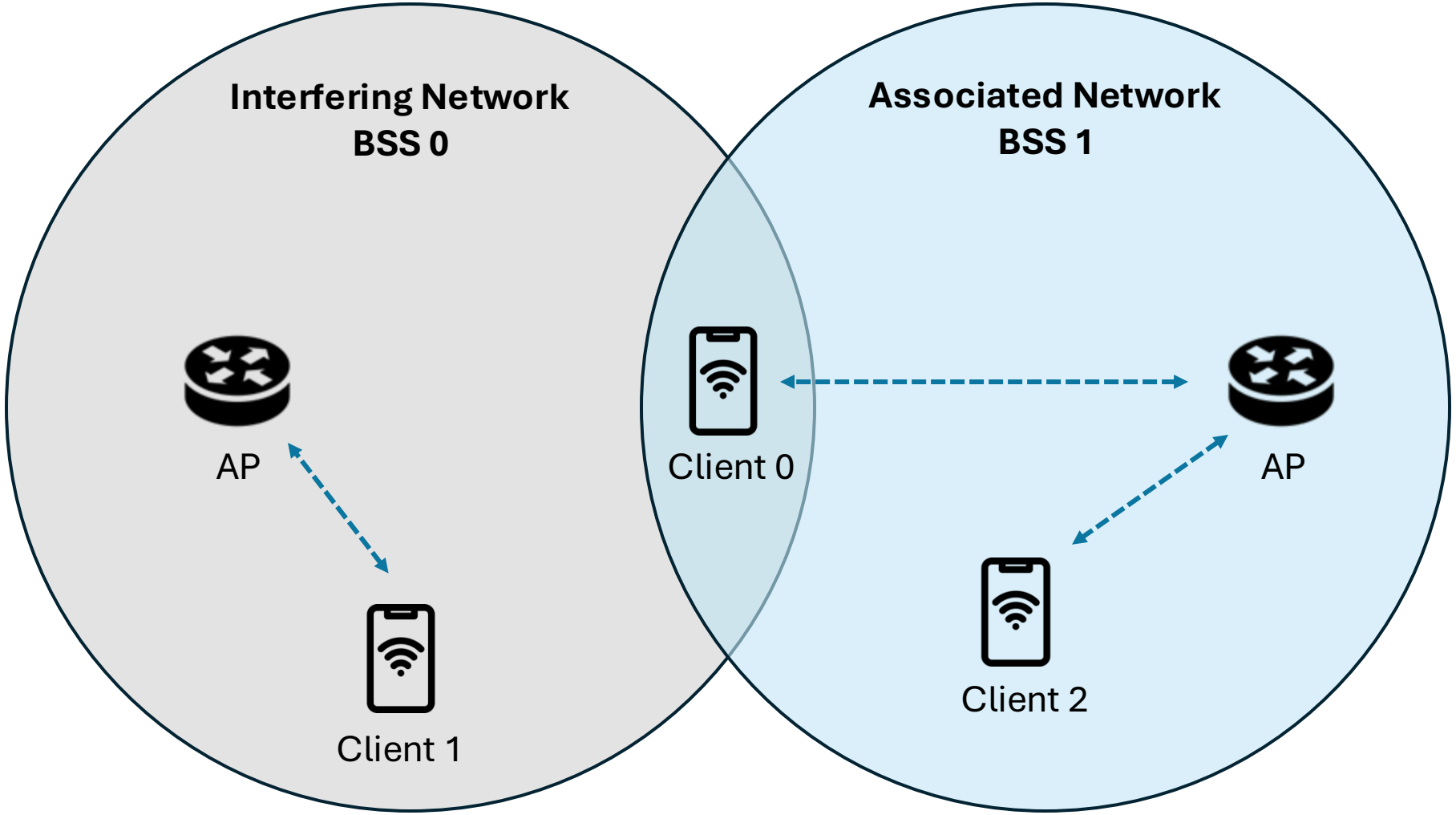
Improves coexistence between multiple APs

BSS Coloring



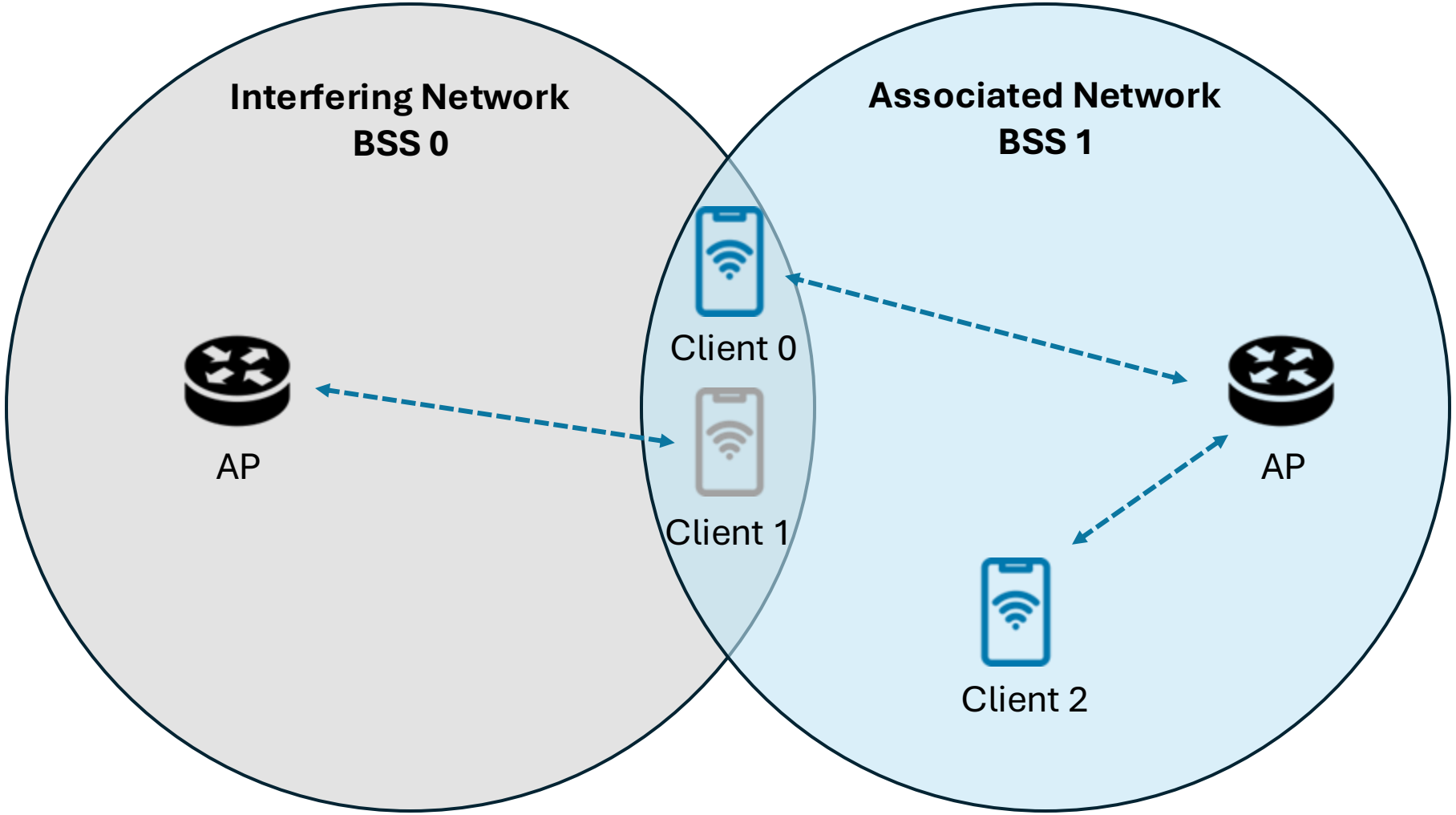
Used when there is a BSS Color collision with an **overlapping BSS**

BSS Coloring Example



In range of interfering AP signal, so check preamble bits

BSS Coloring Example



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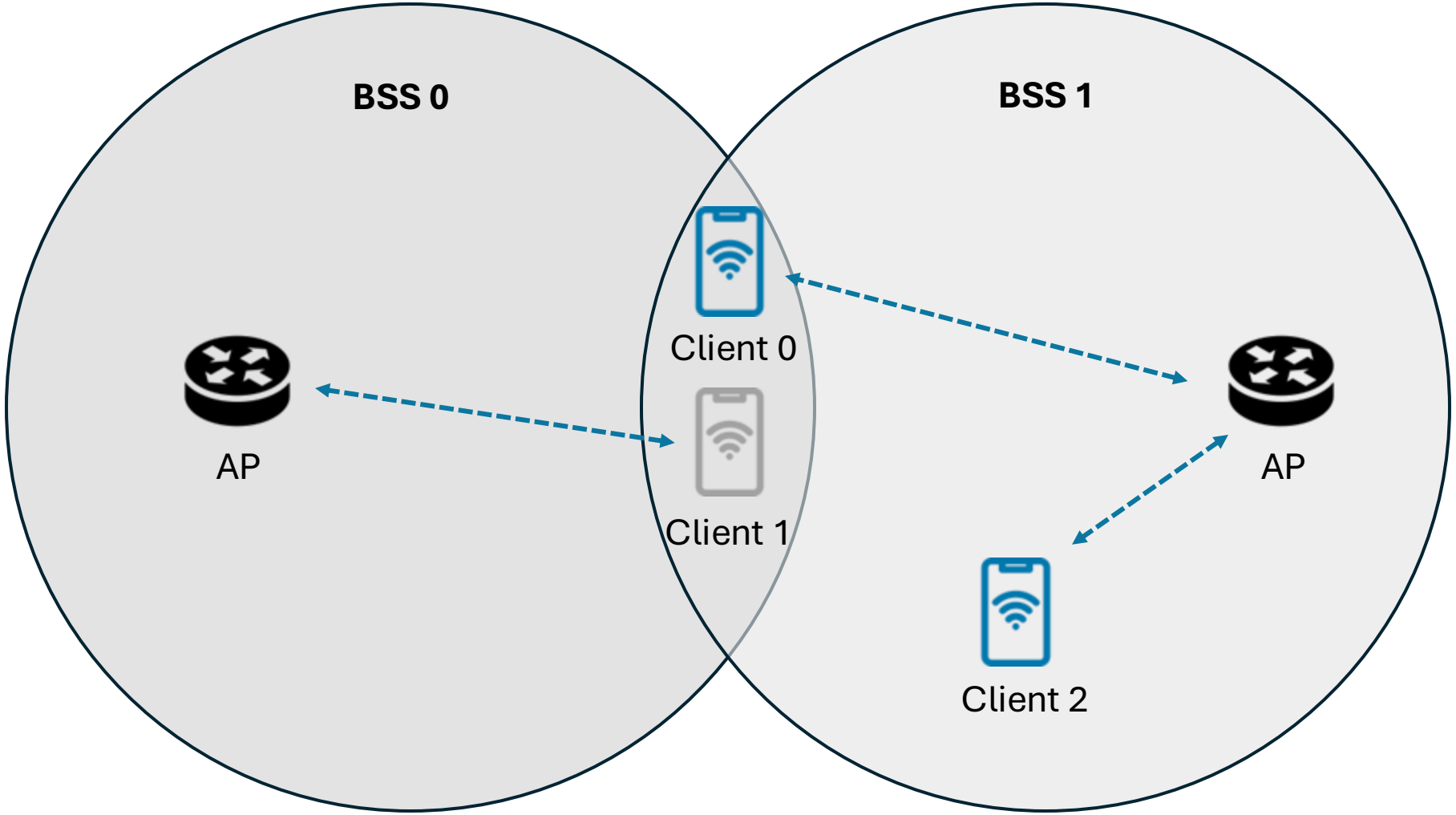
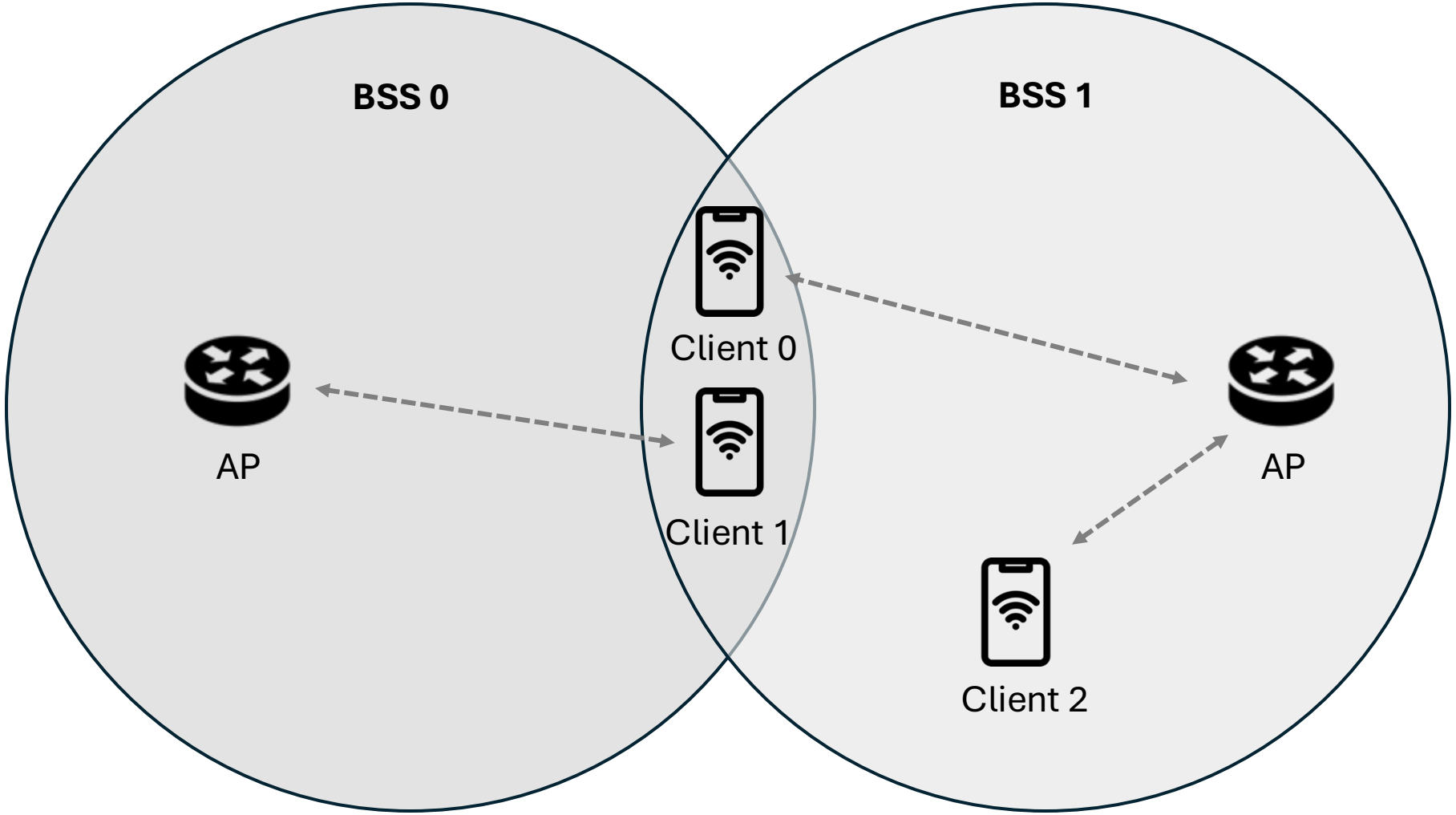


Problem!
Both BSS networks use the same color, a **color collision**

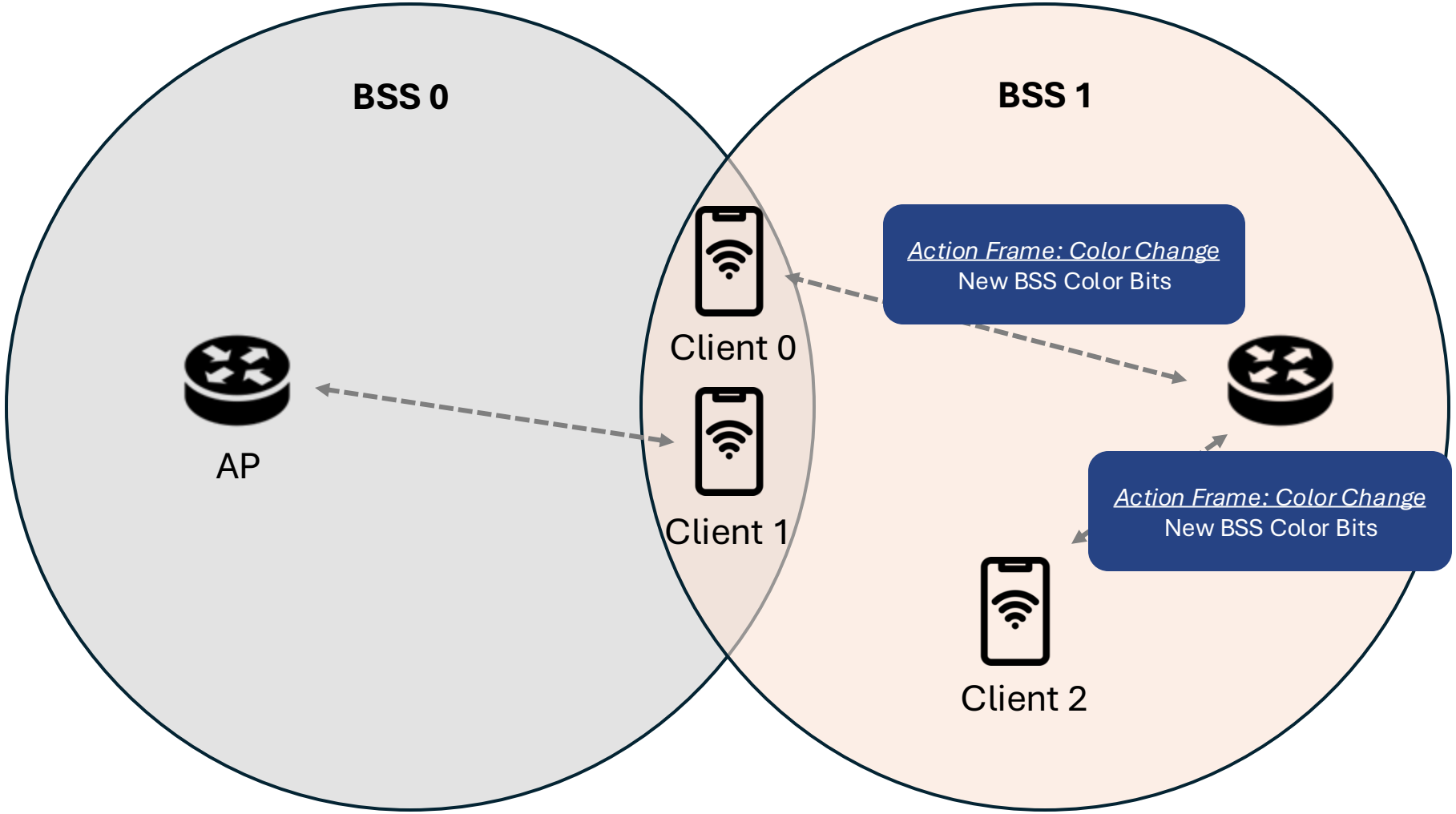
BSS Coloring Example



Problem!
Both BSS networks use the same color, a **color collision**

Solution:
Turn off the color, but **fall back to legacy medium access**

BSS Coloring Example



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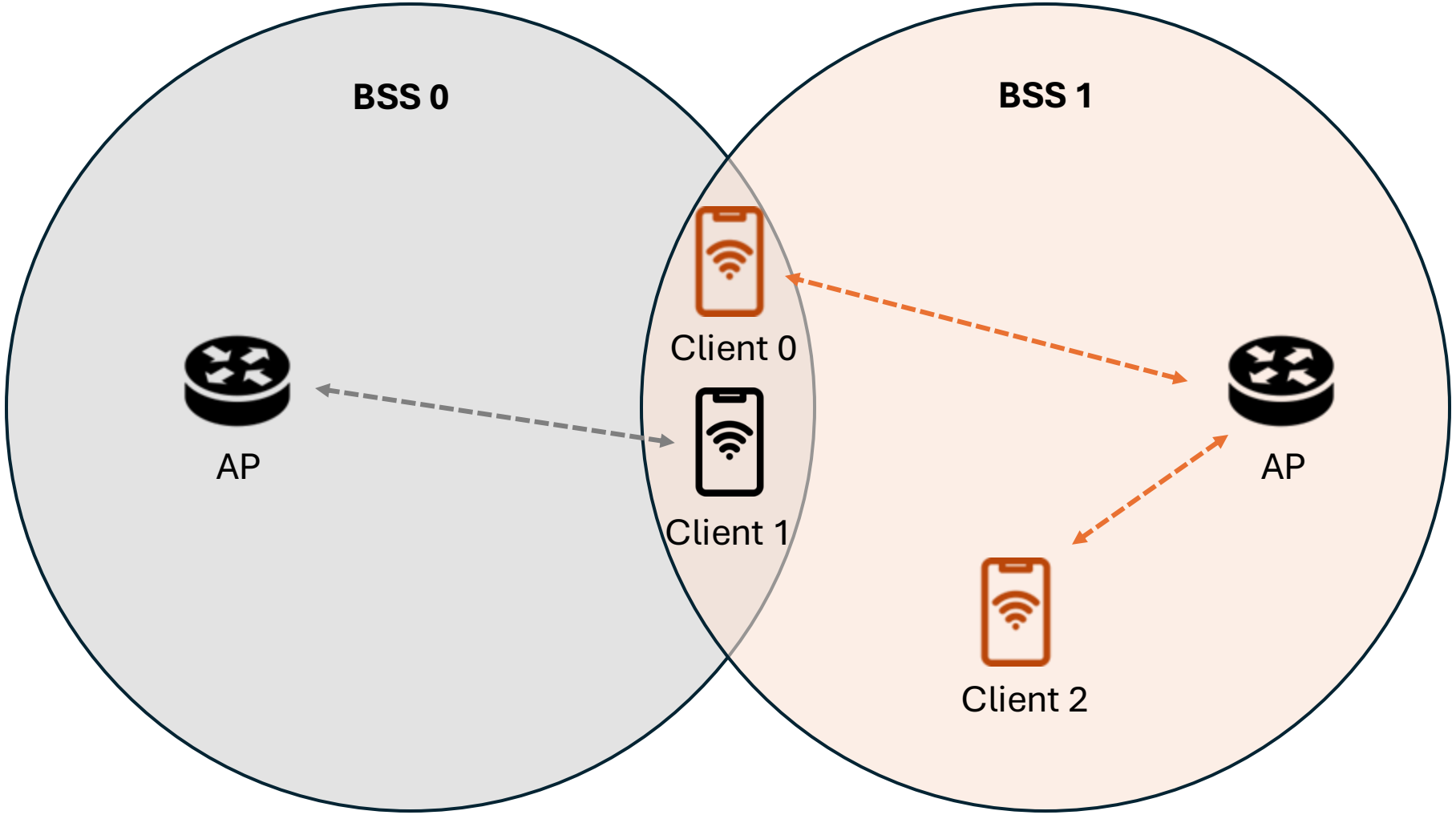
Better Solution:
Use a **Color Change Announcement**

BSS Coloring Example



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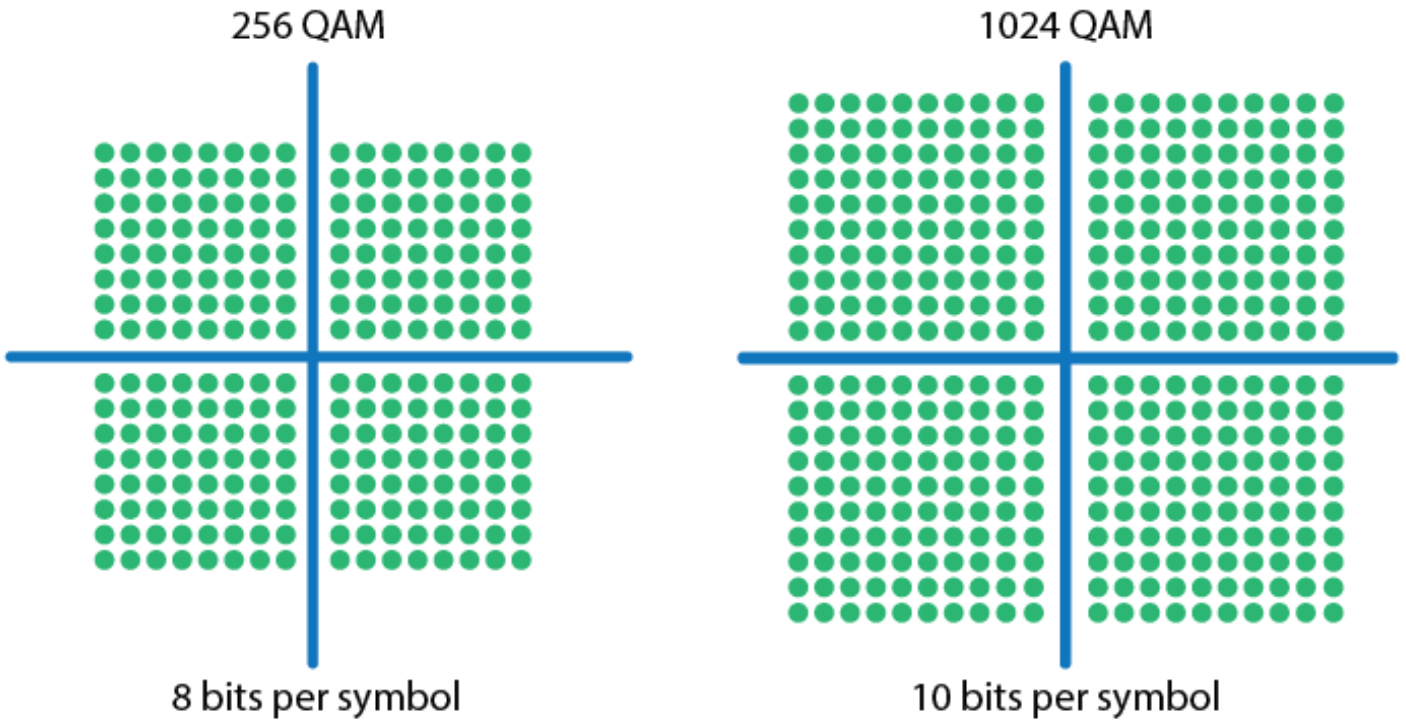
Better Solution:
Use a **Color Change Announcement**

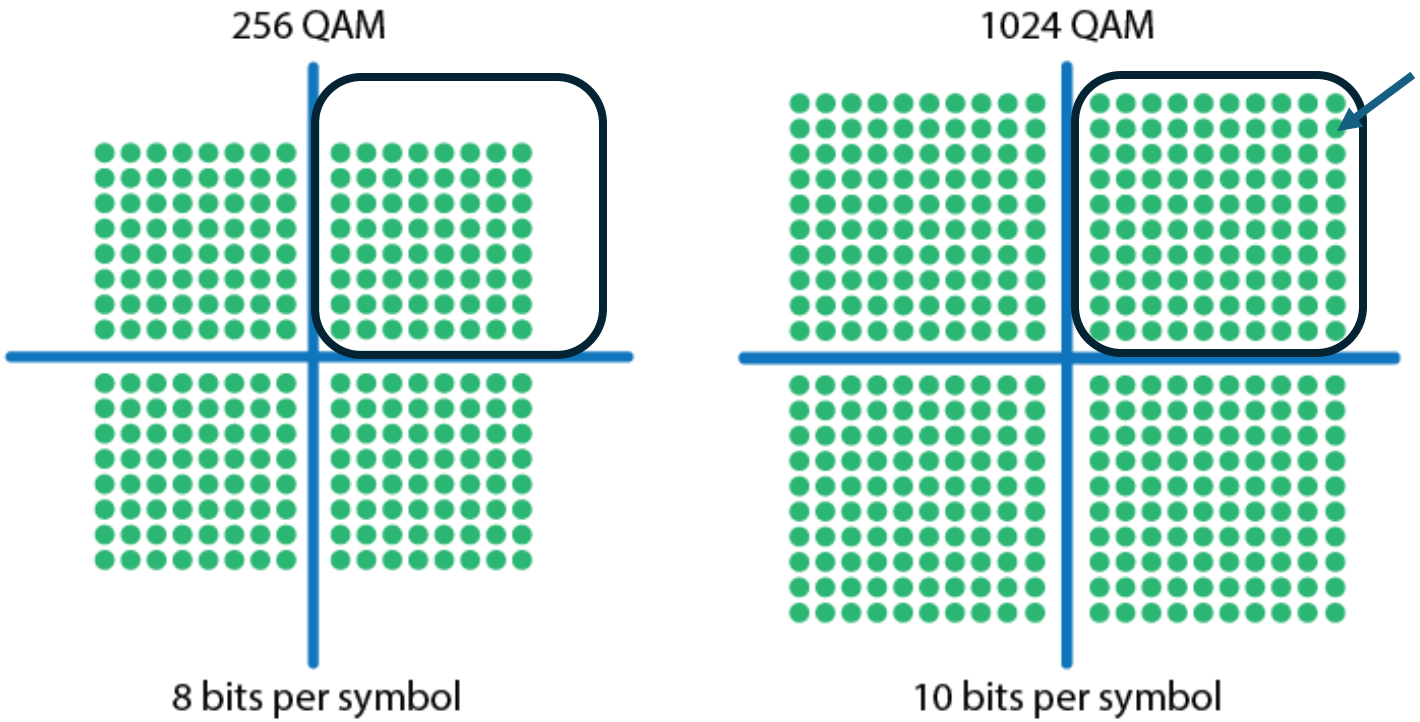
MU-MIMO Enhancements

- Increased from 4x4 (Rx:Tx antennas) in Wi-Fi 5 to 8x8 in Wi-Fi 6
- Supports simultaneous communication with multiple devices
- Enables both uplink and downlink MU-MIMO

Modulation Enhancements



Modulation Enhancements



More points

More bits per symbol

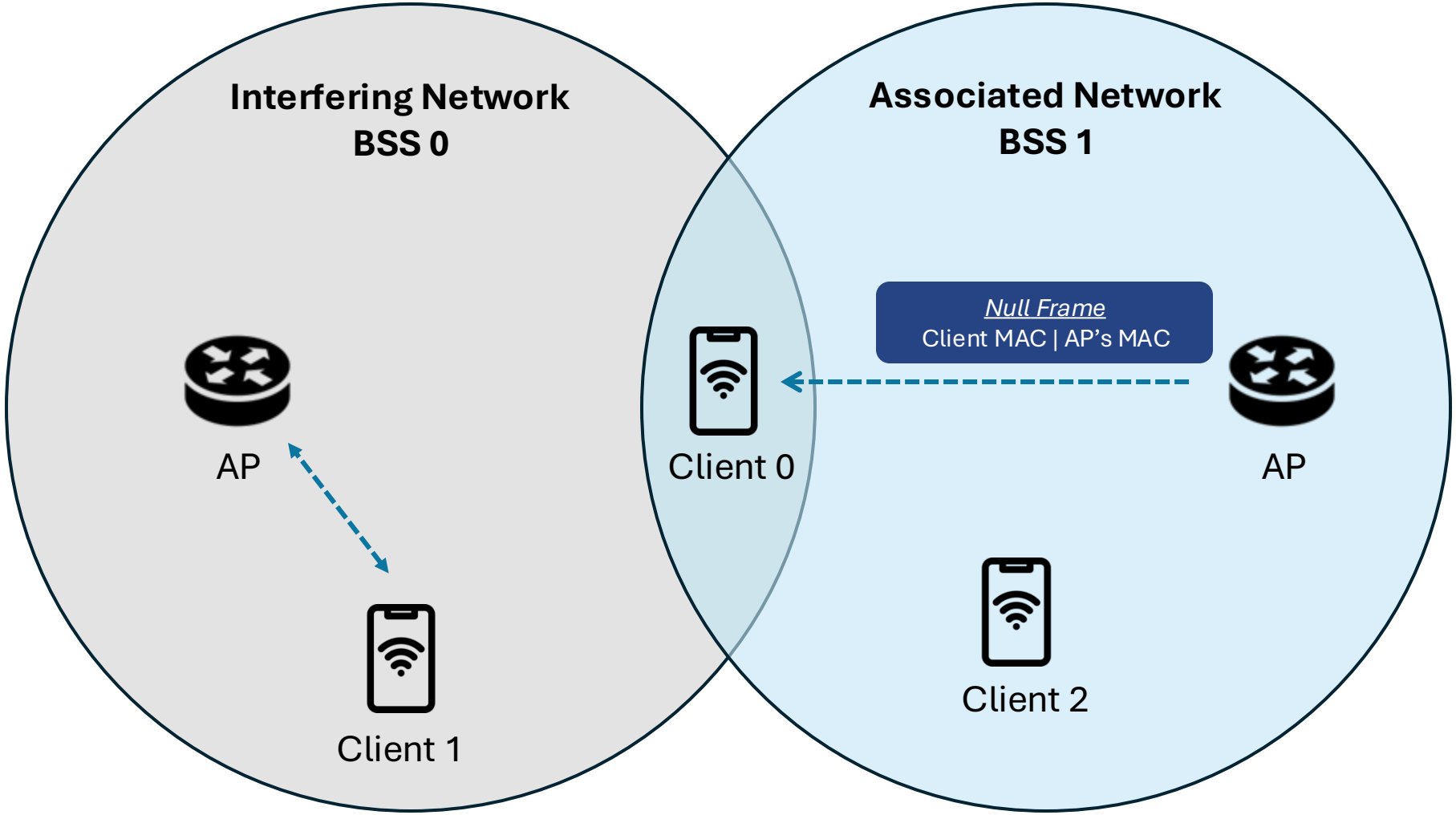
Higher throughput

25% higher capacity per symbol

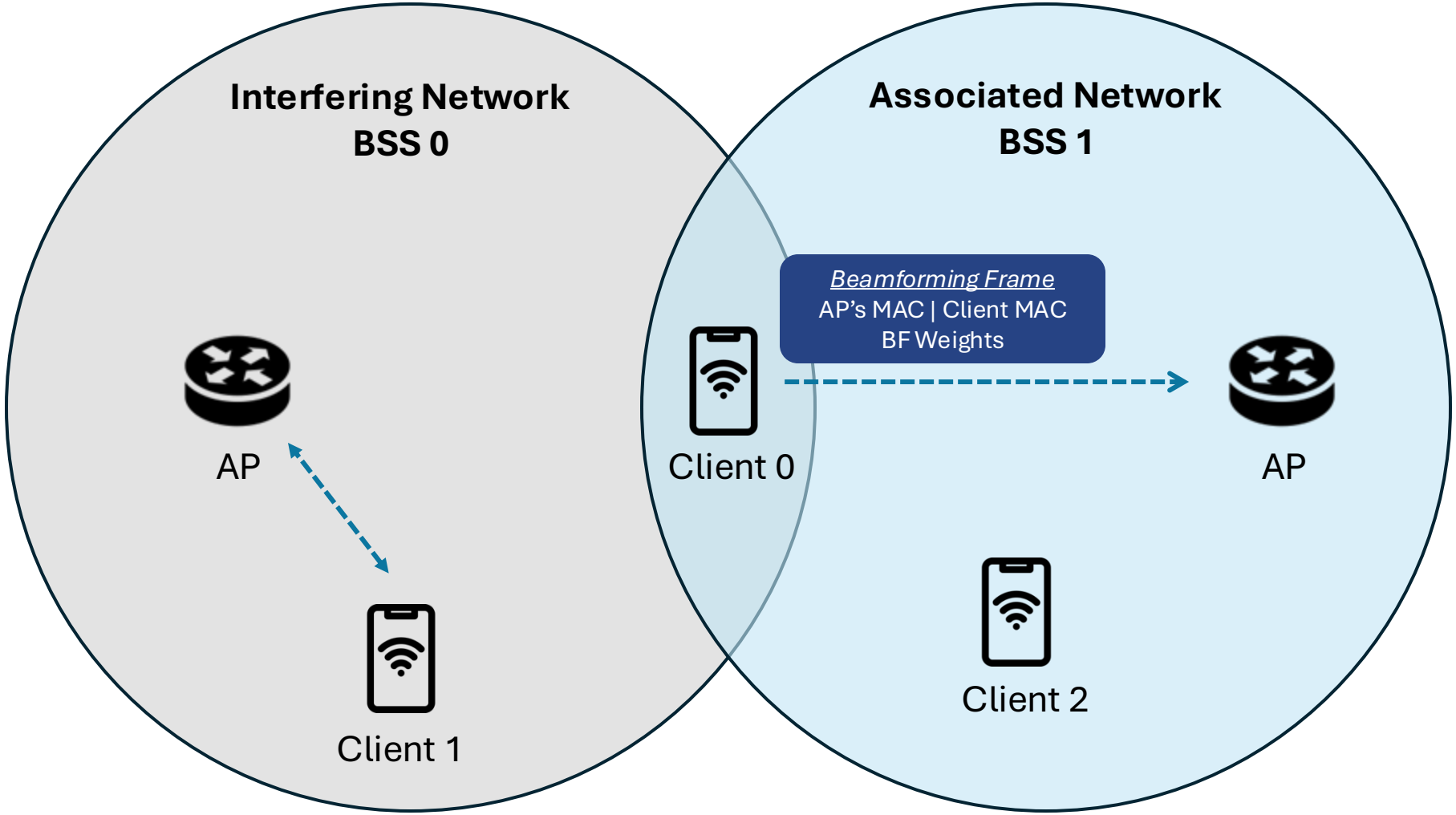
Beamforming

- Enables dynamic adjustment of the wireless signal direction
- Minimizes interference from nearby networks using BSS coloring

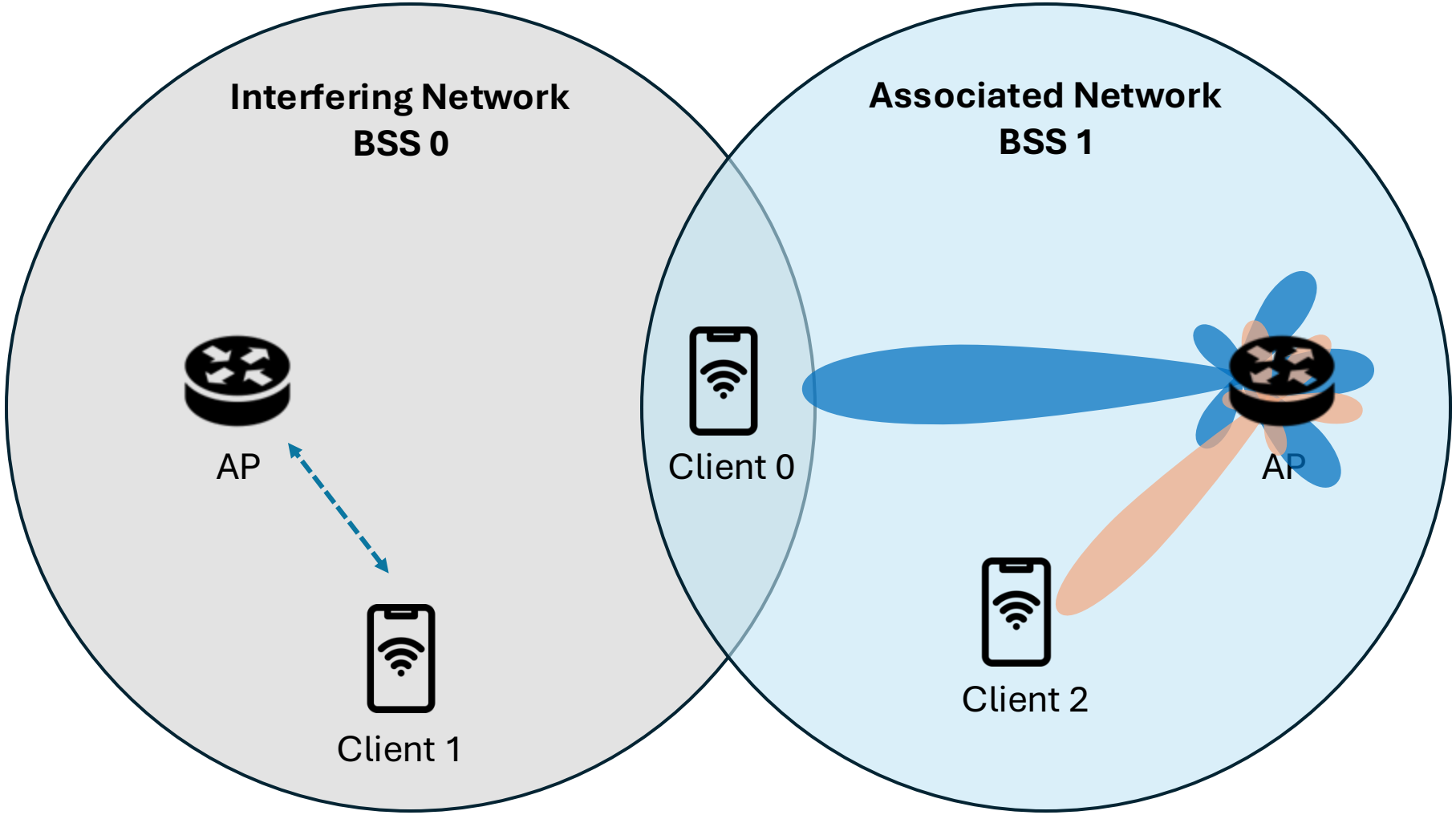
Beamforming Example



Beamforming Example



Beamforming Example

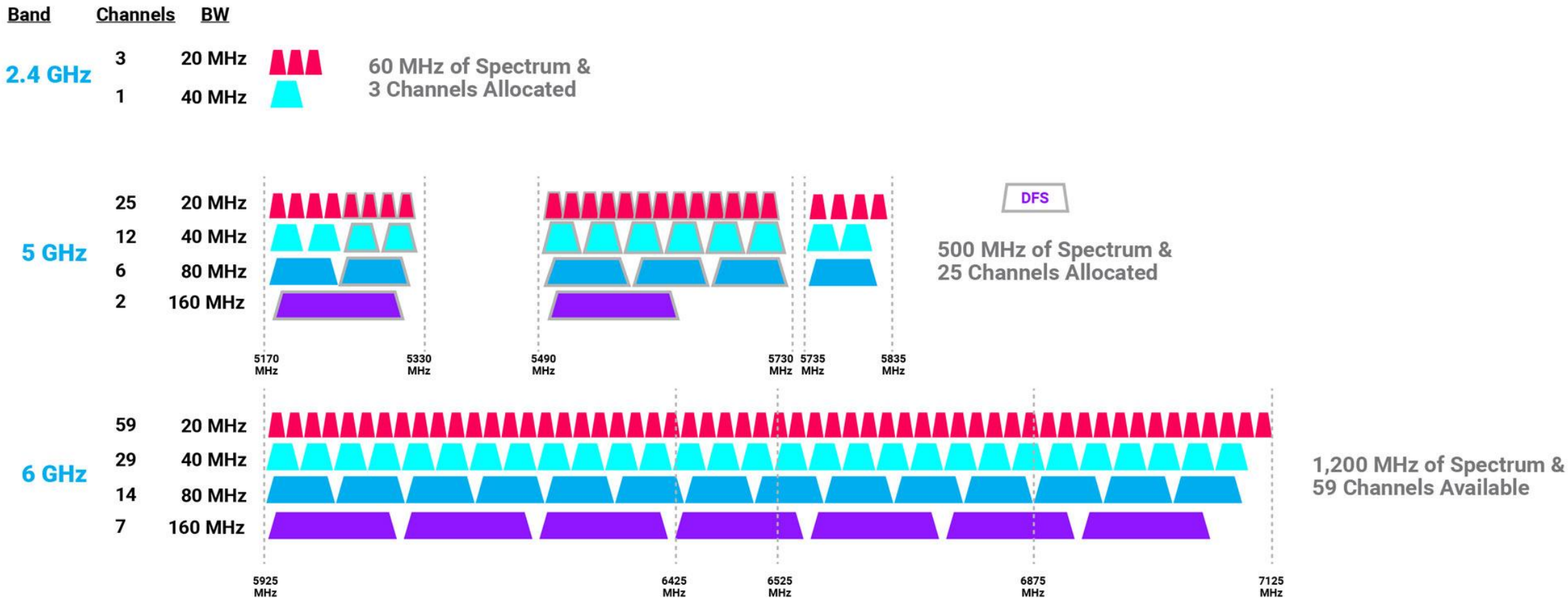


Beamforming optimizes signal strength and throughput

Wi-Fi 6E: Expanding to 6 GHz

- Introduces a new 6 GHz band
- Provides additional 1,200 MHz of bandwidth
- Allows for faster data rates and lower latency
- Offers more channels, reducing congestion in high-density areas

Wi-Fi 6E



https://engeniustech.com/wi-fi-6e-how-the-unlicensed-6-ghz-spectrum-will-drive-innovation/

That wraps up Wi-Fi 6!

Additional Resources

Wi-Fi 6

- Qualcomm whitepapers on MU-MIMO, Scheduling, and OFDMA
  https://www.qualcomm.com/products/technology/wi-fi/wi-fi-6
- Cisco whitepaper
  https://www.cisco.com/c/en/us/products/collateral/wireless/white-paper-c11-740788.html
- Aruba whitepaper
  https://www.arubanetworks.com/resource/802-11ax-white-paper/

Wi-Fi 7

- Comparison with Wi-Fi 6
  https://www.tp-link.com/ae/blog/730/how-is-wifi-7-different-from-wifi-6-/
- TP-Link Wi-Fi 7 features
  https://www.tp-link.com/us/wifi7/
- Multi-link Operation
  https://www.tp-link.com/us/blog/1067/what-is-wifi-7-s-multi-link-operation-mlo-/
- 4096-QAM Modulation
  https://www.rfwireless-world.com/Articles/4096-QAM-Modulation-in-WiFi-7.html