

# Wireless LAN II

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<https://eduassistpro.github.io/stream WiFi>

**IEEE 802.11a/**  
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**c/ax/be**

# Overview

1. IEEE 802.11 Amendments
2. 802.11a/b/g
3. 802.11e: Enhancements, Frame Bursting
4. 802.11n [WiFi 5]: Beamforming, MIMO
5. 802.11ac [WiFi 6]: High efficiency
6. 802.11ax [WiFi 7]: Extremely high throughput

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# Mainstream 802.11 Amendments

802.11 Amendment	Key Enhancements	Max. Data Rate
802.11-1997	Legacy WiFi in 2.4GHz (now extinct!)	2 Mbps
802.11b-1999	Higher speed modulation in 2.4GHz	11 Mbps
802.11a-1999	Higher speed modulation in 5GHz	54 Mbps
802.11g-2003	<a href="https://eduassistpro.github.io/">https://eduassistpro.github.io/</a>	54 Mbps
802.11n-2009	Higher throughput in 2.4GHz	600 Mbps
802.11ac-2013	Very high throughput in 5GHz	~7 Gbps
802.11ax-2020	High efficiency in 2.4/5GHz	~9.6 Gbps
802.11be-2024 (expected)	Extremely high throughput in 2.4/5/6GHz	~46 Gbps

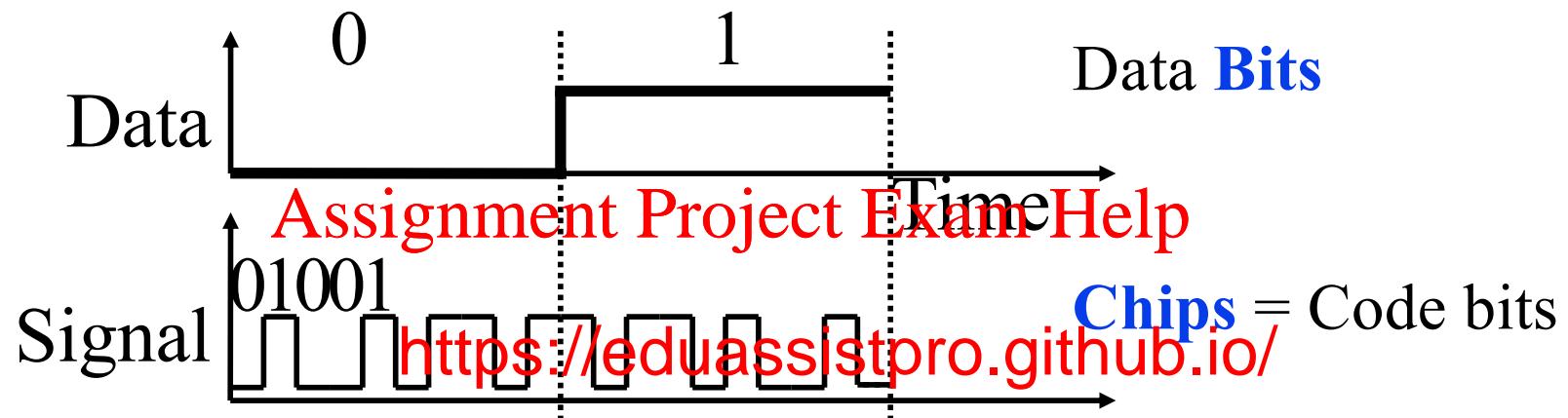
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# IEEE 802.11b-1999

- Direct Sequence Spread Spectrum:



- Complementary Code Keying (CCK)

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Multi-bit symbols with appropriate code to minimize errors

- IEEE 802.11-1997:  $\frac{1}{2}$  rate binary convolution encoder, 2 bit/symbol, 11 chips/symbol, DQPSK =  $\frac{1}{2} \times 22 \times \frac{1}{11} \times 2 = 2$  Mb/s using 22 MHz
- IEEE 802.11b-1999:  $\frac{1}{2}$  rate binary convolution encoder, 8 bit/symbol, 8 chips/symbol, CCK =  $\frac{1}{2} \times 22 \times \frac{1}{8} \times 8 = 11$  Mb/s using 22 MHz

Ref: P. Roshan and J. Leary, "802.11 Wireless LAN Fundamentals," Cisco Press, 2003, ISBN:1587050773, Safari book

# Example

- A WLAN standard is employing a spread spectrum coding with only  $\frac{1}{2}$  rate, which produces chips at a rate of  $\frac{1}{2}$  chips per Hz. It uses 8 chips to code a symbol and 16 QAM modulation to modulate the symbol stream. What would be the data rate for 22 MHz channels?

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$$\text{Chip rate} = \frac{1}{2} \times 22 = 11$$

$$\text{Symbol rate} = 11/8 = 1.$$
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$$\text{Bits per symbol} = \log_2(16) = 4 \text{ [Add WeChat: edu_assist_pro]}$$

$$\text{Data rate} = 1.375 \times 4 = 5.5 \text{ Mbps}$$

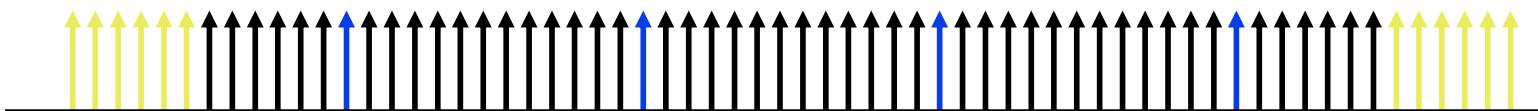
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<https://eduassistpro.github.io> - 1999

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## IEEE802.11a-1999

- ❑ To increase the data rate, 802.11a uses OFDM.
- ❑ 20 MHz divided into 64 subcarriers. 6 subcarriers at each side are used as guards and 4 as pilot, which leaves 48 for data.



- ❑ Each OFDM symbol is carried over 48 subcarriers in parallel.
- ❑ OFDM has a symbol  $\text{bols/s}$ 
  - 3200ns (data pulse  $\frac{4000\text{ns}}{4} = 4\mu\text{s}$ )
- ❑ With a binary modulation (e.g., BPSK) Add WeChat [edu\\_assist\\_pro](https://eduassistpro.github.io/) e 1 coded bit per subcarrier for each OFDM symbol, or 4 per OFDM symbol in total (over 48 subcarriers)
- ❑ Data rate depends on the combination of *modulation* and *coding*
- ❑ 802.11a supports 8 different data rates, 6 Mbps up to 54 Mbps, by selecting a **combination of modulation and coding**
- ❑ 802.11a supports three coding rates,  $\frac{1}{2}$ ,  $\frac{2}{3}$ , and  $\frac{3}{4}$  (the ratio indicates the ratio of data bits over all coded bits transmitted).

©2021 Mahbub Hassan E.g.,  $\frac{1}{2}$  indicates that only *half* of the total transmitted bits contain data.

# IEEE802.11a-1999 Data Rates

Modulation	Coding Rate	Coded bits per subcarrier	Coded bits per symbol	Data bits per symbol	Data Rate (Mbps)
BPSK	1/2	1	48	24	6
BPSK	3/4	1	48	36	9
QPSK	1/2	2	48	48	12
QPSK	3/4	2	96	96	18
16-QAM	1/2	4	19	19	24
16-QAM	3/4	4	192	144	36
64-QAM	2/3	6	288	192	48
64-QAM	3/4	6	288	216	54

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# **IEEE 802.11g-2003**

- OFDM – Same as 802.11a  $\Rightarrow$  54 Mbps
- 2.4 GHz band  $\Rightarrow$  Cheaper than 5 GHz 802.11a
- Fall back to 802.11b CCK

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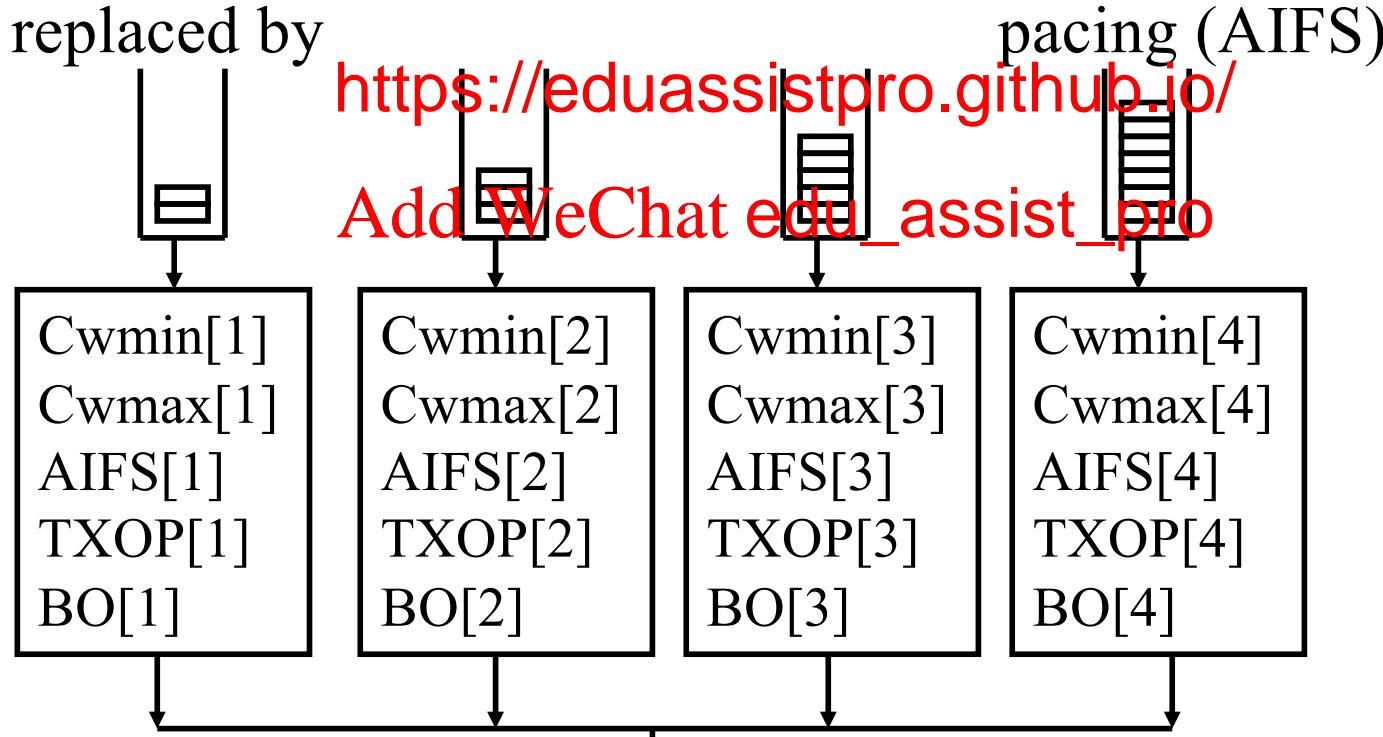
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# IEEE 802.11e-2005 (Enhanced QoS)

1. Hybrid Coordination Function (**HCF**) w two components
  - a. Contention Free Access: Polling
  - b. Contention-based Access: Enhanced DCF (**EDCF**)
2. **EDCF** <https://eduassistpro.github.io/>
  1. Multiple Priority levels with IFO queues  
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  2. Frame bursting and Group e
3. Direct link

# Enhanced DCF – Multiple Queues

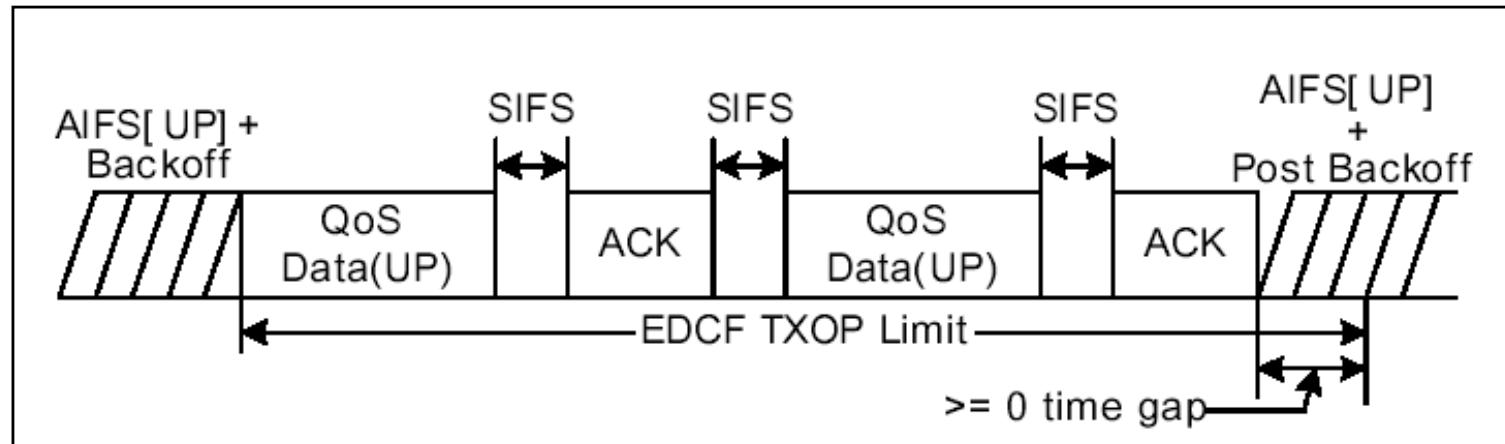
- Up to 4 queues. Each Q gets a different set of four Parameters:
  - $CW_{min}/CW_{max}$
  - Arbitrated Inter-Frame Spacing (**AIFS**) = DIFS
  - Transmit Assignment Project Exam Help
- DIFS replaced by



# EDCF - Frame Bursting

- EDCF allows *multiple* frame transmission
  - Both individual and group ACK allowed
- Max time = Transmission Opportunity (TXOP)
  - Covers total time including multiple data frames
- Voice/gaming has hi ze
- Video/audio has low <https://eduassistpro.github.io/>

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# **Direct Link in 802.11e**

- ❑ Direct Link is another feature introduced by 802.11e
- ❑ Direct link allows two WiFi devices to communicate directly without going through the AP, which reduces latency (great for delay-sensitive applications)

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<https://eduassistpro.github.io> - 2009

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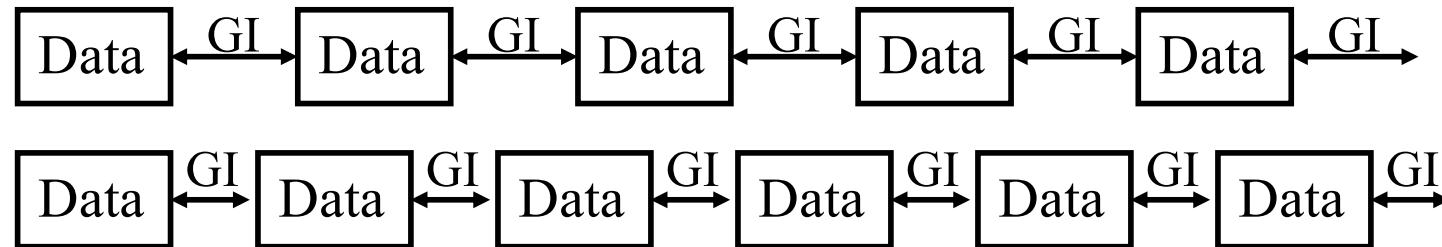
# IEEE 802.11n-2009

1. First WLAN to use MIMO (Multi-input Multi-Output)
2. MIMO (Multi-input Multi-Output) Multiplexing:  
 $n \times m:k \Rightarrow n$  transmitters,  $m$  receivers,  $k$  streams  
 $k = \text{degrees of freedom}$   
 $\Rightarrow k$  times more <https://eduassistpro.github.io/>  
E.g.,  $2 \times 2:2$ ,  $2 \times 3:2$ ,  $3 \times 2:2$ ,  $4 \times 4:4$   
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3. MIMO Beamforming: Focus the signal directly on the target antenna for increased coverage and signal strength
4. MIMO Power Save: Use multiple antennas only when needed

# IEEE 802.11n-2009 (Cont)

5. **Frame Aggregation**: Pack multiple input frames inside a frame  
⇒ Less overhead ⇒ More throughput
6. **Lower FEC Overhead**:  $5/6$  instead of  $3/4$
7. **Reduced Guard Interval**: 400 ns instead of 800 ns
8. **Reduced Inter-** Assignment Project Exam Help  $\mu\text{s}$ , instead of 10  $\mu\text{s}$ )
9. **Greenfield Mo** <https://eduassistpro.github.io/> for a/b/g  
(shorter and hig
10. **Dual Band**: 2.4 and 5 GHz Add WeChat edu\_assist\_pro
11. **Space-Time Block Code**
12. **Channel Bonding**: Use two adjacent 20 MHz channels
13. **More subcarriers**: 52+4 instead of 48+4 with 20 MHz, 108+6 with 40MHz

# Guard Interval



- Rule of Thumb: Guard Interval =  $4 \times$  Multi-path delay spread
- Initial 802.11a de <https://eduassistpro.github.io>  
⇒ 800 ns GI + 3200 ns data ⇒ 20 ns overhead
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- Most indoor environment have 5 ns
- So if both sides agree, 400 ns can be used in 802.11n  
⇒ 400 ns GI + 3200 ns data ⇒ 11% overhead

Ref: M. Gast, “802.11n: A Survival Guide,” O’Reilly, 2012, ISBN:978-1449312046, Safari Book

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# Example

- Compared to 802.11a/g, 802.11n has higher coding rate, wider channel bandwidth, lower coding overhead, and reduced guard interval. On top of this, 802.11n uses MIMO multiplexing to further boost the data rate. Given that 802.11a/g has a data rate of 54 Mbps, can you estimate the data rate for 802.11n that uses 4 MIMO streams (assume 64 QAM for both of them, i.e., there is no improvement in modulation)?

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54 Mbps is achieved with 0 GI for a/g, which basically uses a sin <https://eduassistpro.github.io/>

802.11n has the following improvement

- Streaming factor = 4
- Coding factor =  $(5/6)/(3/4) = 1.11$
- OFDM subcarrier (plus wider bandwidth) factor =  $(108/48) = 2.25$
- Guard interval factor =  $(3200+800)/(3200+400) = 1.11$
- Total improvement factor =  $4 \times 1.11 \times 2.25 \times 1.11 = 11.1$

Improved data rate for 802.11n =

$$4 \times [(5/6)/(3/4)] \times (108/48) \times [(3200+800)/(3200+400)] \times 54 \Rightarrow 600 \text{ Mbps}$$

# 802.11n Channel Bonding

- Two adjacent 20 MHz channels used
- OFDM: 52+4 instead of 48+4 with 20 MHz,  
108+6 with 40MHz (No guard subcarriers between two bands)
- **Primary 20 MHz channel:** Used with stations not capable of channel bonding  
<https://eduassistpro.github.io/>
- Channel bonding indicates the primary and secondary 20 MHz channel.
- **Secondary 20 MHz channel:** Just below the primary channel (indicated by the primary channel number and up/down indicator)
  - E.g., in 5 GHz band, 36+ would indicate that channel bonding is achieved by combining 36 and 40 (both 36 and 40 are 20 MHz channels)

## **Modulation, Coding, Data Rates of 802.11n: Single Stream**

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# Example: 802.11n

**Question:** 802.11n can use either 20 MHz channels or 40 MHz channels with channel bonding. For 40 MHz bandwidth, data rate can be improved by what factor if channel bonding is used?

**Solution:** Data rate is proportional to the number of OFDM subcarriers used for data.

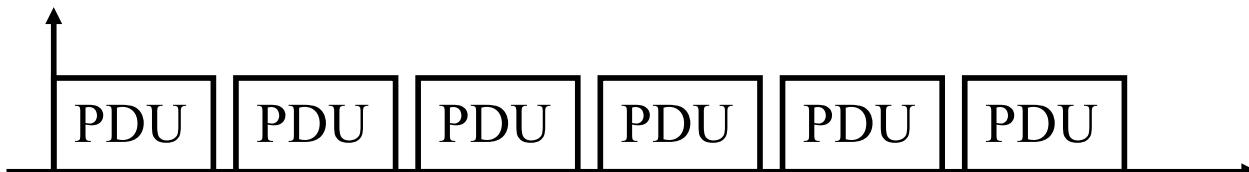
# of subcarriers for 20 M <https://eduassistpro.github.io/> ding) = 52

# of subcarriers for 40 MHz channels with [Add WeChat edu\\_assist\\_pro](#) ding) = 108

Channel bonding improvement over 40 M =  $108/(52+52) = 1.04$   
or 4%

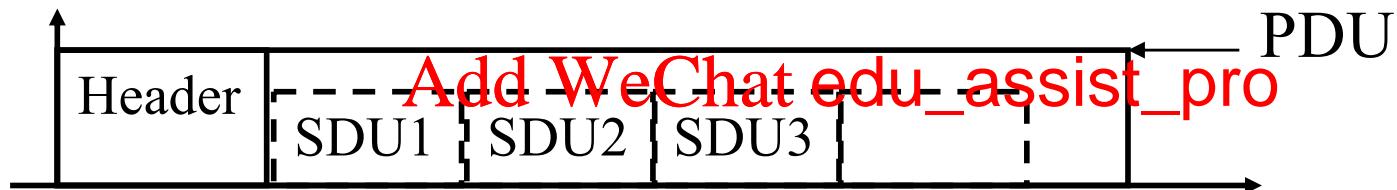
# Frame Aggregation

- **Frame Bursting:** Transmit multiple PDUs together

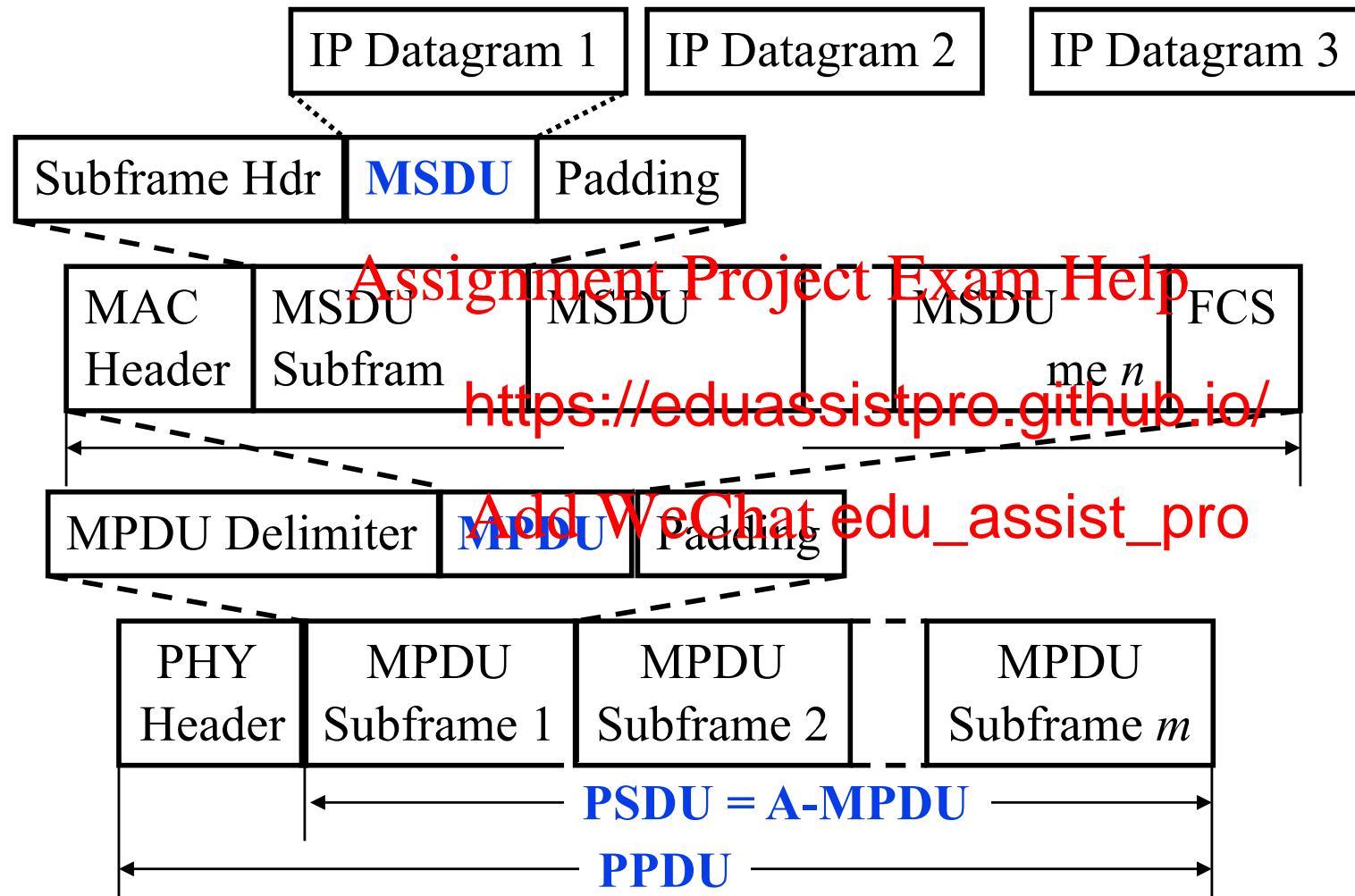


- **Frame Aggregation:** Multiple SDUs in one PDU

All SDUs must have the same source and receiver address  
<https://eduassistpro.github.io/>

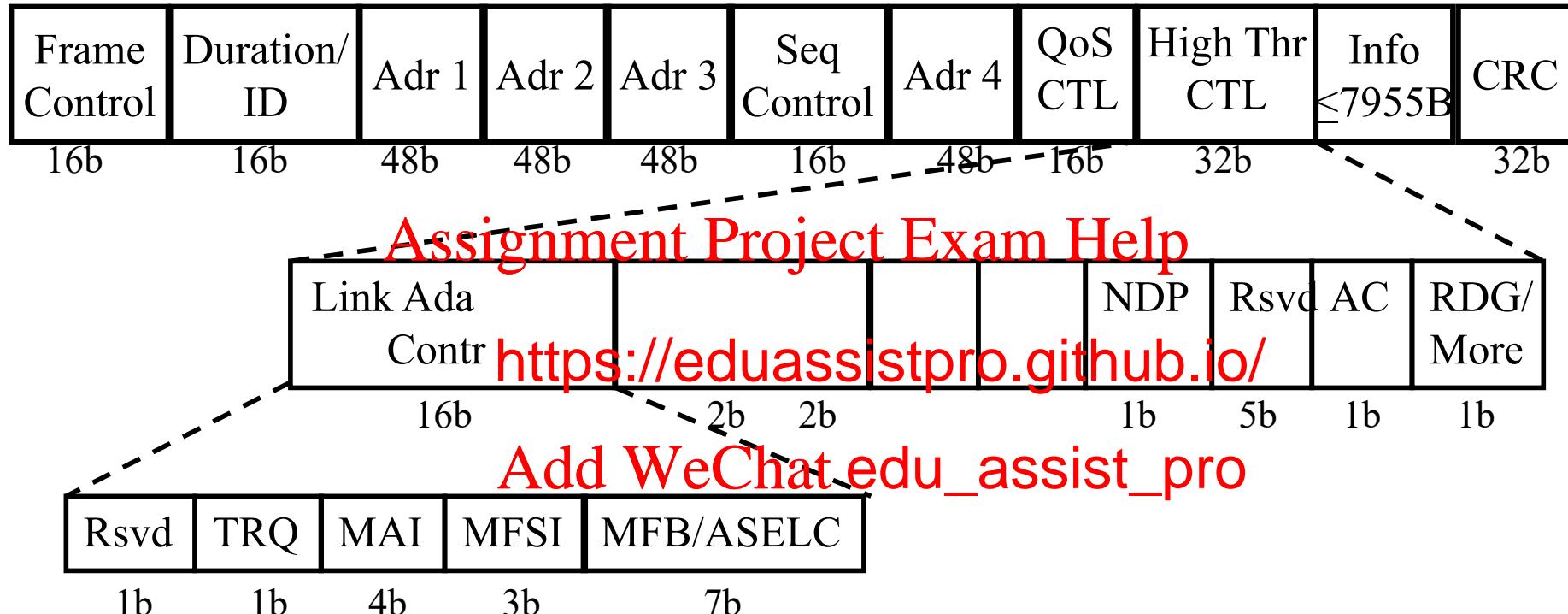


# 802.11n Frame Aggregation



Ref: D. Skordoulis, et al., “IEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High-Throughput WLANs,” IEEE Wireless Magazine, February 2008, <http://tinyurl.com/k2gv12g>  
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## 802.11n MAC Frame – CSI Feedback Opportunity



- ❑ 802.11n introduced a “High Throughput Control” field to exchange channel state information (CSI)
- ❑ Receivers can derive CSI from the pilots embedded in the transmissions (e.g., OFDM pilot subcarriers), but the transmitters cannot learn it unless receivers explicitly feedback this information. This new field in 802.11n provides this opportunity

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# IEEE 802.11ac

- Supports 80 MHz and 80+80 (channel bonding) MHz channels
- 5 GHz only. No 2.4 GHz.
- 256-QAM 3/4 and 5/6: 8/6 times 64-QAM  $\Rightarrow$  1.33X (of 11n)
- 8 Spatial streams: <https://eduassistpro.github.io/> .
- **Multi-User MIMO** [Add WeChat edu\\_assist\\_pro](#)
- Less pilots/more data subcarriers                           MHz), 108+6 (40 MHz), 234+8 (80 MHz), 468+16 (160 MHz)

Ref: M. Gast, “802.11ac: A Survival Guide,” O’Reilly, July 2013, ISBN:978-1449343149, Safari Book

# Bandwidth and Subcarriers of 802.11ac

Bandwidth	# of Data Subcarriers	# of Pilot Subcarriers
20 MHz	52	4
40 MHz	<a href="https://eduassistpro.github.io/">https://eduassistpro.github.io/</a>	6
80 MHz	Add WeChat edu_assist_pro 234	8
160 MHz	468	16

## **Modulation, Coding, Data Rates of 802.11ac: Single Stream**

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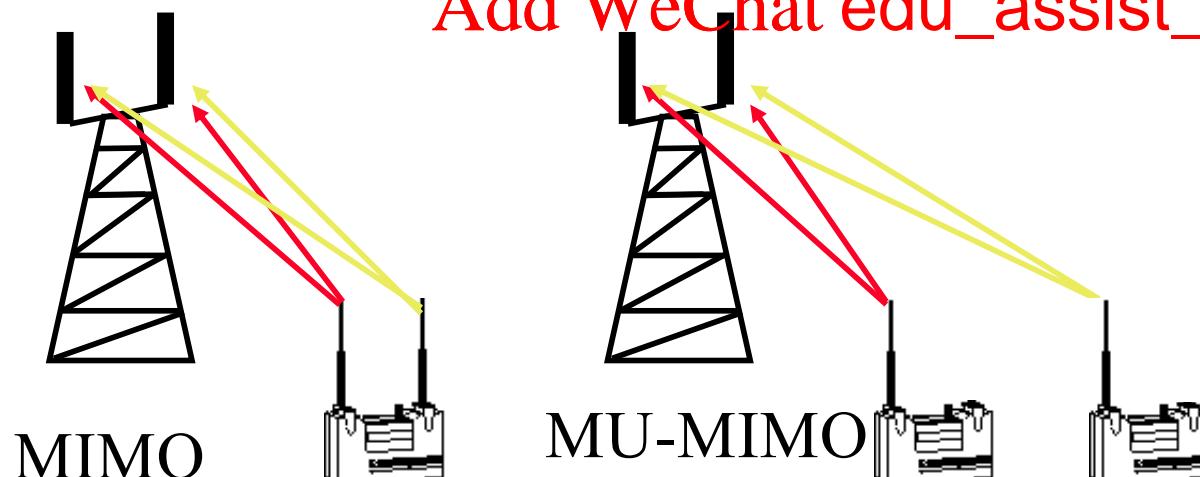
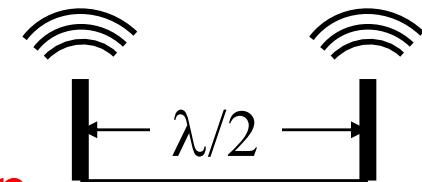
# Beamforming

- Direct energy towards the receiver
- Requires an antenna array to alter direction per frame  
    ⇒ A.k.a. Smart Antenna
- Implicit: Channel estimation → Packet loss
- Explicit: Transmission → Collaborate for channel estimation  
<https://eduassistpro.github.io/>  
[Add WeChat edu\\_assist\\_pro](#)
- 802.11ac supports a more “standard” beamforming so multi-vendor products can cooperate easily

# Multi-User MIMO

- **MIMO:** Multiple uncorrelated spatial beams  
Multiple antenna's separated by  $\lambda/4$  or  $\lambda/2$  (*absolute minimum*)
  - Cannot put too many antennas on a small device; also cost increases with number of antennas

- **MU-MIMO:** Two single-antenna users can act as one multi-antenna device. The users do not really need to know each other. They do not even exist in a MU-MIMO system! <https://eduassistpro.github.io/>

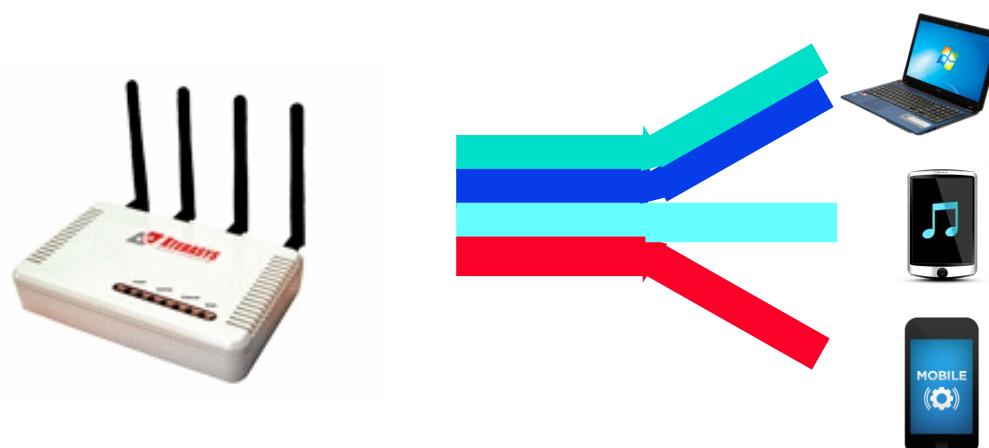


# Beamforming with Multi-User MIMO

- **Single User MIMO:** Colors represent transmission signals not frequency.



- **Multi User MIMO:**



# **802.11n vs. 802.11ac**

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[https://www.cisco.com/c/en/us/products/collateral/wireless/aironet-3600-series/white\\_paper\\_c11-713103.html](https://www.cisco.com/c/en/us/products/collateral/wireless/aironet-3600-series/white_paper_c11-713103.html)

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## Goal of 802.11ax: Efficiency vs. Speed

- ❑ Up until 802.11ac, pushing the data rates had been the main goal
  - 3500X increase from 2Mbps in 1997 to 7Gbps in 2013
  - 802.11ac increased data rates by ~11X compared to its immediate predecessor, 802.11n
- ❑ Instead of speed, problems: <https://eduassistpro.github.io/> wo efficiency
  - Efficient WiFi in densely deployed areas)
  - Efficient communications for mach
- ❑ 802.11ax has a modest data rate increase of only 37% against its immediate predecessor, 802.11ac

# Parameters of 802.11ax

- Band: 802.11ax supports both 2.4GHz and 5GHz bands.
- Coding rate: There is no change for the coding rate; 5/6 remains the maximum allowed coding rate.
- Channel width: There is also no change for the allowed channel width, i.e. 40MHz and 160MHz remain the maximum for 2.4GHz and 5GHz bands, respectively.
- MIMO streams: Like its predecessor, 802.11ax maintains the maximum number of MIMO streams to 8 only.
- Modulation: 802.11ax supports a modulation rate of up to 1024 QAM.
- Symbol interval: 802.11ax increases symbol interval to address longer delay spread in challenging environments. The symbol interval is increased to 12.8μs (vs. 3.2μs in 11a/g/n/ac) while the guard interval is also increased to 0.8μs, 1.6μs, or 3.2μs (3 options).
- OFDM subcarrier: subcarrier spacing is reduced to 78.125 kHz (vs. 312.5kHz in 11a/g/n/ac), which yields a total number of subcarriers as follows: 256 for 20MHz, 512 for 40MHz, 1024 for 80MHz, and 2048 for 160MHz, which includes two new types of subcarriers, DC and null subcarriers, in addition to the conventional data, pilot, and guard subcarriers used in previous WiFi versions. The number of data carriers available are as follows: 234 for 20MHz, 468 for 40MHz, 980 for 80MHz, and 1960 for 160MHz.

## **Modulation, Coding, Data Rates of 802.11ax: Single Stream**

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# Multiple Access in 802.11ax: OFDMA

- ❑ Up until 802.11ac, CSMA had been used for channel access
- ❑ OFDMA had been used in cellular networks for many years, but for WiFi it was introduced for the first time in 802.11ax
  - OFDMA is available as an option

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- ❑ 802.11ax OFDMA
  - Centrally allocate c ed time-frequency resource units (Rus)
  - Subcarriers are called tones
  - Each tone = single subcarrier of 78.125
  - The tones are then grouped into 6 different sizes of resource units (RUs): 26, 52, 106, 242, 484, or 996 tones
  - 26 tones = ~2MHz ( $26 \times 78.125\text{kHz} = 2031.25\text{kHz}$ )
  - 996 tones = ~80MHz ( $996 \times 78.125\text{kHz} = 77812.5\text{kHz}$ )
  - A WiFi client can be allocated a maximum of 2 996 tones = ~160 MHz

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## 802.11ax Resource Units

<b>RU</b>	<b>20MHz</b>	<b>40MHz</b>	<b>80MHz</b>	<b>160(80+80)MHz</b>
<b>26-tone</b>	9	18	37	74
<b>52-tone</b>	$4^{+1}$	$8^{+2}$	$16^{+5}$	$32^{+10}$
<b>106-tone</b>	$2^{+1}$			$16^{+10}$
<b>242-tone</b>	1			$8^{+2}$
<b>484-tone</b>	NA	1		$4^{+2}$
<b>996-tone</b>	NA	NA	1	2

where  $+n$  means ‘plus  $n$  26-tone RUs’. For example, to allocate ~20MHz, the access point would allocate 4 52-tone RUs plus 1 26-tone, which results in a total of  $4 \times 52 + 26 = 234$  subcarriers allocated to the station.

## Example 802.11ax

**Question:** A single antenna 802.11ax client receives a 26-tone RU allocation from the AP when trying to transmit a 147-byte data frame. What could be the minimum possible time required to transmit the frame assuming at least 2 non-data subcarriers?

**Solution:**

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Single antenna means <https://eduassistpro.github.io/>

Number of data subcarriers

Symbol length = data-interval-guard = ~~1.25μs~~ 1.25μs

Maximum data rate for single-stream 26-

AM@5/6, 0.8μs GI )

= symbol-rate x (bits/symbol) x coding-rate

$$= (1/13.6) \times (10 \times 24) \times (5/6)$$

$$= 14.7 \text{Mbps}$$

Data frame length in bits:  $147 \times 8$  bits

$$\text{Minimum frame transmission time: } (147 \times 8) / 14.7 \mu\text{s} = 80 \mu\text{s}$$

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## 802.11be: Next Generation WiFi (WiFi 7)

- 802.11ax is perfectly capable of serving today's needs, but
- Work on next generation WiFi must continue to keep WiFi future safe
- 802.11be is the next generation WiFi
  - work has already started
- Data rates will be increased by several parameters
  - Increase bandwidth from 160MHz to 320MHz band)
  - Increase number of bits per symbol (4096 QAM)
  - Increase MIMO streams to 16
- New Features
  - Multi-band communications (better throughput and reliability)
  - Multi-AP coordination (better spectral efficiency and quality of experience)

# 802.11be vs. previous WiFi generations

Table 5.10 Comparison of 802.11be with previous amendments

Parameter	802.11n	802.11ac	802.11ax	802.11be
Band	2.4/5GHz	5Ghz	2.4/5GHz	2.4/5/6GHz
Max. Channel Bandwidth	40MHz	160MHz	160MHz	320MHz
Max Modulation	64QAM	4QAM	4QAM	4096QAM
MIMO	4 streams	4 streams	ms	16 streams
Max. Data Rate	600Mbps	6.9Gbps	9.6Gbps	46Gbps

## Example 802.11be

**Question:** Calculate the maximum data rate of 802.11be.

**Solution:**

Enhancements against 802.11ax:

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Channel bandwidth factor:

Modulation factor: 12 bits  $\text{Mbps} = \frac{\text{Mbps}}{\text{MHz}} \times (\log_2 4096 - 1) = 1.2$

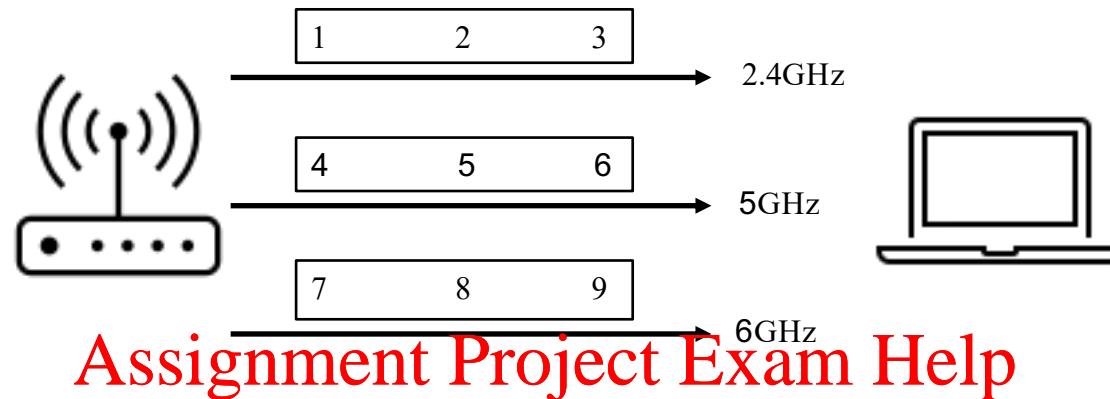
MIMO factor = 16 streams/8 streams = 2

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Therefore 802.11be is expected to achieve a 4.8X ( $2 \times 1.2 \times 2 = 4.8$ ) improvement against 802.11ax.

Given that 802.11ax has a maximum data rate of 9.6Gbps, 802.11be is expected to achieve a maximum data rate of  $4.8 \times 9.6 = 46.08$ Gbps.

# 802.11be Multi-band Communications

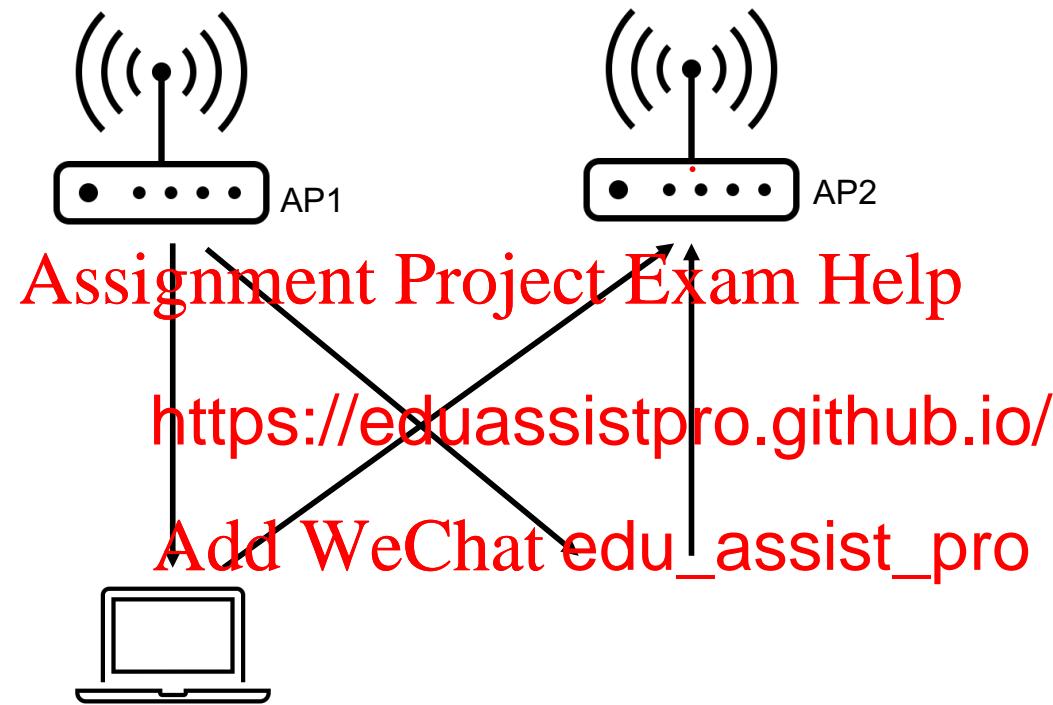


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**Top:** Improving **throughput** by allocating data from one traffic stream to multiple bands;  
**Bottom:** Improving **reliability** by sending duplicate data from one traffic stream over multiple bands;

# 802.11be Multi-AP Coordination Example



Downlink is handled by AP1, while AP2 handles the uplink.

# Summary

1. 802.11a/g use OFDM with 64 subcarriers in 20 MHz, which includes 48 Data, 4 Pilot, 12 guard subcarriers.
2. 802.11e introduces 4 queues with different AIFS and TXOP durations and a QoS field in frames to provide enhanced support for QoS.
3. 802.11n adds MIMO, aggregation, dual band, and channel bonding.
4. IEEE 802.11ac supports 0+80 MHz channels with 256-QAM and 8 streams.  
<https://eduassistpro.github.io/>
5. IEEE 802.11ax supports 1024QAM, carrier spacing to 78.125kHz and increases data symbol spacing to 0.8μs. It introduced OFDMA.
6. 802.11be expects to increase data rates up to 46Gbps by using 4096 QAM, 320MHz channel bandwidth, and 16 MIMO streams. It uses 6GHz band along with 2.4GHz and 5GHz.

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