Wireless LAN II

Mainstream WiFi

IEEE 802.11a/b/g/n/ac/ax/be

Overview

1. IEEE 802.11 An[illegible]s
2. 802.11a/b/g
3. 802.11e: Enhanced DCF, Multiple Queues, Frame Bursting
4. 802.11n [WiFi 4]: Bonding, Aggregation
5. 802.11ac [WiFi 5]: Beamforming, Multi-User MIMO
6. 802.11ax [WiFi 6]: High efficiency
7. 802.11be [WiFi 7]: Extremely high throughput

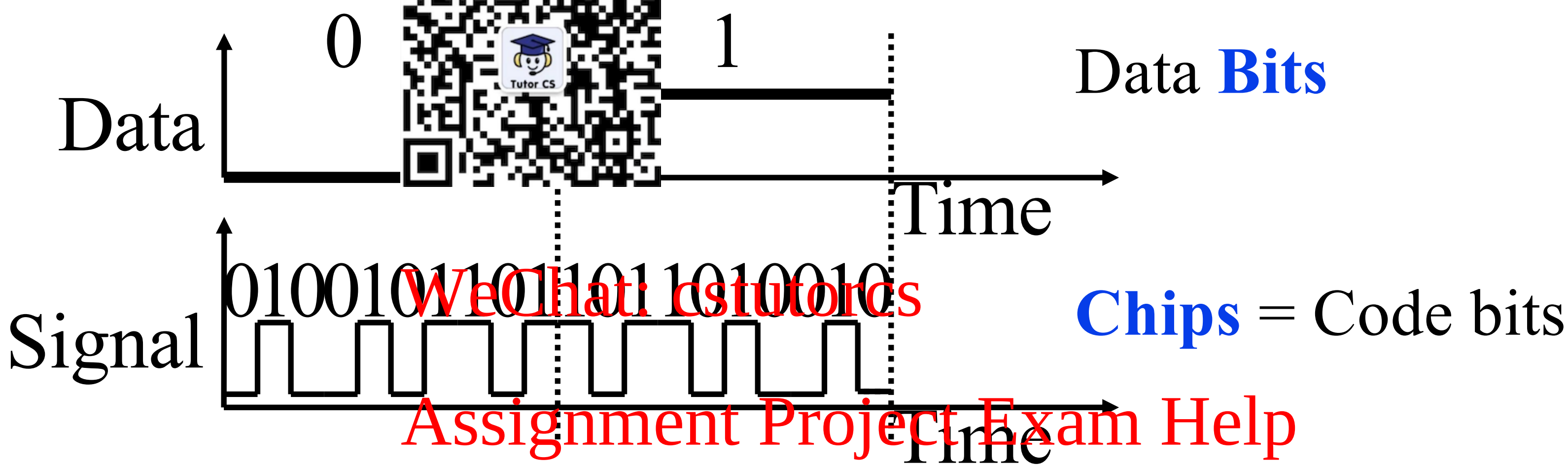
Mainstream 802.11 Amendments

802.11 Amendment	K[illegible]ments	Max. Data Rate
802.11-1997	L[illegible]n 2.4GHz (now extinct!)	2 Mbps
802.11b-1999	Higher speed modulation in 2.4GHz	11 Mbps
802.11a-1999	Higher speed PHY (OFDM) in 5GHz	54 Mbps
802.11g-2003	Higher speed PHY (OFDM) in 2.4GHz	54 Mbps
802.11n-2009	Higher throughput in 2.4/5GHz	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

802.11B - 1999

IEEE 802.11b-1999

- Direct Sequence Spread Spectrum:



- **Complementary Code Keying (CCK)**: Multi-bit symbols with appropriate code to minimize errors
- IEEE 802.11-1997: ½ rate binary convolution encoder, 2 bit/symbol, 11 chips/symbol, DQPSK = ½ × 22 × 1/11 × 2 = 2 Mb/s using 22 MHz
- IEEE 802.11b-1999: ½ rate binary convolution encoder, 8 bit/symbol, 8 chips/symbol, CCK = ½ × 22 × 1/8 × 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 [illegible] a spread spectrum coding with only ½ rate, which produces chips [illegible] ½ chips per Hz. It uses 8 chips to code a symbol and 16 QAM [illegible] to modulate the symbol stream. What would be the data rate [illegible] z channels?

Chip rate = ½ x 22 = 11 Mcps

Symbol rate = 11/8 = 1.375 Msps

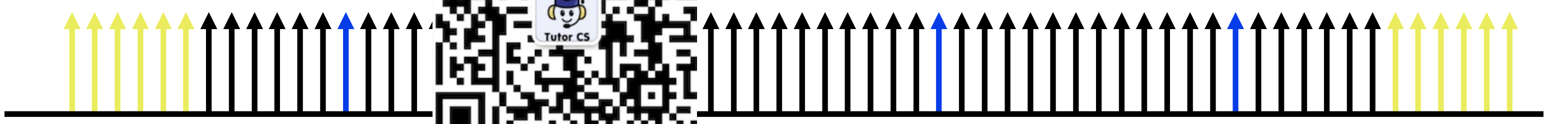
Bits per symbol = $\log_2(16)$ = 4 [16 QAM produces 4 bits per symbol]

Data rate = 1.375 x 4 = 5.5 Mbps

802.11A - 1999

IEEE802.11a-1999

- To increase the data rate, 802.11 uses OFDM
- 20 MHz divided into 64 subcarriers. 6 subcarriers at each side are used as guards and 4 as pilot, [illegible]s 48 for data.



- Each OFDM symbol is carried over 48 subcarriers in parallel.
- OFDM has a symbol length of 4 μs → 0.25 M symbols/s
  - 3200ns (data pulse) + 800ns (guard interval) = 4000ns = 4μs
- With a binary modulation (e.g., BPSK) , there will be 1 coded bit per subcarrier for each OFDM symbol, or 48 coded bits 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, ½, 2/3, and ¾ (the ratio indicates the ratio of data bits over all coded bits transmitted).
  - E.g., ½ indicates that only *half* of the total transmitted bits contain data.

IEEE802.11a-1999 Data Rates

Modulation	Coding Rate	Coded [illegible]er	Coded bits per symbol	Data bits per symbol	Data Rate (Mbps)
BPSK	1/2	[illegible]	48	24	**6**
BPSK	3/4	1	48	36	**9**
QPSK	1/2	2	96	48	**12**
QPSK	3/4	2	96	72	**18**
16-QAM	1/2	4	192	96	**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**

802.11G - 2003

IEEE 802.11g-2003

- OFDM – Same as 802.11a ⇒ 54 Mbps
- 2.4 GHz band ⇒ [illegible]er than 5 GHz 802.11a
- Fall back to 802.11b CCK

802.11E - 2005

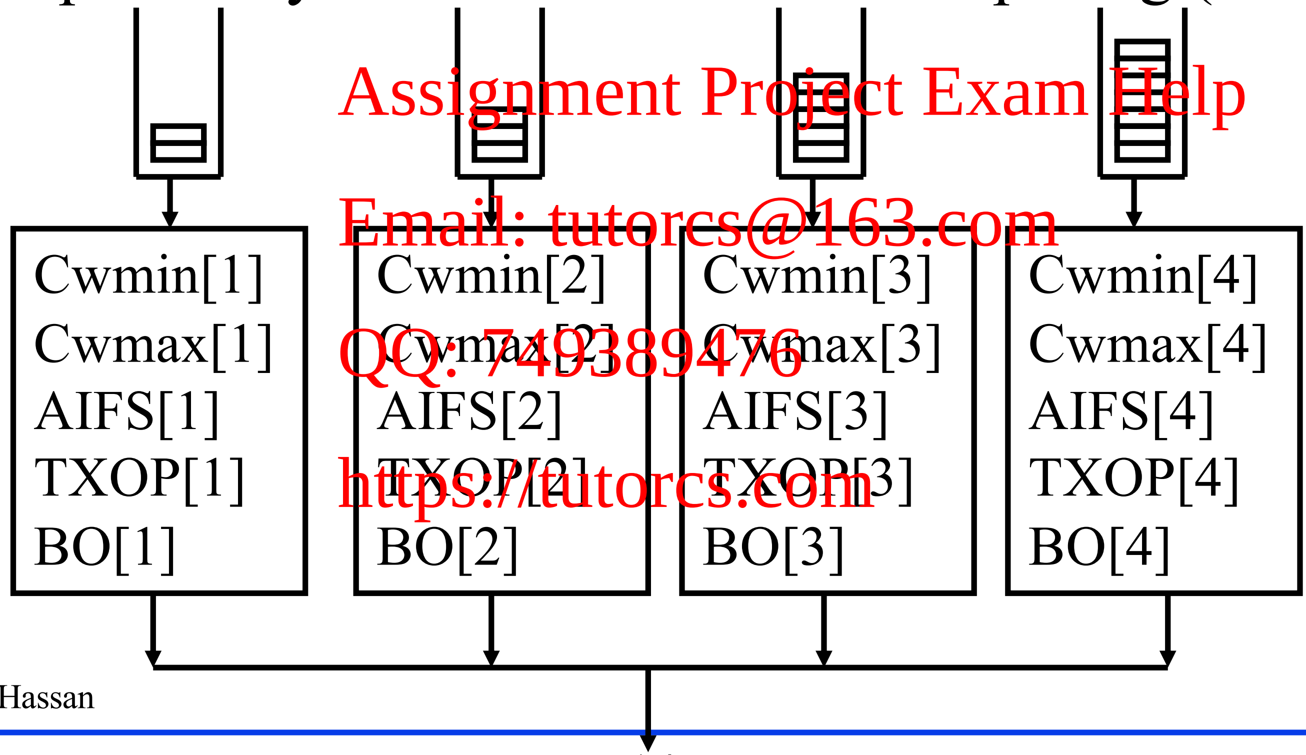
IEEE 802.11e-2005 (Enhanced QoS)

1. Hybrid Coordina[illegible]tion (**HCF**) w two components
   a. Contention F[illegible]s: Polling
   b. Contention-based Access: Enhanced DCF (**EDCF**)

2. **EDCF**
   1. Multiple Priority levels with *multiple* FIFO queues
   2. Frame bursting and Group Acknowledge
3. Direct link

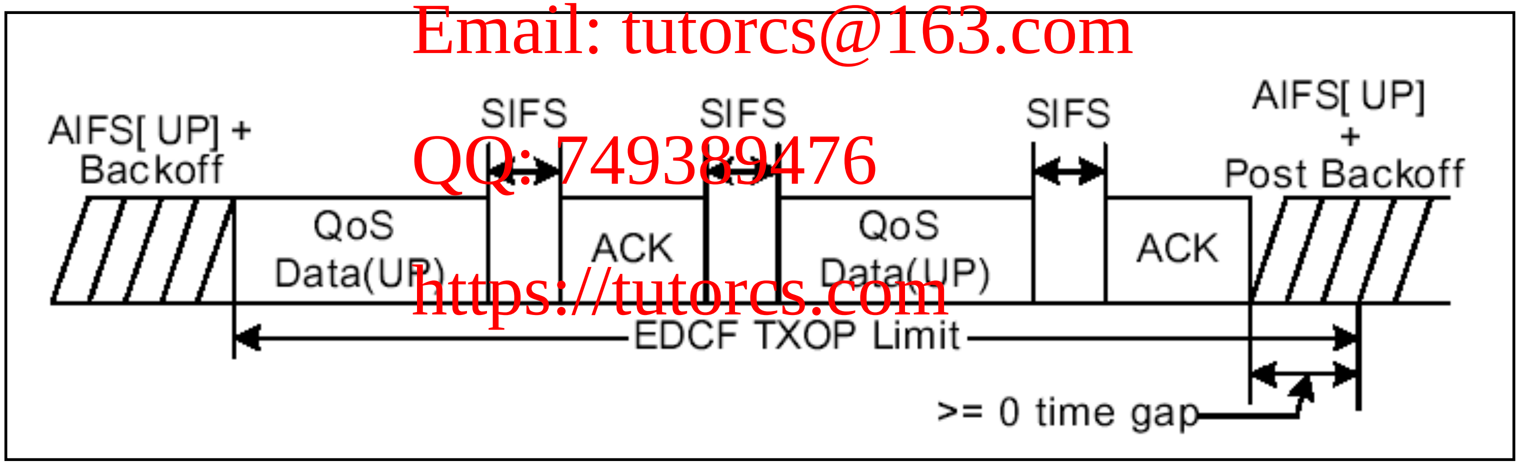
Enhanced DCF – Multiple Queues

- Up to 4 queues. Ea[illegible] a different set of four Parameters:
  - CW_{min}/CW_{max}
  - Arbitrated Inte[illegible]pacing (**AIFS**) = DIFS
  - Transmit Opportunity (**TXOP**) duration
- DIFS replaced by Arbitrated Inter-frame Spacing (AIFS)



EDCF - Frame Bursting

- EDCF allows *multiple* [illegible] transmission
  - Both individual and [illegible] allowed
- Max time = Transmis[illegible]unity (TXOP)
  - Covers total time including multiple data frames
- Voice/gaming has high priority but small burst size
- Video/audio has lower priority but large burst size



Direct Link in 802.11e

- Direct Link is another feature introduced by 802.11e
- Direct link allows two W[illegible]o communicate directly without going through the AP, which reduces la[illegible]for delay-sensitive applications)

802.11N – 2009

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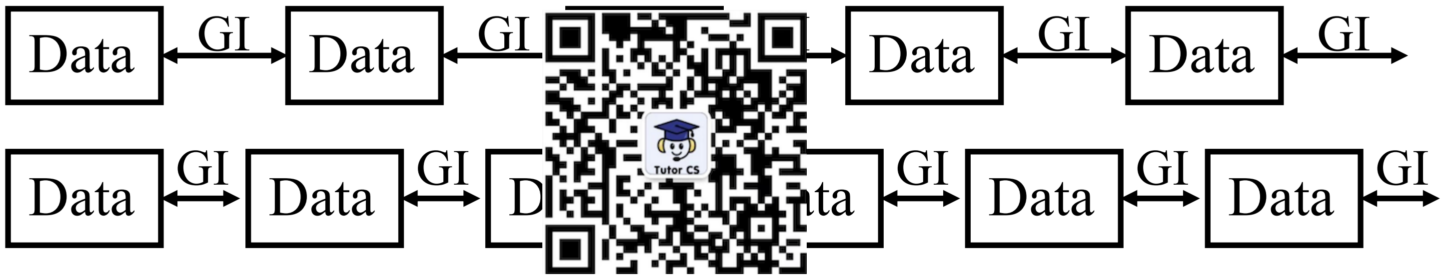
IEEE 802.11n-2009

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
   $k = degrees\ of\ freedom = \min(n,m)$
   $\Rightarrow k$ times more throughput
   E.g., $2 \times 2{:}2$, $2 \times 3{:}2$, $3 \times 2{:}2$, $4 \times 4{:}4$, $8 \times 4{:}4$
3. **MIMO Beamforming**: Focus the beam 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 Aggrega**[illegible]k multiple input frames inside a frame
   ⇒ Less overhea[illegible]e throughput
6. **Lower FEC Ov**[illegible]/6 instead of ¾
7. **Reduced Guard Interval**: 400 ns instead of 800 ns
8. **Reduced Inter-Frame Spacing** (SIFS=2 μs, instead of 10 μs)
9. **Greenfield Mode**: Optionally eliminate support for a/b/g (shorter and higher rate preamble)
10. **Dual Band**: 2.4 and 5 GHz
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 × Multi-path delay spread
- Initial 802.11a design assumed 200ns delay spread
  ⇒800 ns GI + 3200 ns data ⇒20% overhead
- Most indoor environment have smaller 50-75 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

Example

- Compared to 802.11a/g, 802.11n has higher coding rate, wider channel bandwidth, lower co[illegible]ead, and reduced guard interval. On top of this, 802.11n uses M[illegible]plexing to further boost the data rate. Given that 802.11a/[illegible] rate of 54 Mbps, can you estimate the data rate for 802.11n tha[illegible]MO streams (assume 64 QAM for both of them, i.e., there is n[illegible]ent in modulation)?

54 Mbps is achieved with ¾ coding for 3200 Data+800 GI for a/g, which basically uses a single stream (no MIMO).

802.11n has the following improvement factors:

- 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 = 4x1.11x2.25x1.11 = **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 Mbps**

802.11n Channel Bonding

- Two adjacent 20 M[illegible] used
- OFDM: 52+4 instea[illegible]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
- Channel bonding is achieved by combining a secondary 20 MHz channel.
- **Secondary 20 MHz channel**: Just below or just above 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

MCS index	Spatial streams	Modulation type	Coding rate	Data rate (Mbit/s)			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15
1	1	QPSK	1/2	13	14.4	27	30
2	1	QPSK	3/4	19.5	21.7	40.5	45
3	1	16-QAM	1/2	26	28.9	54	60
4	1	16-QAM	3/4	39	43.3	81	90
5	1	64-QAM	2/3	52	57.8	108	120
6	1	64-QAM	3/4	58.5	65	121.5	135
7	1	64-QAM	5/6	65	72.2	135	150

Example: 802.11n

Question: 802.11n can u[illegible] MHz channels or 40 MHz channels with channel bonding. For 40 [illegible]idth, data rate can be improved by what factor if channel bonding [illegible]

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

# of subcarriers for 20 MHz channels (no channel bonding) = 52

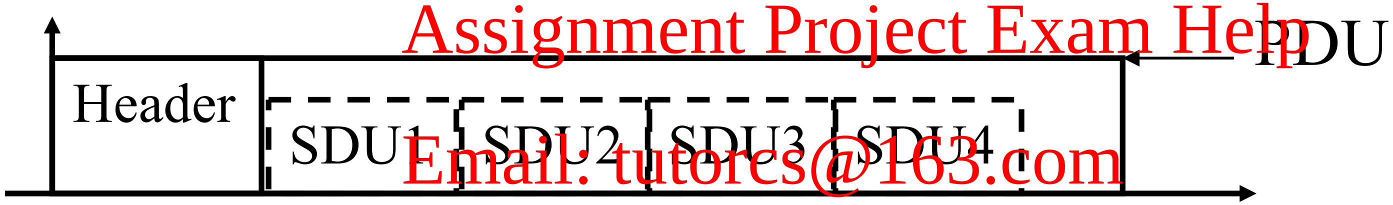
# of subcarriers for 40 MHz channels with channel bonding = 108

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

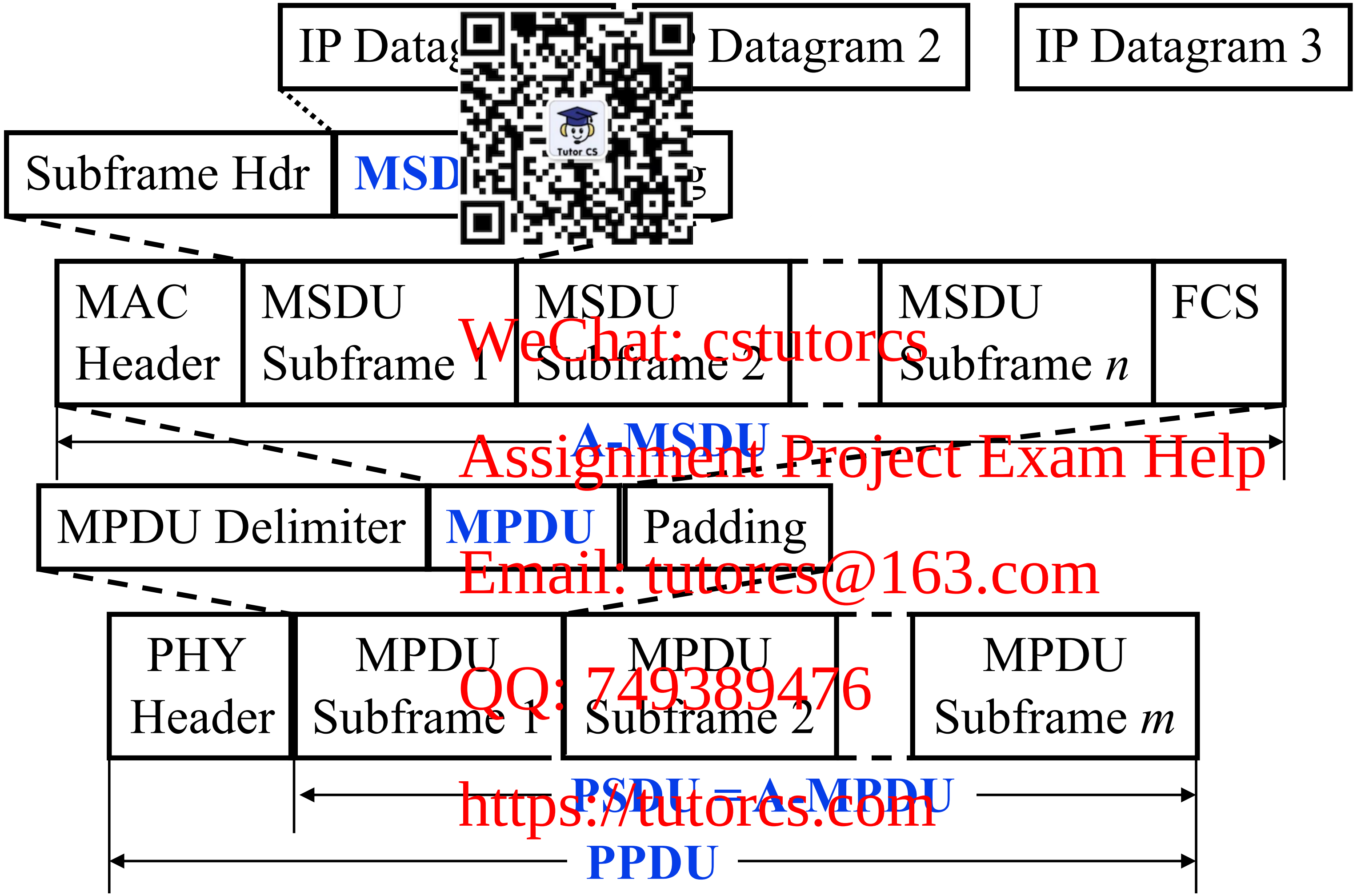
Frame Aggregation

- **Frame Bursting**: multiple PDUs together

- **Frame Aggregation**: Multiple SDUs in one PDU
  All SDUs must have the same transmitter and receiver address



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/k2gvl2g

802.11n MAC Frame – CSI Feedback Opportunity

Frame Control	Duration/ ID	Adr 1	Seq Control	Adr 4	QoS CTL	High Thr CTL	Info ≤7955B	CRC
16b	16b	48b	16b	48b	16b	32b		32b

Link Adaptation Control	Calibration Pos | Seq	Rsvd	CSI	NDP	Rsvd	AC	RDG/ More
16b	2b 2b	2b	2b	1b	5b	1b	1b

Rsvd	TRQ	MAI	MFSI	MFB/ASELC
1b	1b	4b	3b	7b

- 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

802.11AC – 2013

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IEEE 802.11ac

- Supports 80 MHz 0 (channel bonding) MHz channels
- 5 GHz only. No 2.
- 256-QAM 3/4 and 5/6: 8/6 times 64-QAM ⇒ 1.33X (of 11n)
- 8 Spatial streams: 2X (of 11n)
- **Multi-User MIMO**
- Less pilots/more data subcarriers: 52+4 (20 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	Subcarriers	# of Pilot Subcarriers
20 MHz	52	4
40 MHz	108	6
80 MHz	234	8
160 MHz	468	16

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

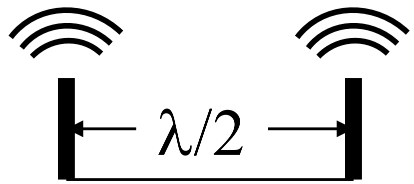
MCS index[b]	Modulation type	Coding rate	[illegible]		40 MHz channels		80 MHz channels		160 MHz channels	
			[illegible]	ns	800 ns GI	400 ns GI	800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65
1	QPSK	1/2	13	14.4	27	30	58.5	65	117	130
2	QPSK	3/4	19.5	21.7	40.5	45	87.8	97.5	175.5	195
3	16-QAM	1/2	26	28.9	54	60	117	130	234	260
4	16-QAM	3/4	39	43.3	81	90	175.5	195	351	390
5	64-QAM	2/3	52	57.8	108	120	234	260	468	520
6	64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585
7	64-QAM	5/6	65	72.2	135	150	292.5	325	585	650
8	256-QAM	3/4	78	86.7	162	180	351	390	702	780
9	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7

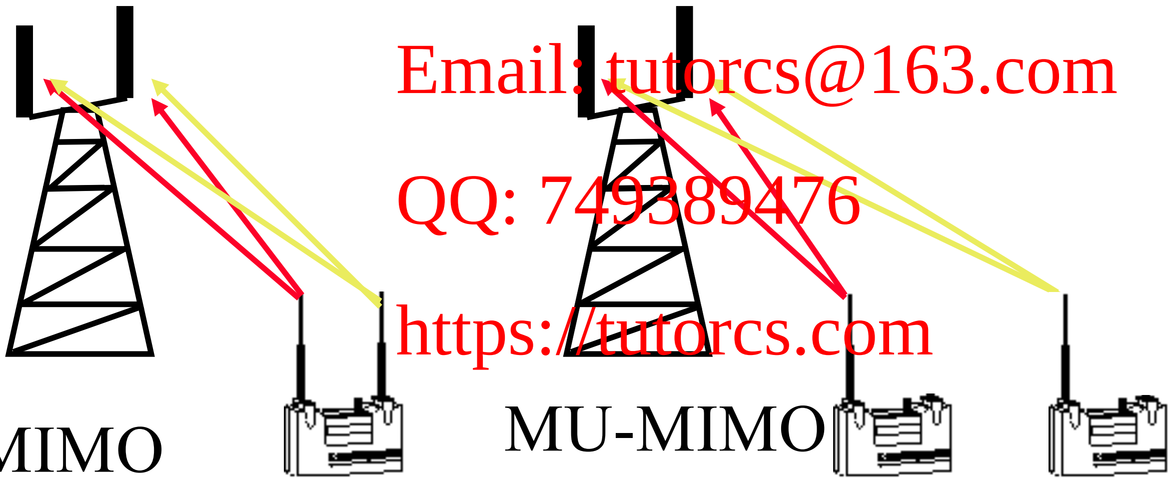
Beamforming

- Direct energy t[illegible]he receiver
- Requires an antenna array to alter direction per frame
  ⇒ A.k.a. Smart Antenna
- Implicit: Channel estimation using packet loss
- Explicit: Transmitter and receiver collaborate for channel estimation
- 802.11ac supports a more "standard" beamforming so multi-vendor products can cooperate easily

Multi-User MIMO

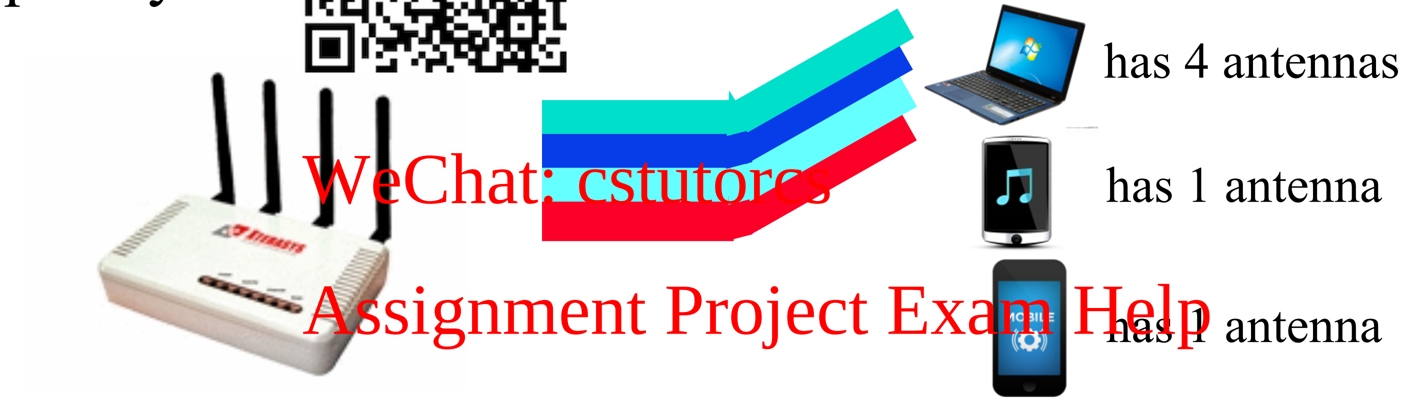
- **MIMO**: Multiple uncorrelated spatial beams
  Multiple antenna's separa[illegible] or $\lambda/2$ (*absolute minimum*)
  - Cannot put too ma[illegible]n a small device; also cost increases with [illegible]ntennas
- **MU-MIMO**: Two single-a[illegible] users can act as one multi-antenna device. The users do not really need to know each other. They do not even know that their antennas are used in a MU-MIMO system!





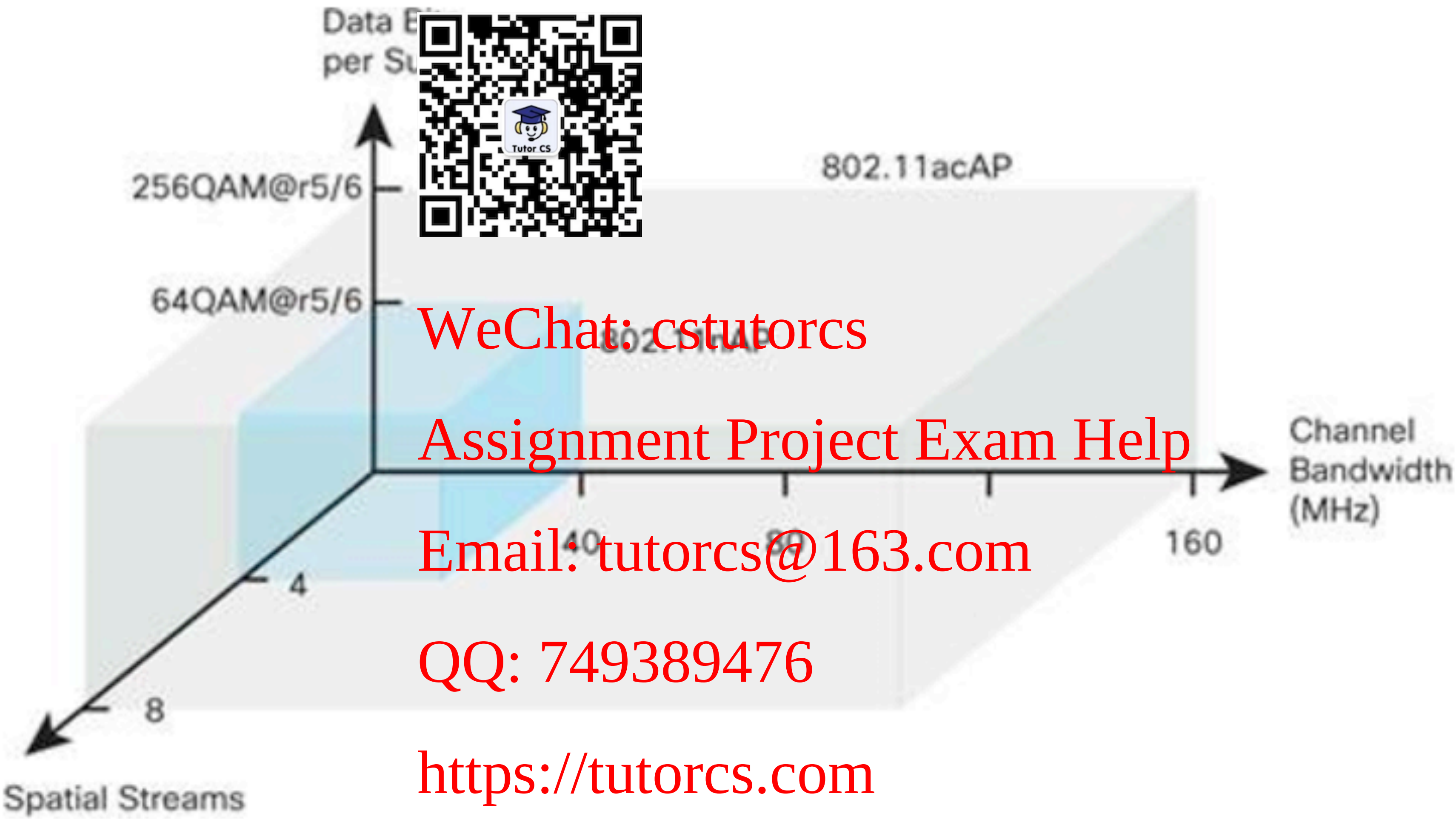
Beamforming with Multi-User MIMO

- **Single User MIM**[illegible]s represent transmission signals not frequency.



- **Multi User MIMO:**

802.11n vs. 802.11ac



https://www.cisco.com/c/en/us/products/collateral/wireless/aironet-3600-series/white_paper_c11-713103.html

802.11AX – 2020

WIFI 6

Goal of 802.11ax: Efficiency vs. Speed

- Up until 802.11ac, [illegible] the data rates had been the main goal
  - 3500X increase fr[illegible]n 1997 to 7Gbps in 2013
  - 802.11ac increase[illegible] by ~11X compared to its immediate predecessor, 802.11n
- Instead of speed, 802.11ax seeks to solve two efficiency problems:
  - Efficient WiFi in densely deployed scenarios (urban areas)
  - Efficient communications for machines (IoT)
- 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 [illegible] ge for the allowed channel width, i.e. 40MHz and 160MHz remain the ma[illegible] 4GHz and 5GHz bands, respectively.
- MIMO streams: Like its [illegible] 802.11ax maintains the maximum number of MIMO streams to 8 only.
- Modulation: 802.11ax supports an increased modulation rate of up to 1024 QAM.
- Symbol interval: 802.11ax uses increased symbol intervals to address longer delay spread in challenging outdoor environments. Symbol data 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

MCS Index	Spatial Stream	Modulation	Coding	20MHz			40MHz			80MHz			160MHz		
				0.8μs GI	1.6μs GI	3.2μs GI	0.8μs GI	1.6μs GI	3.2μs GI	0.8μs GI	1.6μs GI	3.2μs GI	0.8μs GI	1.6μs GI	3.2μs GI
0	1	BPSQ	1/2	8.6	8.1	7.3	17.2	16.3	14.6	36.0	34.0	30.6	72.1	68.1	61.3
1	1	QPSK	1/2	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
2	1	QPSK	3/4	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
3	1	16-QAM	1/2	34.4	32.5	29.3	68.8	65.0	58.5	144.1	136.1	122.5	288.2	272.2	245.0
4	1	16-QAM	3/4	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
5	1	64-QAM	2/3	68.8	65.0	58.5	137.6	130.0	117.0	288.2	272.2	245.0	576.5	544.4	490.0
6	1	64-QAM	3/4	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
7	1	64-QAM	5/6	86.0	81.3	73.1	172.1	162.5	146.3	360.3	340.3	306.3	720.6	680.6	612.5
8	1	256-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
9	1	256-QAM	5/6	114.7	108.3	97.5	229.4	216.7	195.0	480.4	453.7	408.3	960.8	907.4	816.7
10	1	1024-QAM	3/4	129.0	121.9	109.7	258.1	243.8	219.4	540.4	510.4	459.4	1080.9	1020.8	918.8
11	1	1024-QAM	5/6	143.4	135.4	121.9	286.8	270.8	243.8	600.5	567.1	510.4	1201.0	1134.3	1020.8

Multiple Access in 802.11ax: OFDMA

- Up until 802.11ac, CS… en used for channel access
- OFDMA had been use… r networks for many years, but for WiFi it was introduced for the… n 802.11ax
  - OFDMA is availabl… n
- 802.11ax OFDMA
  - Centrally allocate channel resources using fine-grained time-frequency resource units (Rus)
  - Subcarriers are called tones
  - Each tone = single subcarrier of 78.125 kHz bandwidth
  - The tones are then grouped into 6 different sizes of resource units (RUs): 26, 52, 106, 242, 484, or 996 tones
  - 26 tones = ~2MHz (26x78.125kHz = 2031.25kHz)
  - 996 tones = ~80MHz (996x78.125kHz = 77812.5kHz)
  - A WiFi client can be allocated a maximum of 2 996 tones = ~160 MHz

802.11ax Resource Units

RU	20MHz	40MHz	80MHz	160(80+80)MHz
26-tone	9	[illegible]	37	74
52-tone	4^{+1}	8^{+2}	16^{+5}	32^{+10}
106-tone	2^{+1}	4^{+2}	8^{+5}	16^{+10}
242-tone	1	2	4^{+1}	8^{+2}
484-tone	NA	1	2^{+1}	4^{+2}
996-tone	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 4x52+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 [illegible] to transmit a 147-byte data frame. What could be the minimum [illegible]e required to transmit the frame assuming at least 2 non-data subc[illegible]

Solution:

Single antenna means single stream
Number of data subcarriers = 26-2 = 24

Symbol length = data-interval+guard = 12.8+0.8 = 13.6µs
Maximum data rate for single-stream 26-tone (1024-QAM@5/6, 0.8µs GI)

= symbol-rate x (bits/symbol) x coding-rate
= (1/13.6) x (10x24) x (5/6)

= 14.7Mbps
Data frame length in bits: 147x8 bits

Minimum frame transmission time: (147x8)/14.7µs = 80µs

802.11BE – 2024

WIFI 7

802.11be: Next Generation WiFi (WiFi 7)

- 802.11ax is perfec[illegible]e of serving today's needs, but
- Work on next gen[illegible]iFi must continue to keep WiFi future safe
- 802.11be is the next generation WiFi
  - work has already begun; expected to release in 2024

- Data rates will be increased by enhancing several parameters

  - Increase bandwidth from 160MHz to 360MHz (6GHz 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 Com[illegible]02.11be with previous amendments				
Parameter	802.11[illegible]	[illegible]02.11ac	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	256QAM	1024QAM	4096QAM
MIMO	4 streams	4 streams	8 streams	16 streams
Max. Data Rate	600Mbps	6.9Gbps	9.6Gbps	46Gbps

Example 802.11be

Question: Calculate the m[illegible] rate of 802.11be.

Solution:

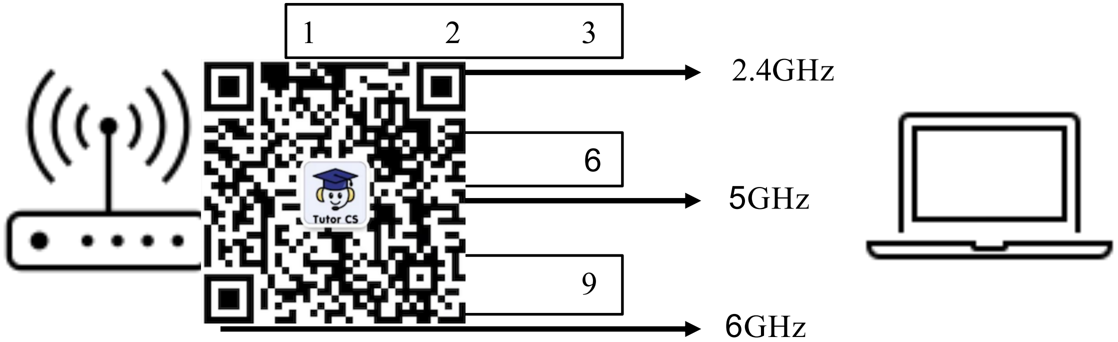
Enhancements against 802.11ax:

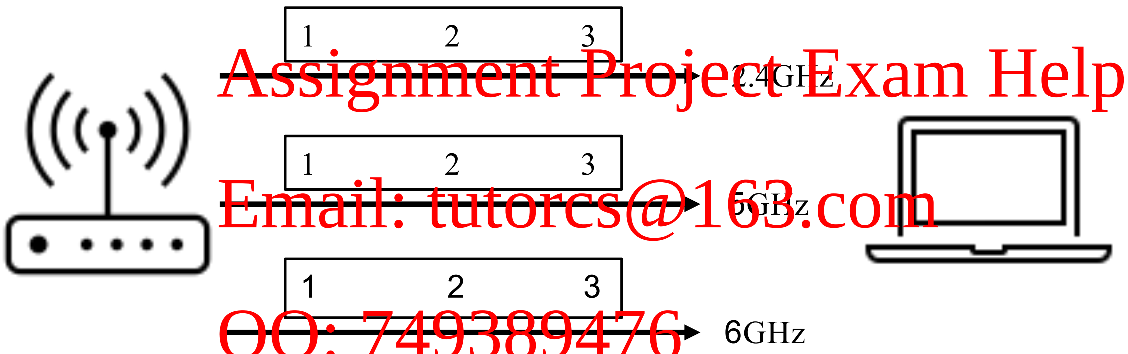
Channel bandwidth factor: 320MHz/160MHz = 2
Modulation factor: 12 bits/symbol ($\log_2 1024$=10)/10 bits/symbol ($\log_2 4096$=12) = 1.2
MIMO factor = 16 streams/8 streams = 2

Therefore 802.11be is expected to achieve a 4.8X (2x1.2x2 = 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 4.8x9.6 = 46.08Gbps.

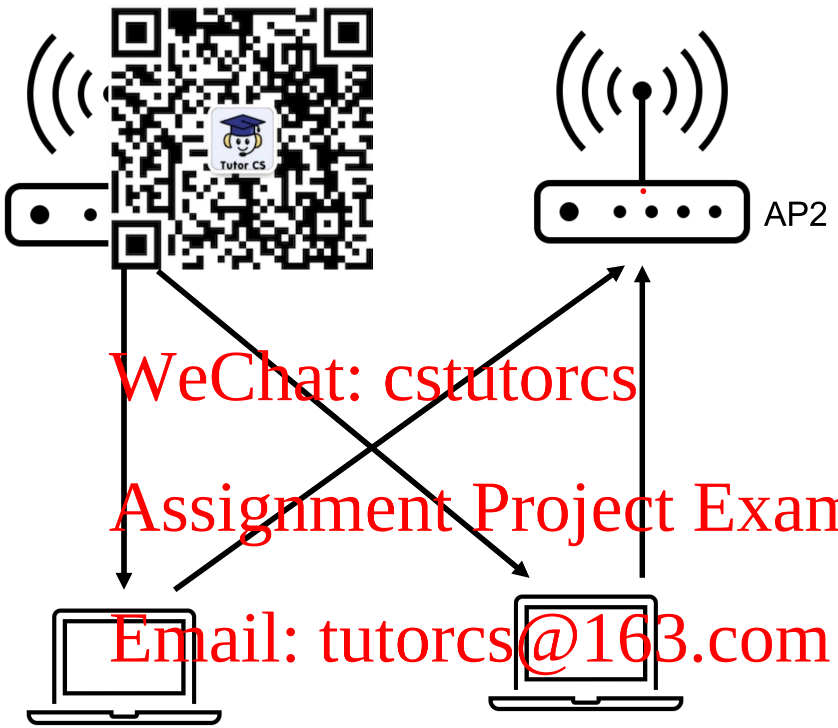
802.11be Multi-band Communications





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 [illegible]bcarriers in 20 MHz, which includes 48 Data, 4 Pilot, 12 gua[illegible]rs.
2. 802.11e introduces 4 [illegible]h different AIFS and TXOP durations and a QoS field in frames t[illegible]nhanced support for QoS.
3. 802.11n adds MIMO, aggregation, dual band, and channel bonding.
4. IEEE 802.11ac supports multi-user MIMO with 80+80 MHz channels with 256-QAM and 8 streams to give 6.9 Gbps
5. IEEE 802.11ax supports 1024QAM, reduces OFDM carrier spacing to 78.125kHz and increases data symbol interval to 12.8μs. 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.