WiFi Part II

IEEE 802.11 Evolution
b→a→g→n→ac→ax

Overview

1. Chronology of IEEE 802.11 Amendments
2. Maths of WiFi Data Rates | Modulation and Coding Scheme
3. 802.11a/b/g
4. 802.11n: Channel Bonding, Aggregation
5. 802.11ac: Multi-User MIMO
6. 802.11ax: OFDMA

WiFi Evolution: Key 802.11 Amendments

5.5x

- **802.11-1997:** 2 Mbps Legacy WiFi in 2.4GHz (now extinct!)
- **802.11b-1999**: Higher speed modulation in 2.4GHz (11Mbps) 4.9x
- **802.11a-1999**: Higher speed PHY (OFDM) in 5GHz (54Mbps) 11.1x
- **802.11g-2003**: Higher speed PHY (OFDM) in 2.4GHz (54Mbps)
- **802.11n-2009**: Enhancements for higher throughput: 2.4/5GHz (600 Mbps)
- **802.11ac-2013**: Very high throughput: 5GHz (~7 Gbps)
  special 1.36x 11.6x
- **802.11ax-2020 (expected)**: High efficiency: 2.4/5GHz (~9.6Gbps, but particularly efficient for *short packets* and *dense deployments*)

Basics of WiFi Data Rates

- Each WiFi version supports a range of specific data rates
  - E.g., 802.11b → 11 Mbps,
  - 802.11a → 6,9,12,18,24,36,48,54 (Mbps)

8 different data rate options!

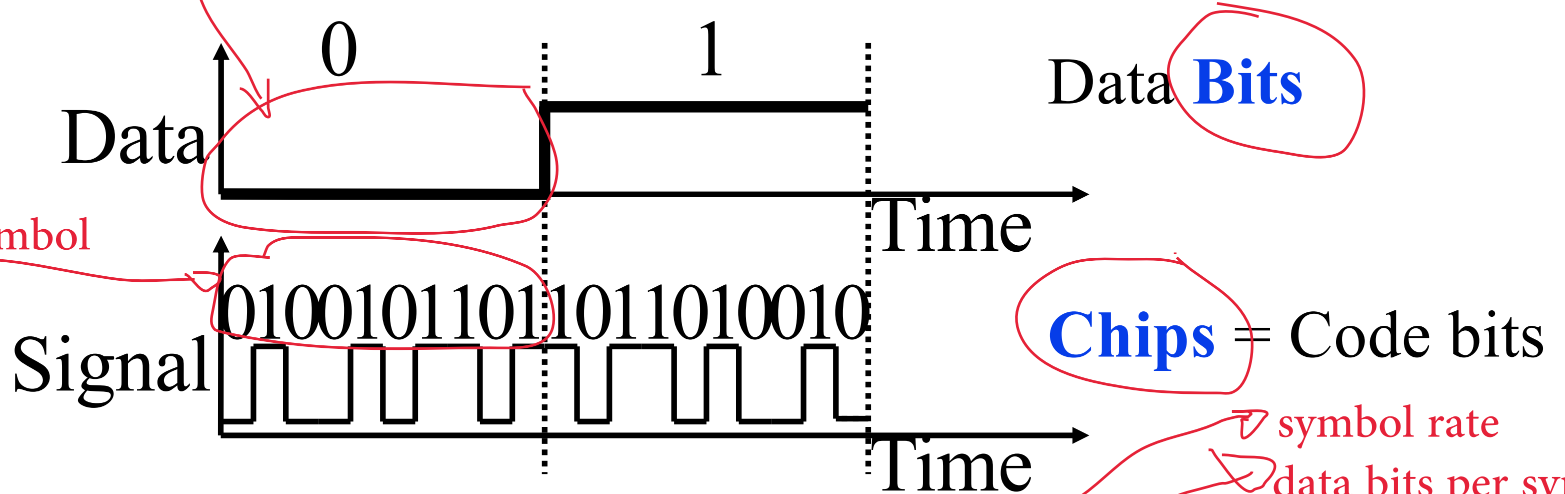
- **Data rate = symbol rate x data bits per symbol**
- Symbol rate = number of symbols per second
- Symbol rate calculation depends on PHY
  - Direct sequence spread spectrum (802.11b)
  - OFDM (802.11a/g/n/ac/ax)
- Data bits per symbol depends on modulation and coding
- WiFi with MIMO can have more than one independent data **stream** => *increases data rate linearly with number of such available streams*

IEEE 802.11b-1999

could be an example
of a binary modulation

- Direct Sequence Spread Spectrum:

10 chips/symbol



symbol rate
data bits per symbol

- **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 employing a spread spectrum coding with only ½ rate, which produces chips at a rate of **½ 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?

Chip rate = ½ x 22 = 11 Mcps (cps = chips per second)

Symbol rate = 11/8 = 1.375 Msps (sps = symbols per second)

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

Data rate = symbol rate x bits per symbol = 1.375 x 4 = 5.5 Mbps

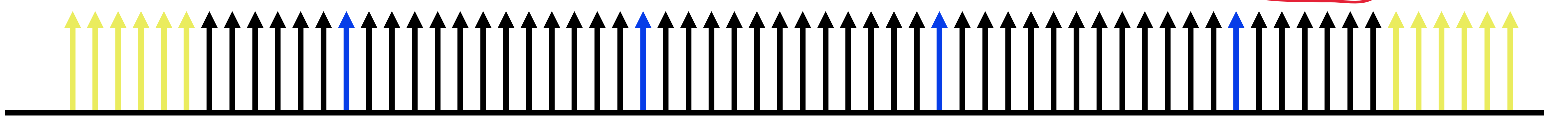
Symbol Rate for OFDM

- OFDM adopted from 802.11a onwards
- OFDM symbol rate = 1/(symbol-interval)
- Symbol interval = data interval + guard interval
- Only the data interval contain the actual symbol
- Guard interval contains no data; it is used to protect against *inter symbol interference*
  - More multipath → longer delay spread → longer guard interval → reduced symbol rate

Bits per symbol - OFDM

- Bits per symbol in OFDM depends on *modulation order* and *subcarrier structure*
- Total # of subcarriers in a WiFi channel = channel-bandwidth/subcarrier-spacing
  - Subcarrier spacing 312.5 kHz in 802.11a/g/n/ac
  - Subcarrier spacing 78.125 kHz in 802.11ax
- Total subcarriers are divided into three categories: data subcarriers + pilot subcarriers + guard subcarriers
  - Only data subcarriers carry data
  - Pilots estimate the wireless channel
  - Guards protect against interference from adjacent channels
- Each OFDM symbol is carried over all data subcarriers in parallel
- M-ary modulation → $\log_2 M$ bits per data subcarrier for the symbol
  - E.g., 16-QAM yields 4 bits per data subcarrier
- Number of **raw (coded)** bits per symbol = $\log_2 M$ ✗ #-of-data-subcarriers

this multiplier
is for OFDM



OFDM subcarrier structure: Black: *Data*, Blue: *Pilot*, Yellow: *Guard*

Impact of error coding on *data bits per symbol* in OFDM

- Error coding is often applied to original data to detect/correct bit errors during transmission
- Coded bit stream = original data bits + code bits
  - E.g., with ¾ code, 4 bits are transmitted for 3 data bits
  - With 2/3 code = 3 bits are transmitted for 2 data bits, and so on
  - ¾, 2/3, etc. are referred to as *coding rate*
- **Data bits per symbol** = *coding rate* ✘ $\log_2 M$ ✘ *#-of-data-subcarriers*

raw (coded) bits per symbol

Example

Question: What is the data rate of an OFDM WiFi applying 64-QAM and a coding rate of ¾ to its 48 data subcarriers? Assume a symbol interval of 4µs.

includes guard interval

Answer:

$\text{Log}_2 M = \log_2 64 = 6$

Coded bits per symbol = $\log_2 M$ ✘ #-of-data-subcarriers = 6x48 = 288

Data bits per symbol = coding rate x 288 = ¾ x 288 = 216

Symbol rate = 1/symbol-interval = ¼ Msps (0.25 million symbols per sec.)

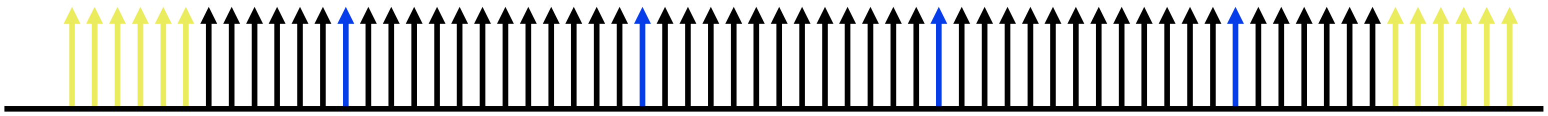
Data rate = symbol rate x data bits per symbol = 216 x ¼ Mbps = **54 Mbps**

5 Key Parameters affecting WiFi data rates

1. Modulation (affects number of bits per symbol)
   - Usually multiple options available
2. Coding (error correction overhead)
   - Usually multiple options available
   - MCS (integer number) defines combination of modulation and coding
3. Guard interval (affects symbol rate)
4. Channel width → # of OFDM data subcarriers
   - Channel width can be increased via *bonding* from 802.11n onwards
5. MIMO streams (number of independent data streams that can be sent in parallel)
   - MIMO available from 802.11n onwards

IEEE802.11a-1999

- To increase the data rate, 802.11a uses OFDM.
- 20 MHz divided into 64 subcarriers (20000/312.5=64). 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.
- 802.11a OFDM has a symbol interval of 4μs → 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 4 different modulations: BPSK, QPSK, 16QAM, 64QAM
- 802.11a supports three coding rates, ½, 2/3, and ¾
- 802.11a supports 8 different data rates, 6 Mbps up to 54 Mbps, by selecting a combination of modulation and coding scheme (MCS)

IEEE802.11a-1999 Data Rates

MCS #	Modulation	Coding Rate	Coded bits per subcarrier	Coded bits per symbol	Data bits per symbol	Data Rate (Mbps)
0	BPSK	1/2	1	48	24	**6**
1	BPSK	3/4	1	48	36	**9**
2	QPSK	1/2	2	96	48	**12**
3	QPSK	3/4	2	96	72	**18**
4	16-QAM	1/2	4	192	96	**24**
5	16-QAM	3/4	4	192	144	**36**
6	64-QAM	2/3	6	288	192	**48**
7	64-QAM	3/4	6	288	216	**54**

IEEE 802.11g-2003

- 802.11a was great at max. data rate of 54Mbps, but
  - Only operates at 5GHz and not backward compatible with 11b
- 802.11g achieved 54Mbps at 2.4GHz using OFDM
  - And could fall back to 11b rates with CCK modulation
  - Was cheaper than 11a (2.4GHz radio had economy of scale)
- OFDM data rates are identical with 11a:
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbps
- CCK data rates:
  - 1, 2, 5.5, 11 Mbps

IEEE 802.11n-2009

MIMO in WiFi

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. The AP is expected to have more antennas than the mobile device

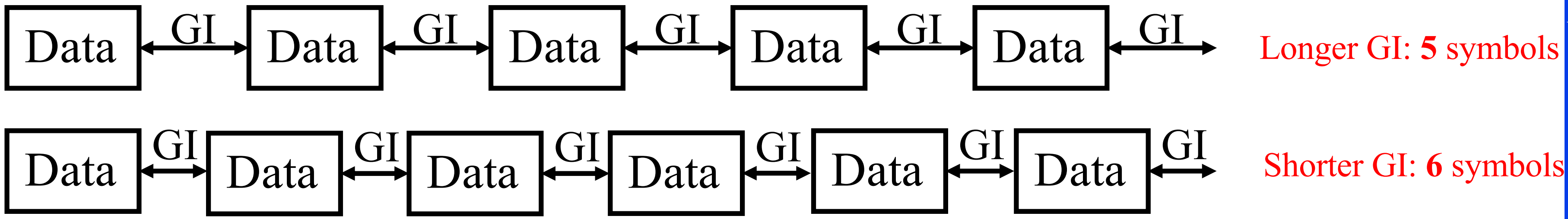
Other New Features of IEEE 802.11n-2009

1. **Frame Aggregation**: Pack multiple input frames inside a frame ⇒ Less overhead ⇒ More throughput
2. **Reduced Inter-Frame Spacing** (SIFS=2 μs, instead of 10 μs)
3. **Greenfield Mode**: Optionally eliminate support for a/b/g (shorter and higher rate preamble)
4. **Dual Band**: 2.4 and 5 GHz

   new coding rate (not available in previous WiFi)
5. **Lower FEC Overhead**: 5/6 instead of ¾
6. **Channel Bonding**: Combine two 20MHz channels to achieve 40MHz
7. **Shorter Guard Interval**: 400 ns instead of 800 ns
8. **More OFDM subcarriers**: Shorter GI in *time domain* enables less guard carriers in *frequency domain*
   - 4 instead of 6 guard carriers on either side of data carriers
   - 52 instead of 48 data carriers with 20 MHz legacy channels
   - 108 data carriers with 40MHz (no guard between two legacy channels)

     $52x2+4 = 108$

Guard Interval



- Rule of Thumb: Guard Interval = 4 × Multi-path delay spread
- Initial 802.11a design assumed 200ns delay spread
  $\Rightarrow$ 3200ns data + 800ns GI $\Rightarrow$ 20% overhead (800/4000=0.2)
- Most indoor environment have smaller delay spread ~50-75ns
- So if both Tx-Rx agree, 400ns GI can be used in 802.11n
  $\Rightarrow$ 3200ns data + 400ns GI $\Rightarrow$ 11.11% overhead (400/3600=11.11)

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

Example: 11n data rate improvement

- 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)?

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 =

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

Example: 802.11n maximum data rate

Question: Calculate the maximum achievable data rate for 802.11n

Answer:

Minimum guard interval: 400ns (data interval=3200ns) → 3.6µs symbol interval

Maximum modulation: 64 QAM

Maximum coding: 5/6

Maximum # of MIMO streams: 4 (4x4 MIMO)

Maximum # of data carriers: 108 (for 40MHz bonded channels)

Coded bits per symbol = $\log_2 64$ ✘ #-of-data-subcarriers = 6x108 = 648

Data bits per symbol = coding rate x 648 = 5/6 x 648 = 540

Symbol rate = 1/symbol-interval = 1/3.6Msps

Data rate (single MIMO stream) = symbol rate x data bits per symbol = 1/3.6 x 540 Mbps = **150 Mbps**

Data rate with 4 streams = 4 x 150 = 600 Mbps

802.11n Data Rates (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

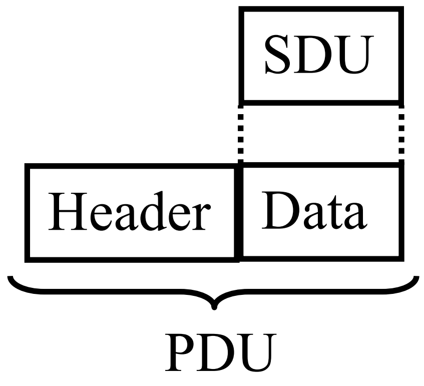
Source: https://www.cablefree.net/wirelesstechnology/wireless-lan/data-rates-in-802-11n/

Data rates for 802.11n (Multiple Streams)

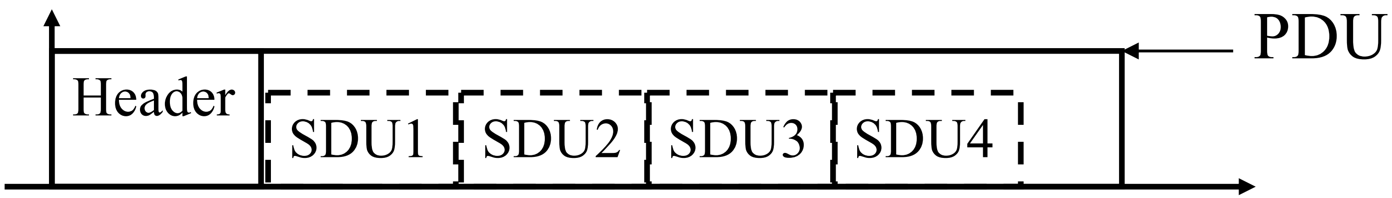
Source: https://www.cablefree.net/wirelesstechnology/wireless-lan/data-rates-in-802-11n/

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
8	2	BPSK	1/2	13	14.4	27	30
9	2	QPSK	1/2	26	28.9	54	60
10	2	QPSK	3/4	39	43.3	81	90
11	2	16-QAM	1/2	52	57.8	108	120
12	2	16-QAM	3/4	78	86.7	162	180
13	2	64-QAM	2/3	104	115.6	216	240
14	2	64-QAM	3/4	117	130	243	270
15	2	64-QAM	5/6	130	144.4	270	300
16	3	BPSK	1/2	19.5	21.7	40.5	45
17	3	QPSK	1/2	39	43.3	81	90
18	3	QPSK	3/4	58.5	65	121.5	135
19	3	16-QAM	1/2	78	86.7	162	180
20	3	16-QAM	3/4	117	130	243	270
21	3	64-QAM	2/3	156	173.3	324	360
22	3	64-QAM	3/4	175.5	195	364.5	405
23	3	64-QAM	5/6	195	216.7	405	450
24	4	BPSK	1/2	26	28.8	54	60
25	4	QPSK	1/2	52	57.6	108	120
26	4	QPSK	3/4	78	86.8	162	180
27	4	16-QAM	1/2	104	115.6	216	240
28	4	16-QAM	3/4	156	173.2	324	360
29	4	64-QAM	2/3	208	231.2	432	480
30	4	64-QAM	3/4	234	260	486	540
31	4	64-QAM	5/6	260	288.8	540	600

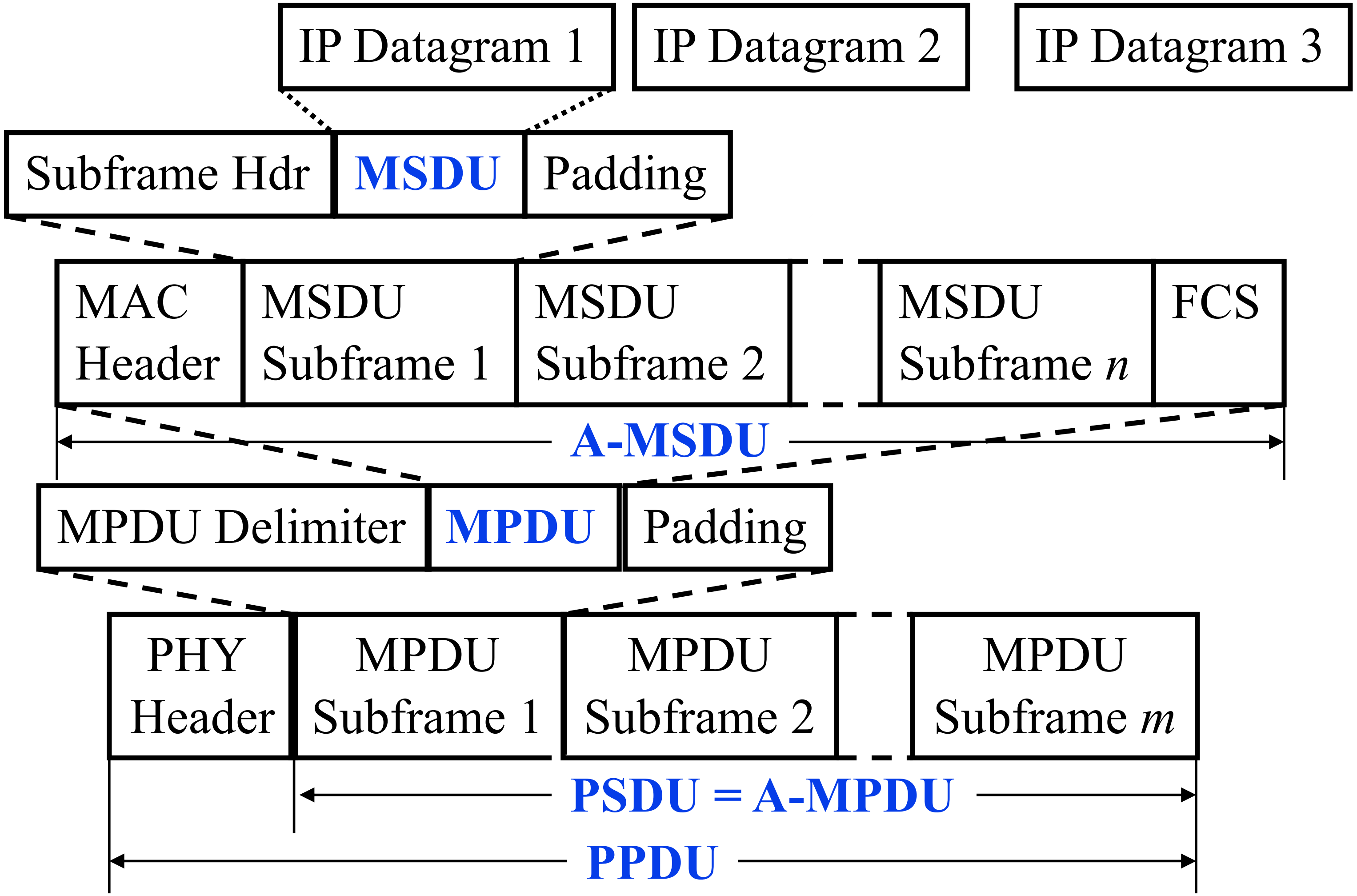
Frame Aggregation



- Each layer has Service Data Units (**SDUs**) as input
- Each layer makes Protocol Data Units (**PDUs**) as output to communicate with the corresponding layer at the other end
  - PDUs have a header specific to the layer (*header means overhead*)
- **Frame Aggregation**: Multiple SDUs in one PDU
  - All SDUs must have the same transmitter and receiver address

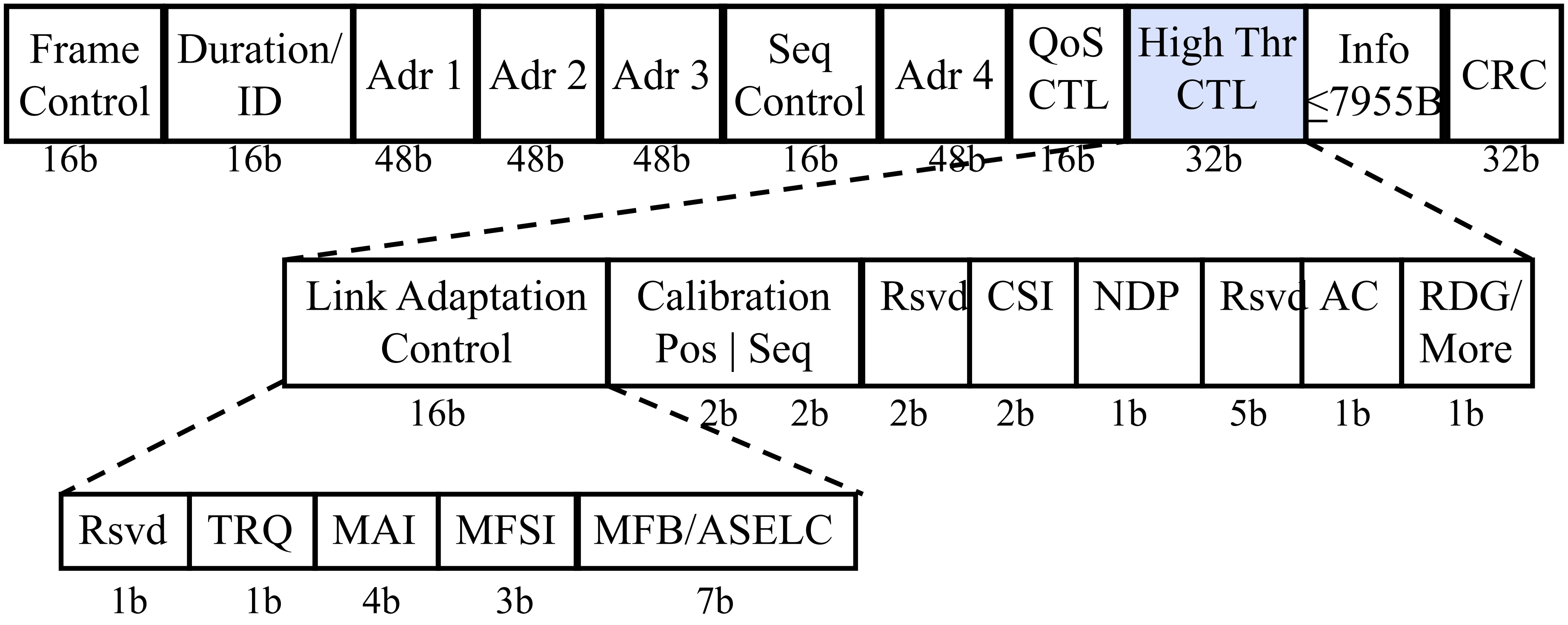


802.11n Frame Aggregation



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 CSI Feedback



- 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

IEEE 802.11ac-2013

IEEE 802.11ac

pilot subcarriers

- 5 GHz only (2.4 GHz not supported)
- Enhanced channel bonding: 20, 40, 80, 160 MHz channels
- More data subcarriers: 52+4 (20 MHz), 108+6 (40 MHz), 234+8 (80 MHz), 468+16 (160 MHz)
  - *More data subcarriers achieved due to wider channels*
  - *Subcarrier spacing remains 312.5 kHz (same as 11a/g/n)*
- Higher modulation: up to 256-QAM $\log_2 256 = 8$
- More MIMO streams: up to 8 streams allowed

needs 8 antennas
5GHz has smaller wavelength -> can pack more antennas because antennas are separated by lambda/2

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

Example: 802.11ac data rate (1)

Question: Calculate the maximum achievable data rate for an 802.11ac mobile client with a *single antenna*.

Answer:

Single antenna → only **1 stream** possible (even if the AP has many antennas)

Minimum guard interval: 400ns (data interval=3200ns) → 3.6μs symbol interval

Maximum modulation: 256 QAM

Maximum coding: 5/6

Maximum # of data carriers: 468 (for 160MHz bonded channels)

Coded bits per symbol = $\log_2 256$ ✘ #-of-data-subcarriers = 8x468 = 3744

Data bits per symbol = coding rate x 3744 = 5/6 x 3744 = 3120

Symbol rate = 1/symbol-interval = 1/3.6Msps

Data rate (single MIMO stream) = symbol rate x data bits per symbol = 1/3.6 x 3120 Mbps = **866.67 Mbps**

Example: 802.11ac data rate (2)

Question: An 802.11ac mobile client fitted with two antennas is connected to a wireless LAN via an 802.11ac access point equipped with four antennas. Calculate the maximum achievable data rate for the mobile client.

Answer:

Max. # of streams = min(2,4) = 2

Max. data rate with single stream(from previous example) = 866.67 Mbps

Therefore, max. data rate with 2 streams = 2x866.67 Mbps = 1.733 Gbps

802.11ac Data Rates in Mbps (Single Stream)

MCS index[b]	Modulation type	Coding rate	20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			800 ns GI	400 ns GI	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

Source: https://www.cablefree.net/wirelesstechnology/wireless-lan/data-rates-802-11ac/

Example: 802.11ac maximum data rate

Question: What is the maximum achievable data rate in 802.11ac?

Answer:

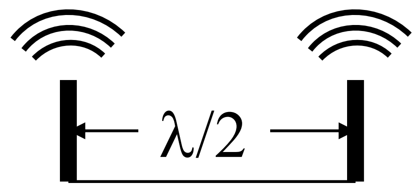
802.11ac allows a maximum of **8** MIMO streams

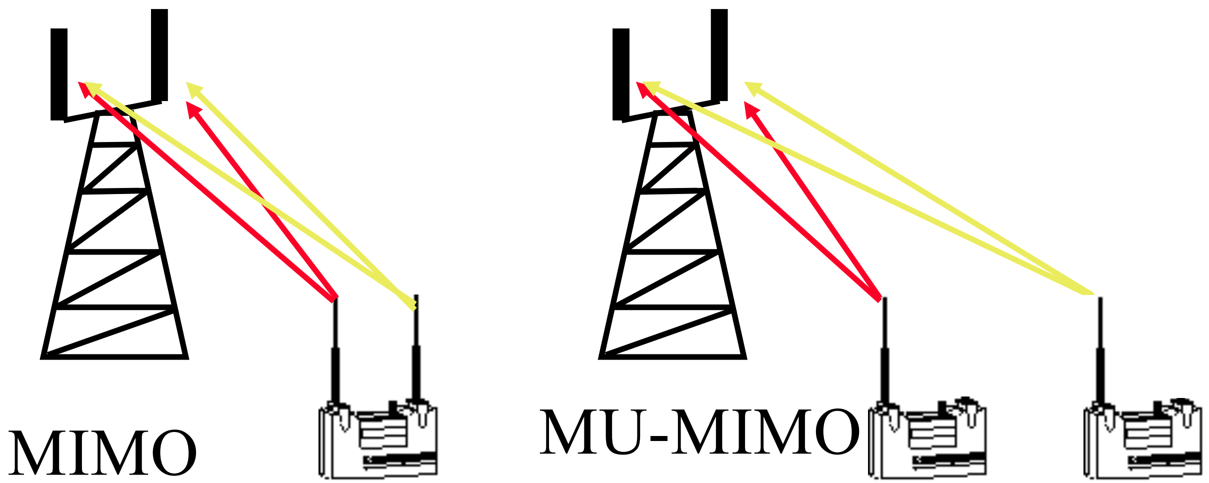
Maximum achievable with single stream = **866.67** Mbps

Maximum achievable data rate of 802.11ac = 8x866.67 = **6.9** Gbps

802.11ac supports Multi-User MIMO

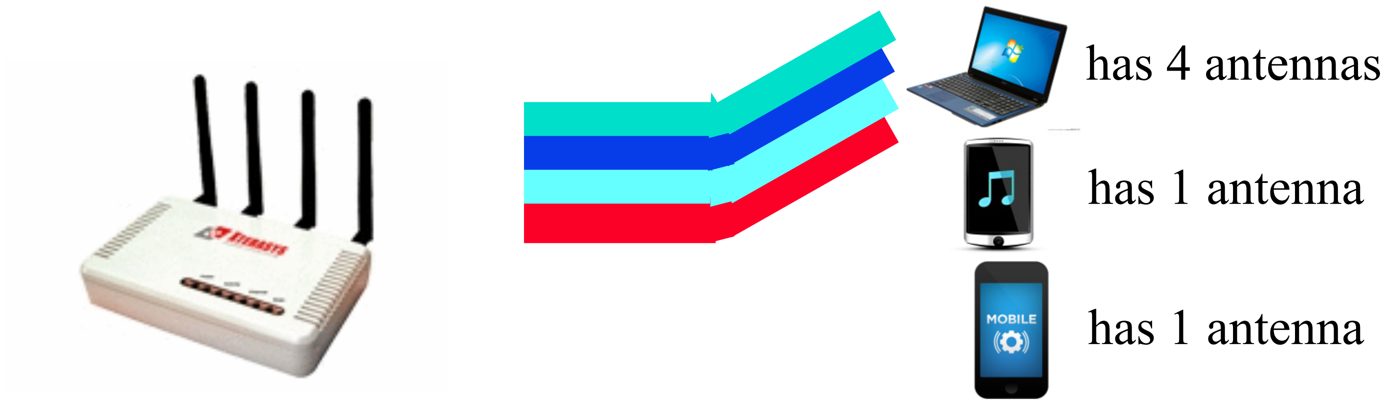
- **MIMO**: Multiple uncorrelated spatial beams
  Multiple antenna's separated by $\lambda/4$ or $\lambda/2$ (*absolute minimum*)
  - Cannot put too many antennas on a small device; also cost increases with number of antennas
- **MU-MIMO**: Two single-antenna users can act as one multi-antenna device. The users do not really need to know each other. They do not even know that their antennas are used in a MU-MIMO system!



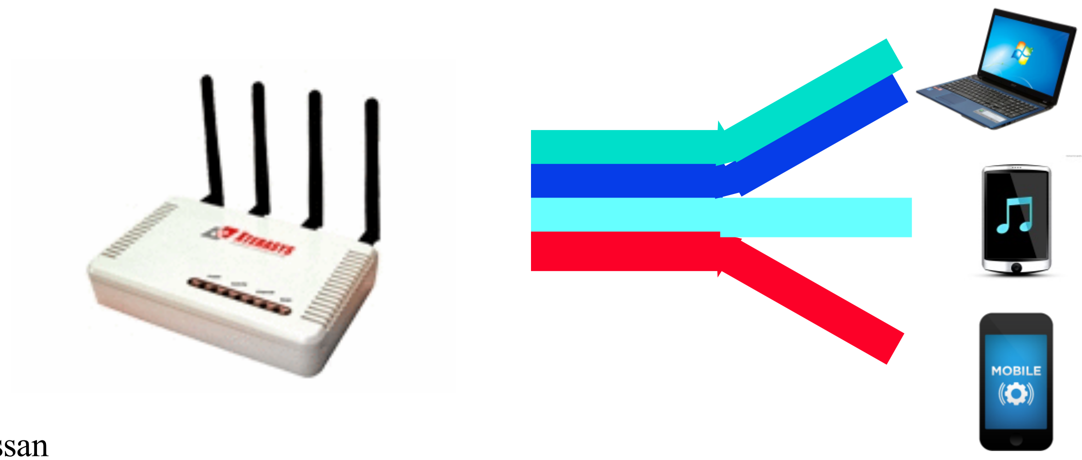


Directing streams with Beamforming in Multi-User MIMO

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

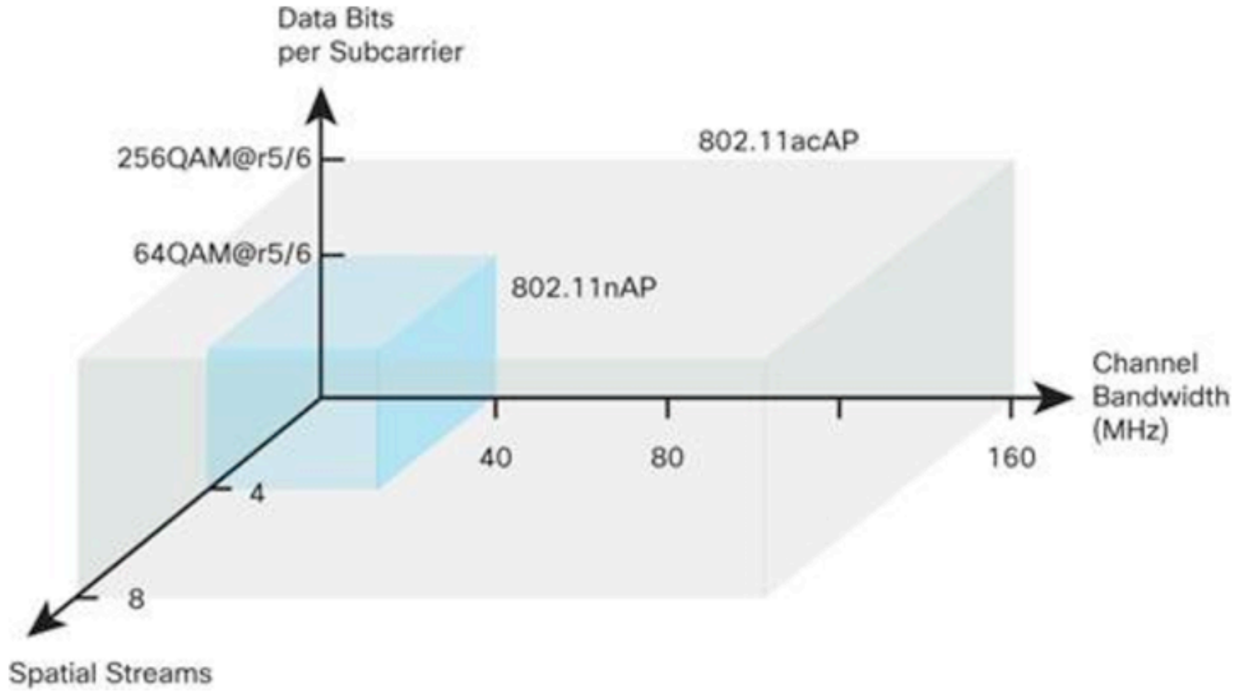


- **Multi User MIMO**:



802.11n vs. 802.11ac

Data Rate Enhancements in 3 Dimensions



[Affects # of data subcarriers]

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

IEEE 802.11ax-2020 (expected)

802.11ax High Efficiency (HE): Motivation

- Up until now, 802.11 evolution was purely driven by pushing the data rates and throughput (we were crazy about speed!)
  - From humble 2Mbps in 1997 (802.11 legacy) to ~7Gbps in 2013 (11ac) an increase of 3500x in just 16 years!
- WiFi has become so popular and dense that we cannot really use all that speed due to congestion, collisions, and interference
- Need a new WiFi that can work **efficiently** in dense deployments, in outdoors, for short message communications between IoT machines etc.
- 802.11ax is more about efficiency for such new environments than pushing the data rates
- 802.11ax has only a modest data rate increase of 37% against its predecessor 802.11ac; whereas 11ac increased data rate by 10x compared to 11n

Parameters of 802.11ax

- Supports both 2.4 and 5GHz bands
- No change for coding rate: 5/6 max.
- No change for channel width: 160 MHz max for 5GHz
  - Upto 40MHz for 2.4GHz band
- No change with MIMO stream numbers: 8 streams max.
- Increased modulation rate: 1024 QAM max.
- Increased symbol interval to address longer delay spread in challenging **outdoor** environments
  - Symbol data interval increased to 12.8µs (vs. 3.2µs in 11a/g/n/ac) overhead = 3.2/16 = 20%
  - Guard interval increased to 0.8µs, 1.6µs, or 3.2µs (3 options allowed)
- OFDM subcarrier spacing reduced to 78.125 kHz (vs. 312.5kHz in 11a/g/n/ac)
  - Total subcarriers: 256 (20MHz), 512 (40MHz), 1024 (80MHz), 2048 (160MHz)
  - Total subcarriers = data+pilot+guard+DC+null (5 types of subcarriers) two additional types
  - Data subcarriers = 234 (20MHz), 468 (40MHz), 980 (80MHz), 1960 (160MHz)

802.11ax OFDM Parameters

PHY	Modulation		R	N_{SS}	N_{SD}				T_{DFT}	T_{GI}		
	Name	N_{BPSCS}			20MHz	40MHz	80MHz	160MHz		Short	Medium	Long
802.11ax (HE)	BPSK	1	1/2	1 to 8	234	468	980	1960	12.8 μs	0.8 μs	1.2 μs	3.2 μs
	QPSK	2	1/2 & 3/4									
	16-QAM	4	1/2 & 3/4									
	64-QAM	6	1/2 & 2/3 & 3/4									
	256-QAM	8	2/3 & 5/6									
	1024-QAM	10	3/4 & 5/6									

N_{BPSCS}: number of coded bits per data subcarrier
R: coding rate
Nss: number of spatial streams
Nsd: number of data subcarriers
T_{DFT}: symbol data interval
T_{GI}: guard interval

Example: 802.11ax OFDM maximum data rate

Question: Calculate the maximum achievable data rate for 802.11ax OFDM

Answer:

Minimum guard interval: 0.8 ~~8~~μs (data interval=12.8μs) → 13.6μs symbol interval

Maximum modulation: 1024 QAM

Maximum coding: 5/6

Maximum # of MIMO streams: 8

Maximum # of OFDM data subcarriers: 1960 (for 160MHz channels)

Coded bits per symbol = $\log_2 1024$ ✘ #data-subcarriers = 10x1960 = 19600

Data bits per symbol = coding rate x 19600 = 5/6 x 19600 = 16333.33

Symbol rate = 1/symbol-interval = 1/13.6Msps

Data rate (single MIMO stream) = symbol rate x data bits per symbol = 1/13.6 x 5/6 x 19600 Mbps = **1.2 Gbps**

Data rate with 8 streams = 8 x 1.2 = 9.6 Gbps

802.11ax OFDM Data Rates in Mbps (Single Stream)

MCS index	Modulation type	Coding rate	Data rate (in Mb/s)							
			20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI
0	BPSK	1/2	4	4	8	9	17	18	34	36
1	QPSK	1/2	16	17	33	34	68	72	136	144
2	QPSK	3/4	24	26	49	52	102	108	204	216
3	16-QAM	1/2	33	34	65	69	136	144	272	282
4	16-QAM	3/4	49	52	98	103	204	216	408	432
5	64-QAM	2/3	65	69	130	138	272	288	544	576
6	64-QAM	3/4	73	77	146	155	306	324	613	649
7	64-QAM	5/6	81	86	163	172	340	360	681	721
8	256-QAM	3/4	98	103	195	207	408	432	817	865
9	256-QAM	5/6	108	115	217	229	453	480	907	961
10	1024-QAM	3/4	122	129	244	258	510	540	1021	1081
11	1024-QAM	5/6	135	143	271	287	567	600	1134	1201

Source: https://www.cablefree.net/wirelesstechnology/wireless-lan/802-11ax/

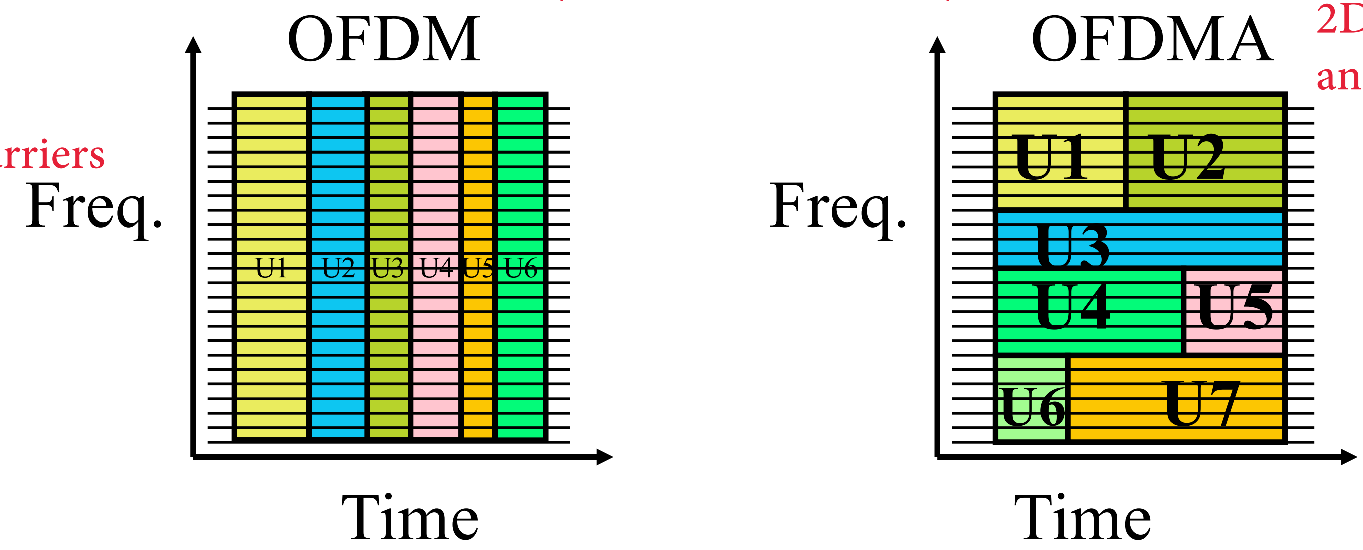
OFDMA: new access control for WiFi

- OFDMA: **O**rthogonal **F**requency **D**ivision **M**ultiple **A**ccess
- 802.11ax introduces OFDMA as an option to centrally allocate channel resources to each competing station using fine-grained time and frequency resource units (RUs) like cellular networks
- Channel bandwidth is first divided into many narrow subcarriers
  - Subcarrier spacing = 78.125kHz (vs. 312.5kHz in previous WiFi)
- Subcarriers are grouped into RUs called tones
- 26, 52, 106, 242, 484, or 996 tones per station. Each tone consist of a single subcarrier of 78.125 kHz bandwidth.
- Smallest resource allocated to an OFDMA communication: 26x78.125kHz = 2031.25kHz (~2MHz)
- Largest tone has: 996x78.125kHz = 77812.5kHz (~80MHz)
- A station can have a maximum of TWO 996 tones allocated

OFDMA Illustrated

1D allocation (only time, not frequency)

subcarriers



2D allocation (both time and frequency/subcarrier)

802.11ax RUs

RU type	20 MHz	40 MHz	80 MHz	160 (80+80) MHz
26-tone	9	18	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

$*^{+n}$ means "plus n 26-tone RUs".

Source: A Tutorial on IEEE 802.11ax High Efficiency WLANs, Khorov et al., IEEE Communications Surveys and Tutorial, 2019.

802.11ax OFDMA Parameters

PHY	Modulation		R	N_{SS}	N_{SD}						T_{DFT}	T_{GI}		
	Name	N_{BPSCS}			26-tone	52-tone	106-tone	242-tone	484-tone	996-tone		Short	Medium	Long
802.11ax (HE)	BPSK	1	1/2	1 to 8	24	48	102	234	468	980	12.8 μs	0.8 μs	1.2 μs	3.2 μs
	QPSK	2	1/2 & 3/4											
	16-QAM	4	1/2 & 3/4											
	64-QAM	6	1/2 & 2/3 & 3/4											
	256-QAM	8	2/3 & 5/6											
	1024-QAM	10	3/4 & 5/6											

HE OFDMA Parameters

N_{BPSCS}: number of coded bits per data subcarrier
R: coding rate
Nss: number of spatial streams
Nsd: number of data subcarriers
T_{DFT}: symbol data interval
T_{GI}: guard interval

802.11ax OFDMA Data Rates in Mbps (Single Stream)

				MU-OFDMA (802.11ax)																	
MCS Index	Spatial Stream	Modulation	Coding	26-tone RU			52-tone RU			106-tone RU			242-tone RU			484-tone RU			996-tone RU		
				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	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI
0	1	BPSQ	1/2	0.9	0.8	0.8	1.8	1.7	1.5	3.8	3.5	3.2	8.6	8.1	7.3	17.2	16.3	14.6	36.0	34.0	30.6
1	1	QPSK	1/2	1.8	1.7	1.5	3.5	3.3	3.0	7.5	7.1	6.4	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3
2	1	QPSK	3/4	2.6	2.5	2.3	5.3	5.0	4.5	11.3	10.6	9.6	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9
3	1	16-QAM	1/2	3.5	3.3	3.0	7.1	6.7	6.0	15.0	14.2	12.8	34.4	32.5	29.3	68.8	65.0	58.5	144.1	136.1	122.5
4	1	16-QAM	3/4	5.3	5.0	4.5	10.6	10.0	9.0	22.5	21.3	19.1	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8
5	1	64-QAM	2/3	7.1	6.7	6.0	14.1	13.3	12.0	30.0	28.3	25.5	68.8	65.0	58.5	137.6	130.0	117.0	288.2	272.2	245.0
6	1	64-QAM	3/4	7.9	7.5	6.8	15.9	15.0	13.5	33.8	31.9	28.7	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6
7	1	64-QAM	5/6	8.8	8.3	7.5	17.6	16.7	15.0	37.5	35.4	31.9	86.0	81.3	73.1	172.1	162.5	146.3	360.3	340.3	306.3
8	1	256-QAM	3/4	10.6	10.0	9.0	21.2	20.0	18.0	45.0	42.5	38.3	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5
9	1	256-QAM	5/6	11.8	11.1	10.0	23.5	22.2	20.0	50.0	47.2	42.5	114.7	108.3	97.5	229.4	216.7	195.0	480.4	453.7	408.3
10	1	1024-QAM	3/4	13.2	12.5	11.3	26.5	25.0	22.5	56.3	53.1	47.8	129.0	121.9	109.7	258.1	243.8	219.4	540.4	510.4	459.4
11	1	1024-QAM	5/6	14.7	13.9	12.5	29.4	27.8	25.0	62.5	59.0	53.1	143.4	135.4	121.9	286.8	270.8	243.8	600.5	567.1	510.4

Source: https://www.semfionetworks.com/blog/mcs-table-updated-with-80211ax-data-rates

Example: 802.11ax OFDMA Communication

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?

Answer:

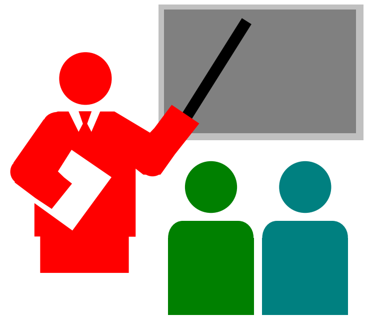
Single antenna means single stream

Maximum data rate for single-stream 26-tone (1024-QAM@5/6, 0.8μs GI) = 14.7Mbps

Data frame length in bits: 147x8 bits

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

Summary



1. 802.11a/g use OFDM with 64 subcarriers in 20 MHz. 48 Data, 4 Pilot, 12 guard.
2. 802.11n adds MIMO and channel bonding.
3. IEEE 802.11ac supports multi-user MIMO with 80+80 MHz channels with 256-QAM and 8 streams to give 6.9 Gbps
4. Multi-User MIMO allows several users with smaller number of antennas to be combined in a large MIMO pool.
5. 802.11ax introduces OFDMA for finer control and allocation of channel resources achieving high efficiency in dense deployments