

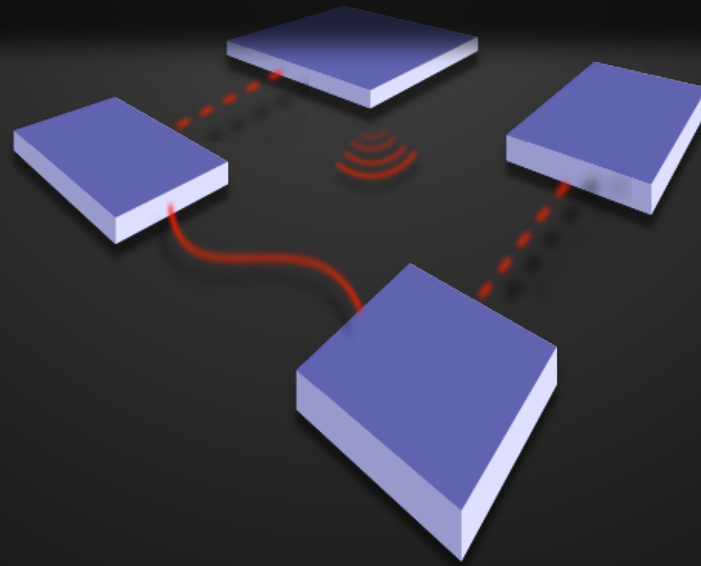
CS-435

spring semester 2025

Network Technology & Programming Laboratory

University of Crete
Computer Science Department

Stefanos Papadakis



CS-435

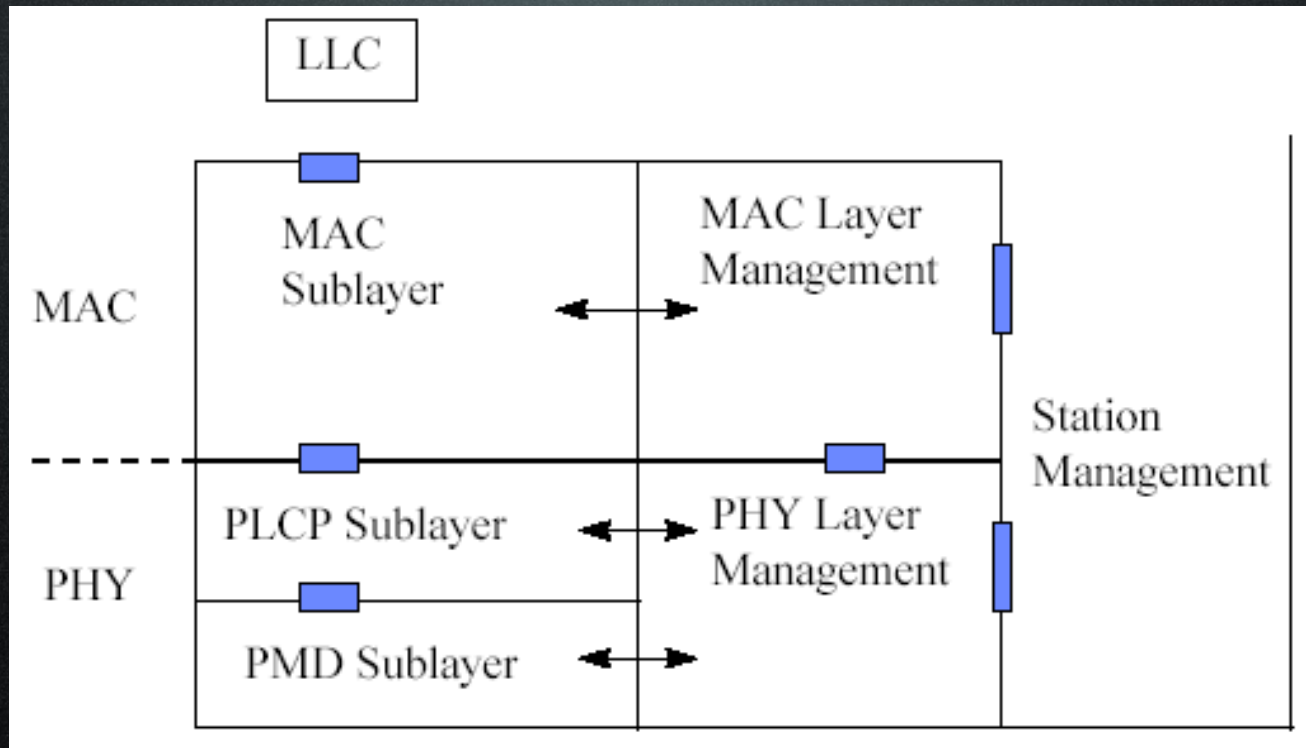
Lecture #12 preview

- IEEE 802.11 standards
- Channels, Spectra , Data Rates

IEEE 802.11 standards

	<i>802.11b</i>	<i>802.11a</i>	<i>802.11g</i>
Standard approved	July 1999	July 1999	June 2003
Maximum data rate	11 Mbps	54 Mbps	54 Mbps
Modulation	CCK	OFDM	OFDM and CCK
Data rates	1, 2, 5.5, 11 Mbps	6, 9, 12, 18, 24, 36, 48, 54 Mbps	CCK: 1, 2, 5.5, 11 OFDM: 6, 9, 12, 18, 24, 36, 48, 54 Mbps
Frequencies	2.4–2.497 GHz	5.15–5.35 GHz 5.425–5.675 GHz 5.725–5.875 GHz	2.4–2.497 GHz

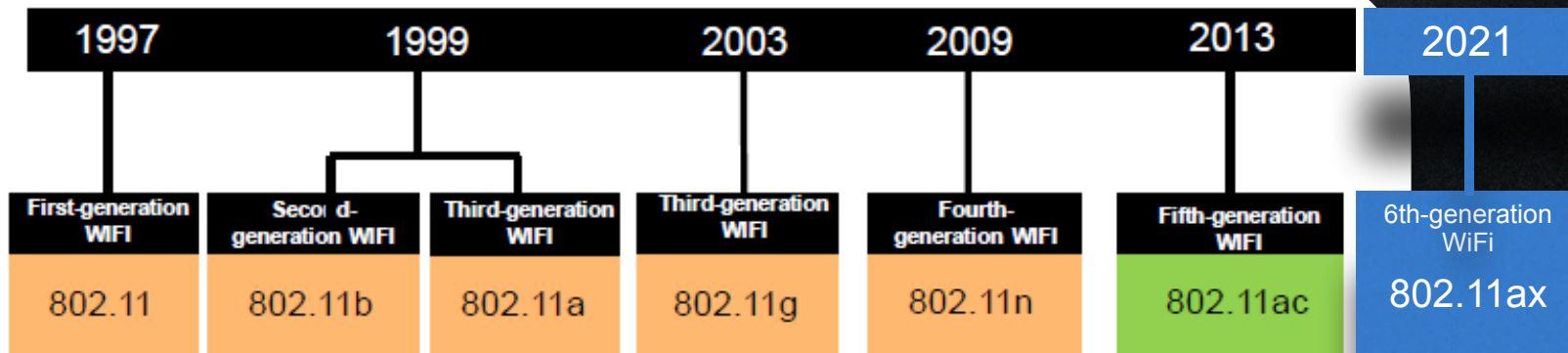
IEEE 802.11 stands here:



802.11 a/b/g/n/ac/... define

- MAC sublayer
 - access mechanisms, fragmentation, encryption
- MAC Management
 - roaming, MIB, power management
- PLCP sublayer
 - clear channel assessment signal (carrier sense)
- PMD sublayer
 - modulation, coding
- PHY Management
 - channel selection, Management Information Base(MIB)
- Station Management
 - coordination of all management functions

IEEE 802.11 history



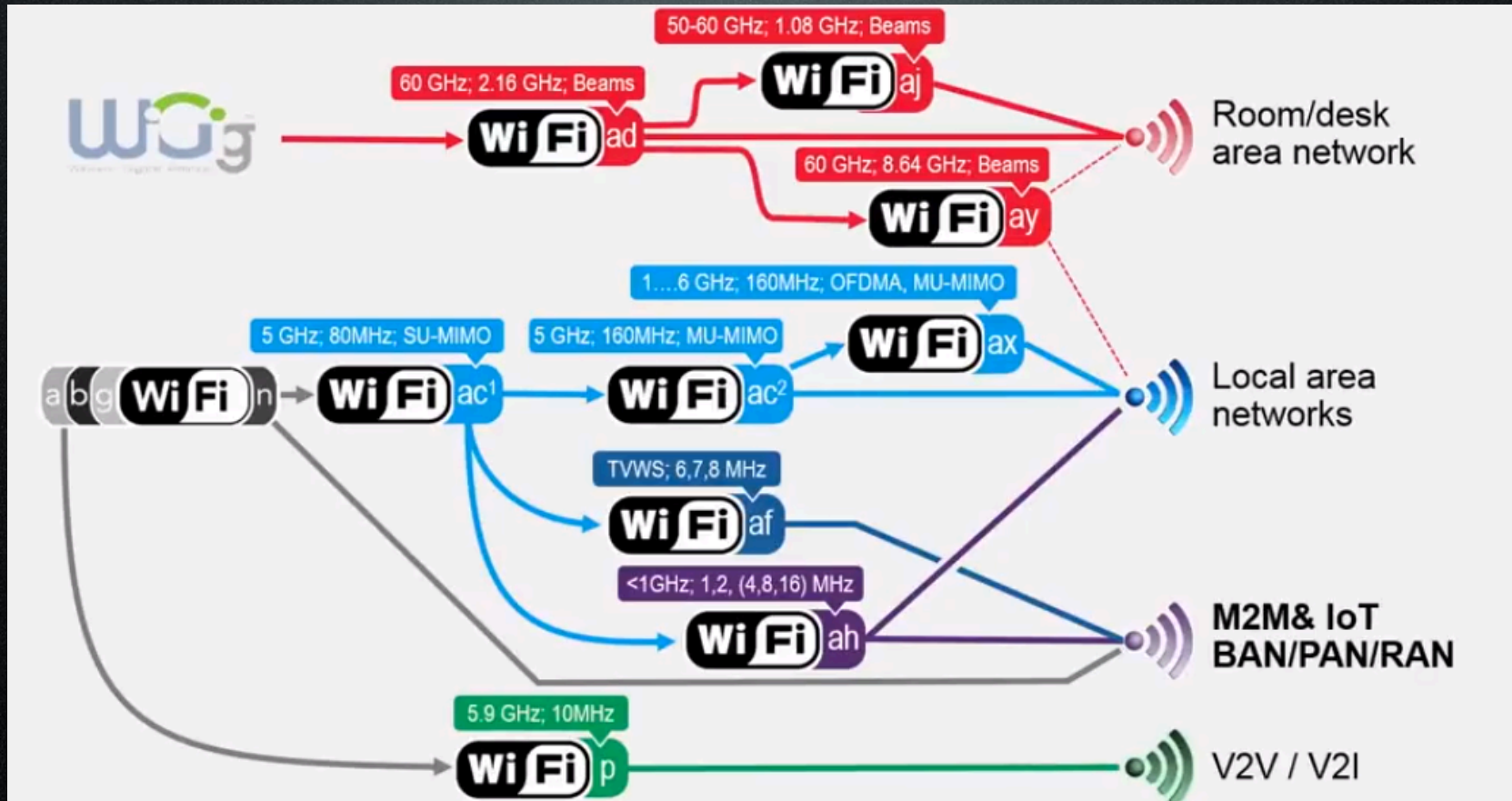
If the most advanced technology a device supports is ...	Then it shall be identified as generation
802.11ax	Wi-Fi 6
802.11ac	Wi-Fi 5
802.11n	Wi-Fi 4

IEEE 802.11 history

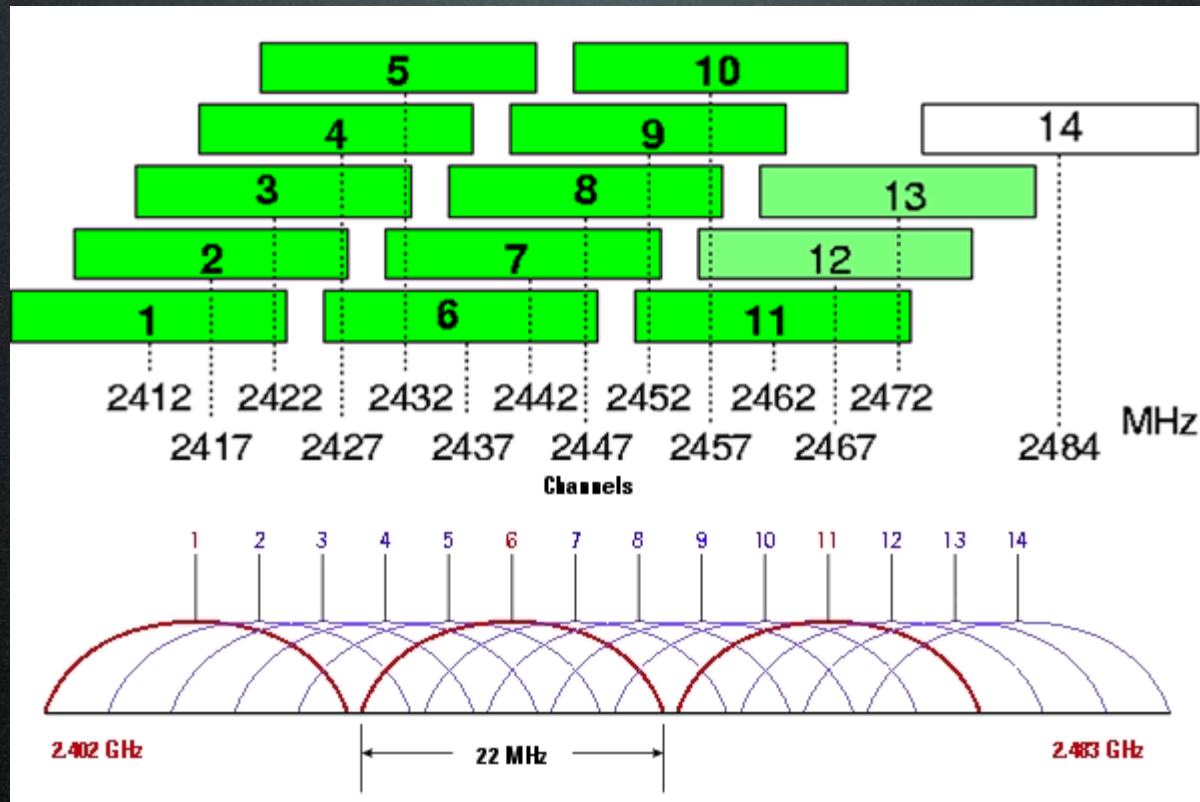
If the most advanced technology a device supports is ...	Then it shall be identified as generation
802.11ax	Wi-Fi 6
802.11ac	Wi-Fi 5
802.11n	Wi-Fi 4

Generation of network connection	Sample user interface visual
Wi-Fi 6	
Wi-Fi 5	
Wi-Fi 4	

IEEE 802.11 history

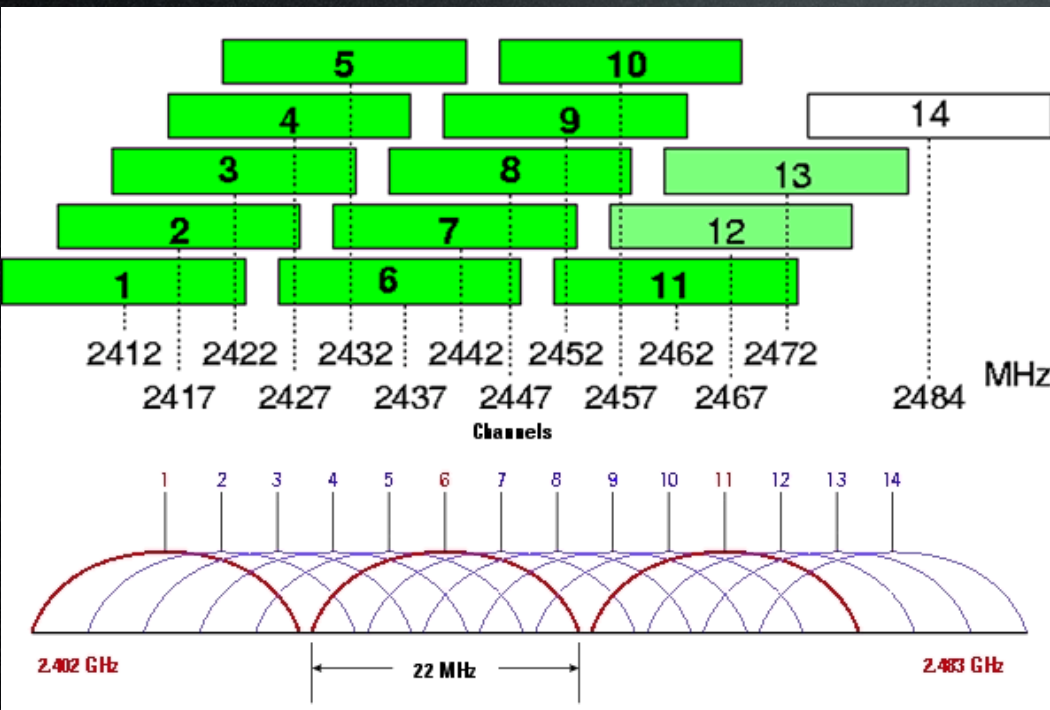


2.4GHz Channelization

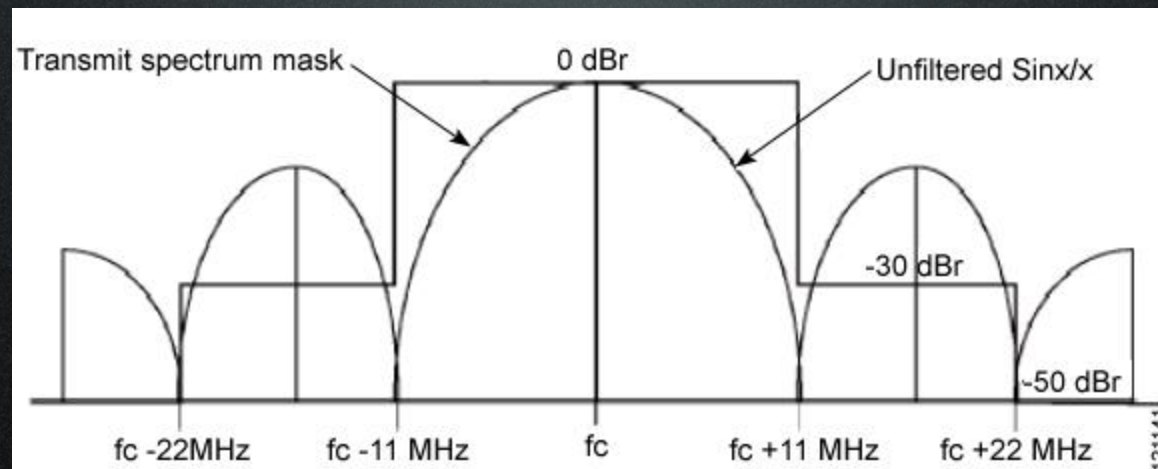


2.4GHz Channelization

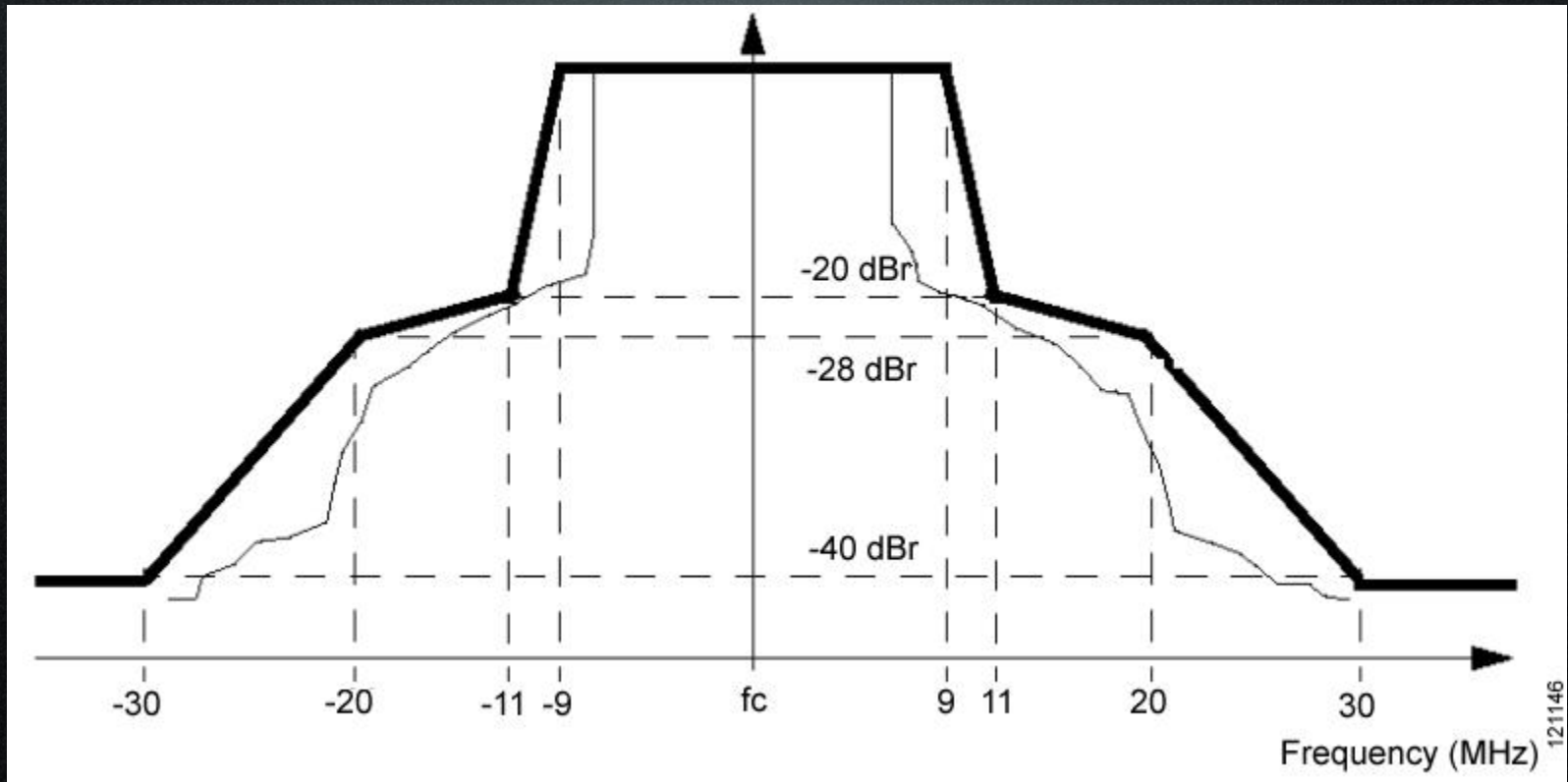
Channel	Frequency (GHz)	Range
1	2.412	2.401 - 2.423
2	2.417	2.406 - 2.428
3	2.422	2.411 - 2.433
4	2.427	2.416 - 2.438
5	2.432	2.421 - 2.443
6	2.437	2.426 - 2.448
7	2.442	2.431 - 2.453
8	2.447	2.436 - 2.458
9	2.452	2.441 - 2.463
10	2.457	2.446 - 2.468
11	2.462	2.451 - 2.473
12	2.467	2.456 - 2.478
13	2.472	2.461 - 2.483
14	2.484	2.473 - 2.495



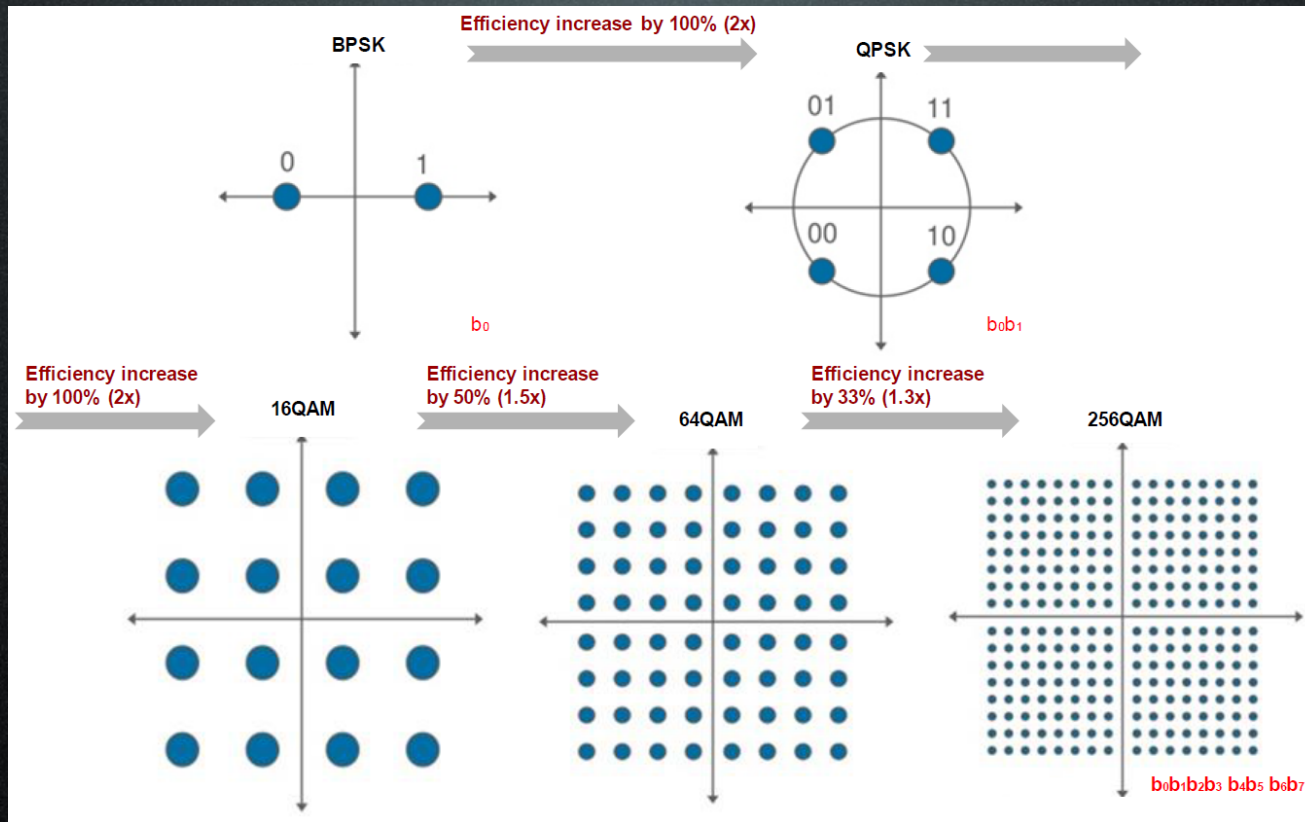
IEEE 802.11b spectrum mask



802.11a/g OFDM mask

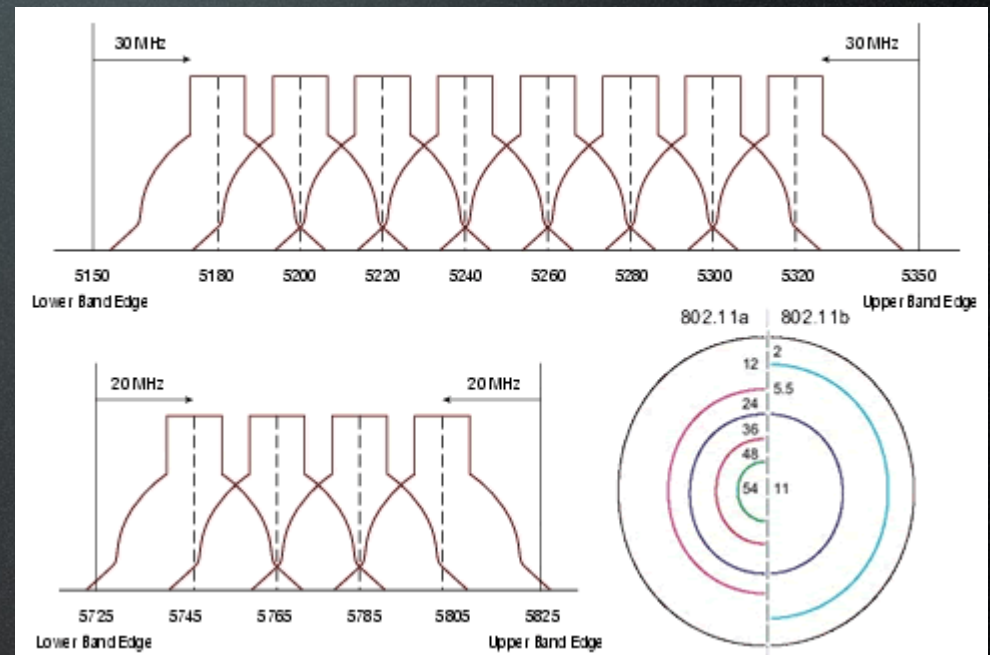


modulation

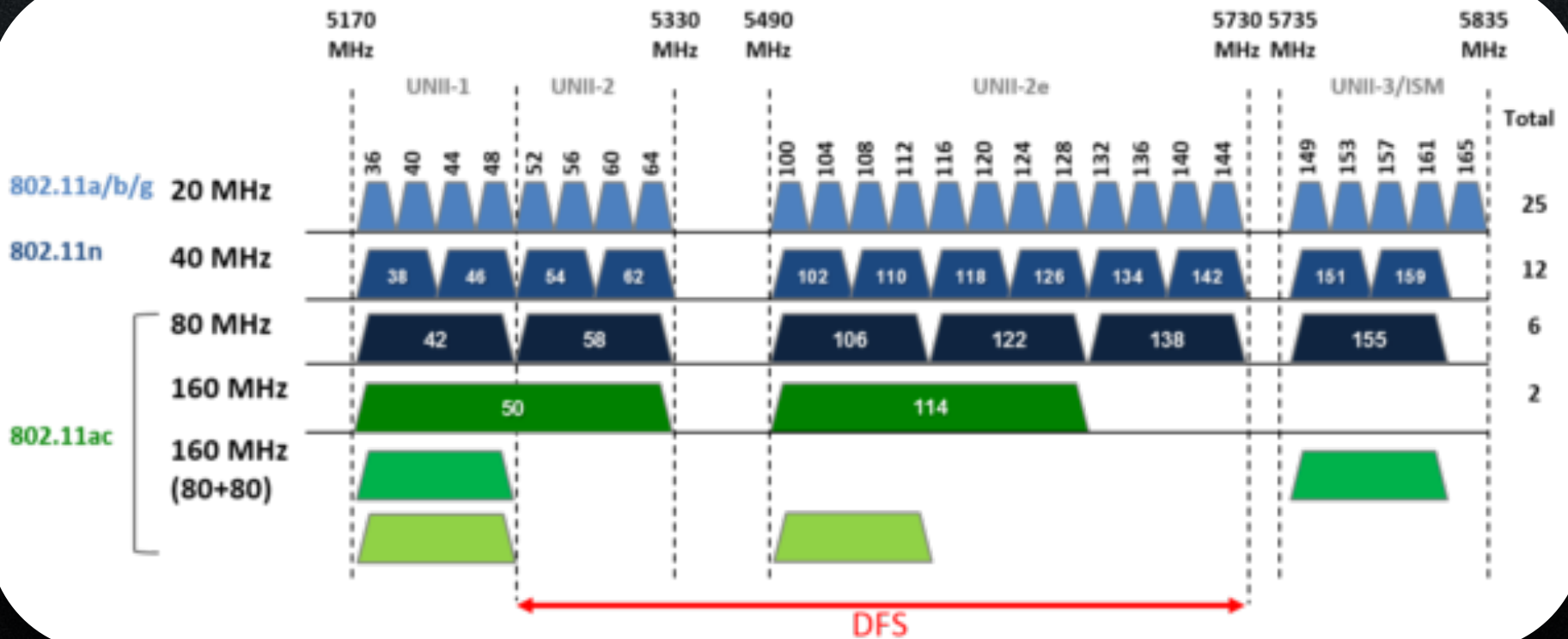


IEEE 802.11a channels

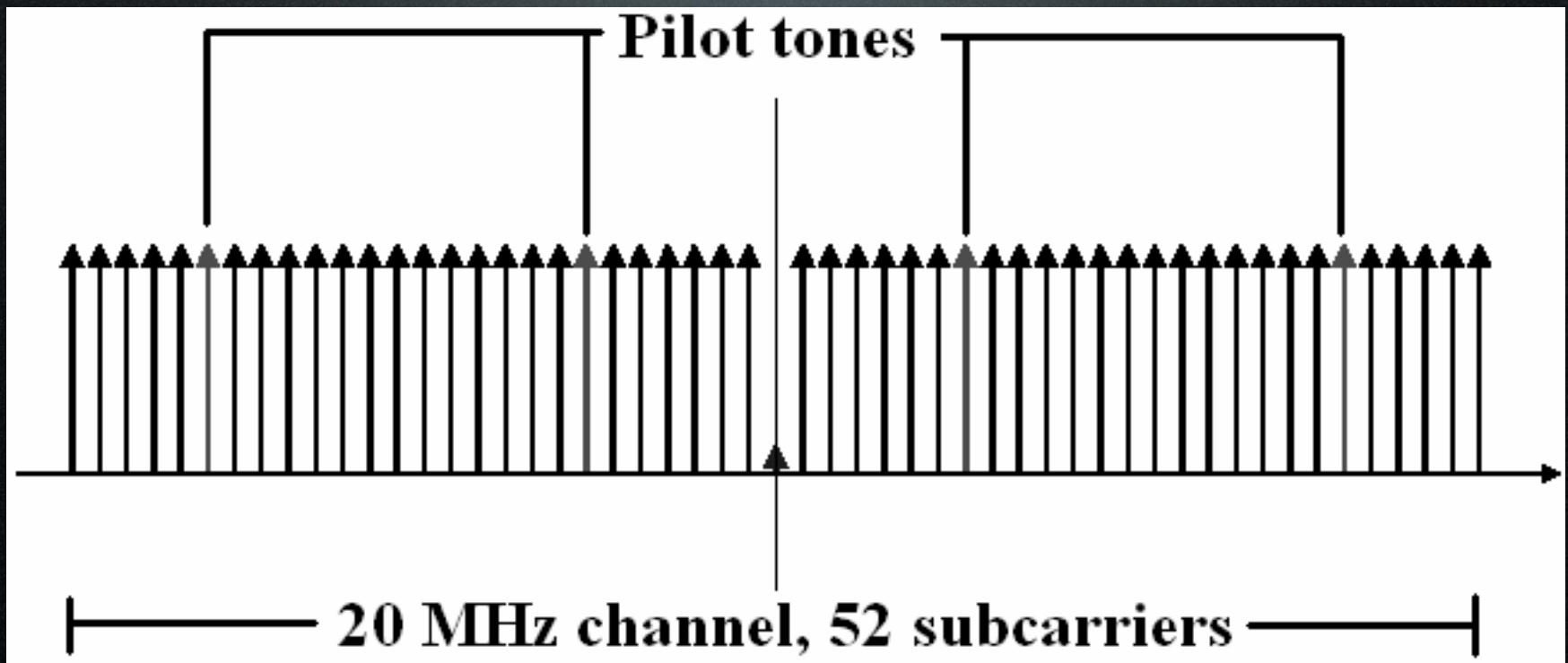
Frequency Band	Channel ID	FCC (GHz)	ETSI (GHz)
Lower Band (36 = default)	34	—	—
	36	5.180	5.180
	38	—	—
	40	5.200	5.200
	42	—	—
	44	5.220	5.220
	46	—	—
	48	5.240	5.240
Middle Band (52 = default)	52	5.260	5.260
	56	5.280	5.280
	58	5.300	5.300
	60	5.320	5.320
H Band	100	—	5.500
	104	—	5.520
	108	—	5.540
	112	—	5.560
	116	—	5.580
	120	—	5.600
	124	—	5.620
	128	—	5.640
	132	—	5.660
	136	—	5.680
	140	—	5.700
Upper Band (149 = default)	149	5.745	—
	153	5.675	—
	157	5.785	—
	161	5.805	—
ISM Band	165	5.825	—



5GHz Channelization



OFDM subcarriers



IEEE 802.11a/g rates & modulations

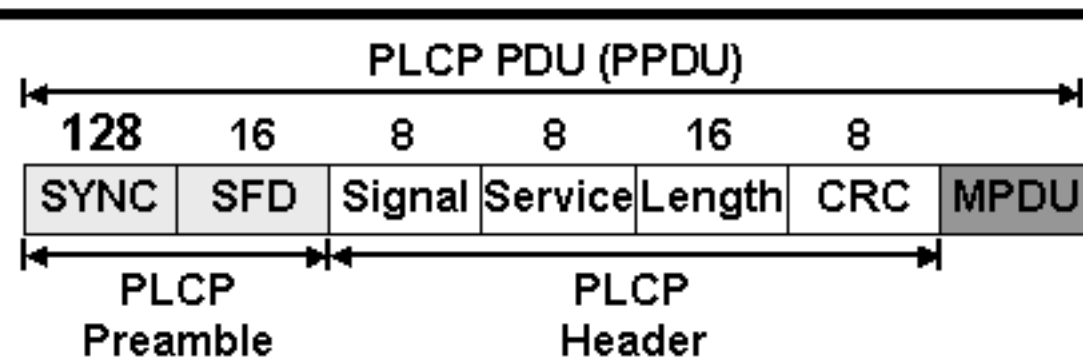
Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

802.11a 16QAM example

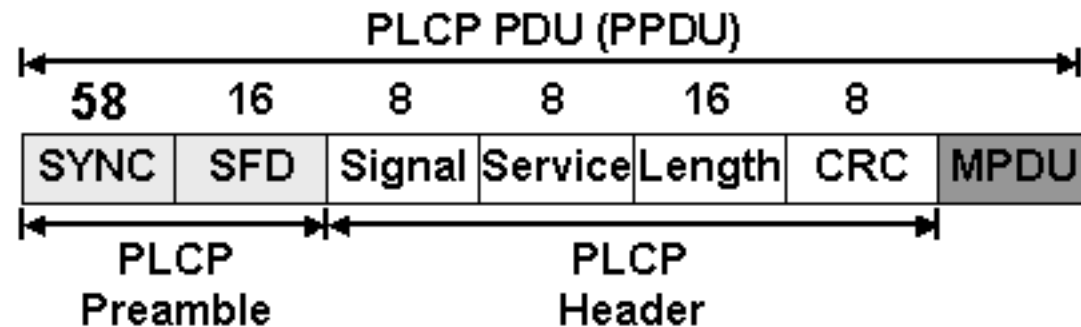
2	6	14	10
00 [.] 10	01 [.] 10	11 [.] 10	10 [.] 10
3	7	15	11
00 [.] 11	01 [.] 11	11 [.] 11	10 [.] 11
1	5	13	9
00 [.] 01	01 [.] 01	11 [.] 01	10 [.] 01
0	4	12	8
00 [.] 00	01 [.] 00	11 [.] 00	10 [.] 00
<u>Gray coded</u>			

802.11b Short/Long (PLCP) preamble

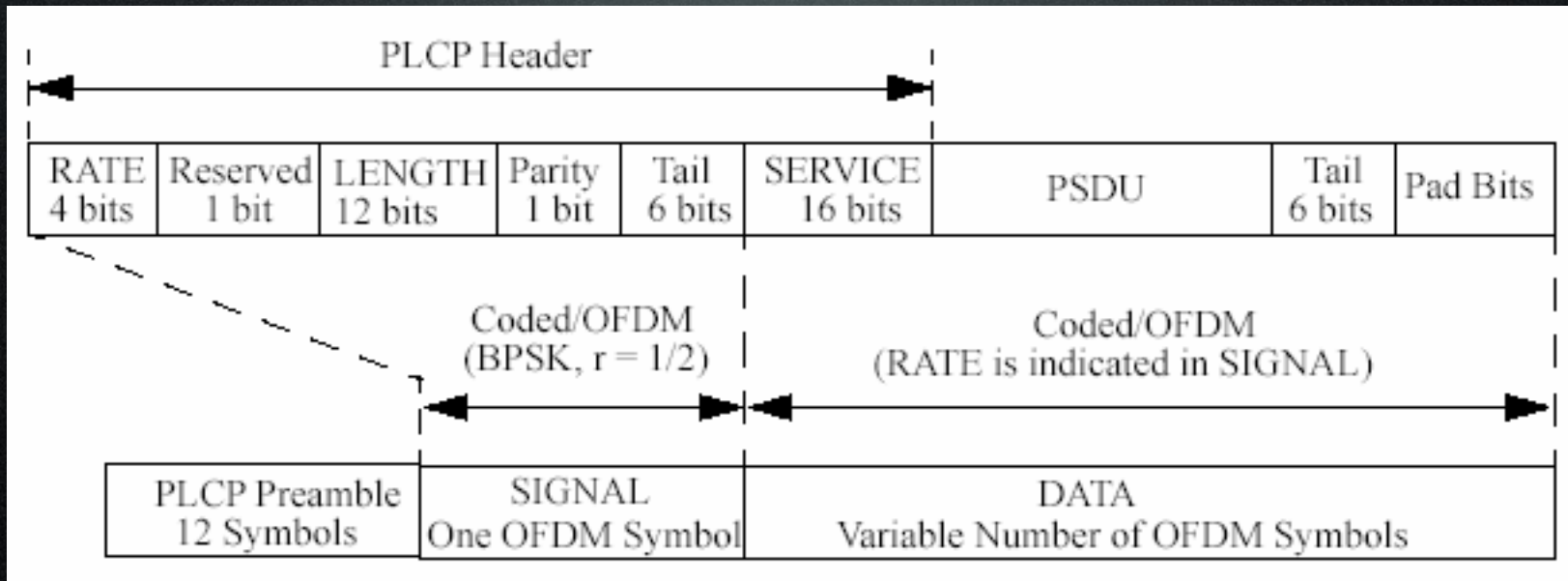
802.11b Long Preamble PLCP PDU



802.11b Short Preamble PLCP PDU



802.11a/g header



802.11a/b/g/n

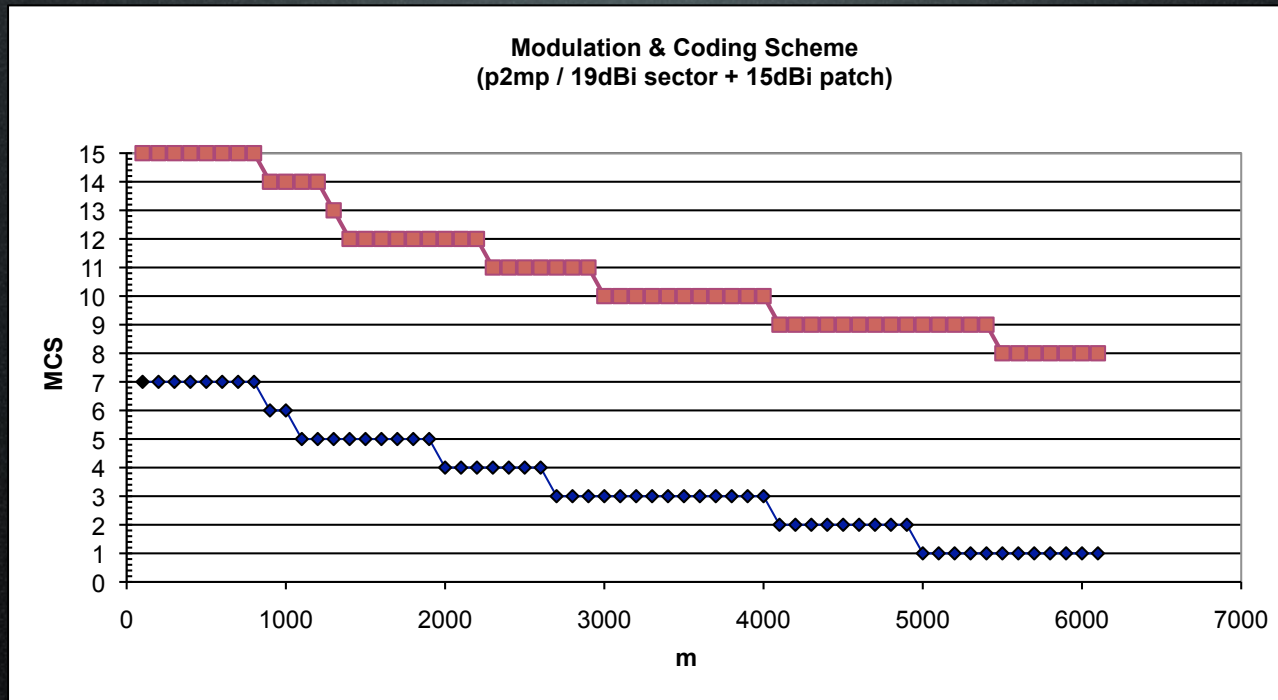
receive sensitivity

Receive Sensitivity	802.11b	802.11g	802.11a	
	-90 dBm @ 1 Mb/s -89 dBm @ 2 Mb/s -87 dBm @ 5.5 Mb/s -85 dBm @ 11 Mb/s	-87 dBm @ 6 Mb/s -86 dBm @ 9 Mb/s -83 dBm @ 12 Mb/s -82 dBm @ 18 Mb/s -81 dBm @ 24 Mb/s -80 dBm @ 36 Mb/s -75 dBm @ 48 Mb/s -74 dBm @ 54 Mb/s	-86 dBm @ 6 Mb/s -85 dBm @ 9 Mb/s -82 dBm @ 12 Mb/s -81 dBm @ 18 Mb/s -80 dBm @ 24 Mb/s -79 dBm @ 36 Mb/s -74 dBm @ 48 Mb/s -73 dBm @ 54 Mb/s	
	2.4-GHz	2.4-GHz	5-GHz	5-GHz
	802.11n (HT20)	802.11n (HT40)	802.11n (HT20)	802.11n (HT40)
	-86 dBm @ MC0	-86 dBm @ MC0	-85 dBm @ MC0	-85 dBm @ MC0
	-85 dBm @ MC1	-85 dBm @ MC1	-84 dBm @ MC1	-84 dBm @ MC1
	-84 dBm @ MC2	-84 dBm @ MC2	-83 dBm @ MC2	-83 dBm @ MC2
	-83 dBm @ MC3	-80 dBm @ MC3	-82 dBm @ MC3	-79 dBm @ MC3
	-80 dBm @ MC4	-77 dBm @ MC4	-79 dBm @ MC4	-76 dBm @ MC4
	-75 dBm @ MC5	-72 dBm @ MC5	-74 dBm @ MC5	-71 dBm @ MC5
	-74 dBm @ MC6	-71 dBm @ MC6	-73 dBm @ MC6	-70 dBm @ MC6
	-73 dBm @ MC7	-70 dBm @ MC7	-72 dBm @ MC7	-69 dBm @ MC7
	-86 dBm @ MC8	-86 dBm @ MC8	-85 dBm @ MC8	-85 dBm @ MC8
	-85 dBm @ MC9	-85 dBm @ MC9	-84 dBm @ MC9	-84 dBm @ MC9
	-84 dBm @ MC10	-84 dBm @ MC10	-83 dBm @ MC10	-83 dBm @ MC10
	-83 dBm @ MC11	-80 dBm @ MC11	-82 dBm @ MC11	-79 dBm @ MC11
	-80 dBm @ MC12	-77 dBm @ MC12	-79 dBm @ MC12	-76 dBm @ MC12
	-75 dBm @ MC13	-72 dBm @ MC13	-74 dBm @ MC13	-71 dBm @ MC13
	-74 dBm @ MC14	-71 dBm @ MC14	-73 dBm @ MC14	-70 dBm @ MC14
	-73 dBm @ MC15	-70 dBm @ MC15	-72 dBm @ MC15	-69 dBm @ MC15

802.11n

MCS index	type	coding rate	spatial streams	20MHz data rate (Mbps)		40MHz data rate (Mbps)	
				800ns	400ns	800ns	400ns
0	BPSK	1/2	1	6.50	7.20	13.50	15.00
1	QPSK	1/2	1	13.00	14.40	27.00	30.00
2	QPSK	3/4	1	19.50	21.70	40.50	45.00
3	16-QAM	1/2	1	26.00	28.90	54.00	60.00
4	16-QAM	3/4	1	39.00	43.30	81.00	90.00
5	64-QAM	2/3	1	52.00	57.80	108.00	120.00
6	64-QAM	3/4	1	58.50	65.00	121.50	135.00
7	64-QAM	5/6	1	65.00	72.20	135.00	150.00
8	BPSK	1/2	2	13.00	14.40	27.00	30.00
9	QPSK	1/2	2	26.00	28.90	54.00	60.00
10	QPSK	3/4	2	39.00	43.30	81.00	90.00
11	16-QAM	1/2	2	52.00	57.80	108.00	120.00
12	16-QAM	3/4	2	78.00	86.70	162.00	180.00
13	64-QAM	2/3	2	104.00	115.60	216.00	240.00
14	64-QAM	3/4	2	117.00	130.00	243.00	270.00
15	64-QAM	5/6	2	130.00	144.40	270.00	300.00

802.11n



path loss exp.= 2.3
fade margin= 5dB

IEEE 802.11ac

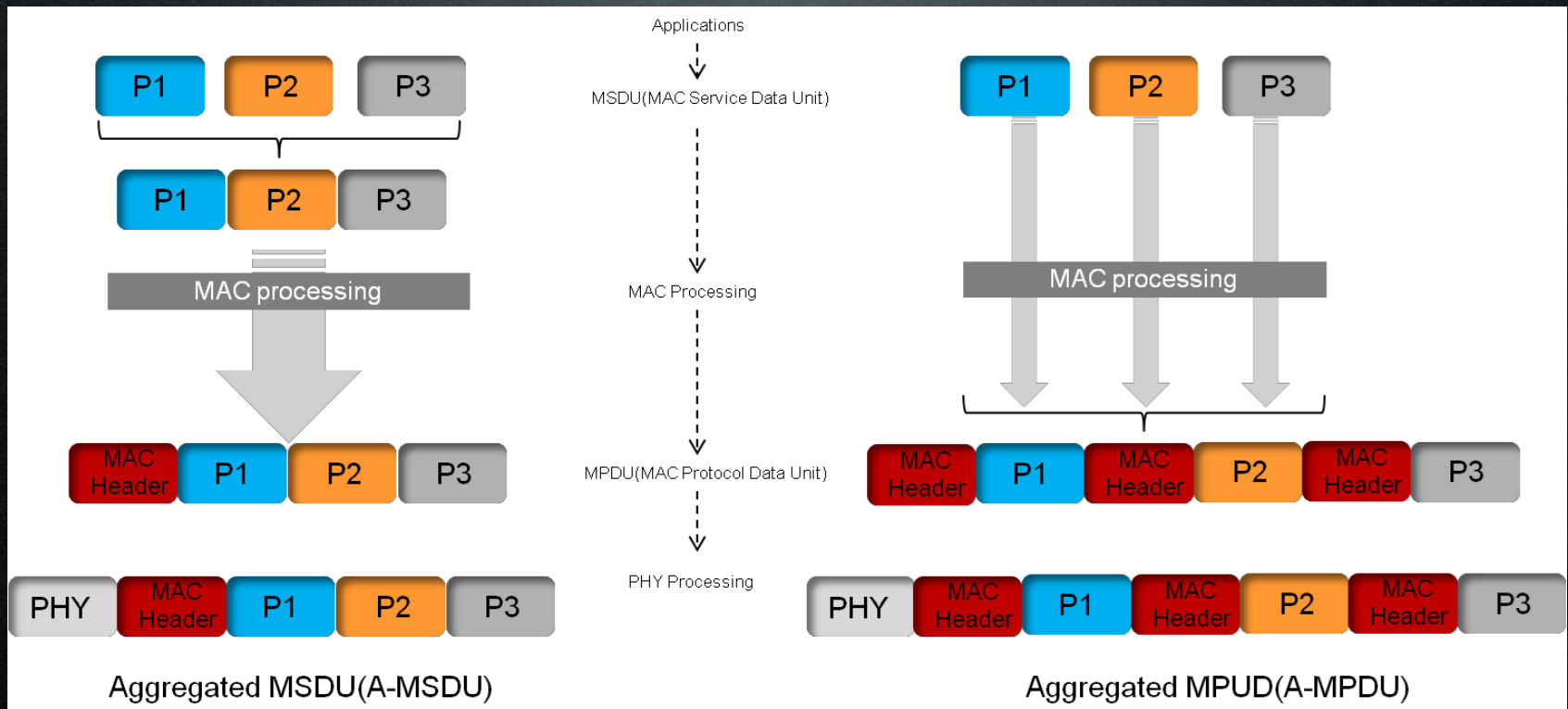
Item	802.11n	802.11ac Wave 1 (Wi-Fi Alliance)	802.11ac Wave 2 (Wi-Fi Alliance)
Channel Bandwidth	20/40 MHz	20/40/80 MHz	20/40/80/80 MHz - 80/160 MHz
Modulation Mode	64-QAM	256-QAM	256-QAM
Spatial Streams	3 (4 as specified by the standard)	3	4
Frequency Band	2.4 GHz and 5 GHz	5 GHz	5 GHz
Theoretical Transmission Rate	450 Mbit/s, 600 Mbit/s as specified by the standard	1.3 Gbit/s	3.47 Gbit/s

PHY	Aggregation	Max Bytes (Layer 2)	Max Bytes (Layer 1)	Max Data Rate	Throughput
802.11b	NO	2304	2336	11 Mbit/s	5-6 Mbit/s
802.11a/g	NO	2304	2336	54 Mbit/s	20-25 Mbit/s
802.11n	YES	7935	65535	450 Mbit/s	270 Mbit/s
802.11ac	YES	11454	1048575	1.3 Gbit/s	800 Mbit/s

IEEE 802.11ac

Item	802.11ac Wave1 (WFA)	802.11ac Wave 2 (WFA)	802.11ac (IEEE)
Band	5 GHz	5 GHz	5 GHz
MIMO	Single User (SU)	Multi User (MU)	Multi User (MU)
Channel width	20, 40, and 80 MHz	20, 40, 80, 80+80, and 160 MHz	20, 40, 80, 80+80, and 160 MHz
Modulation	256QAM	256QAM	256QAM
Spatial streams	3	4	8
PHY rate	1.3 Gbps	3.47 Gbps	6.9 Gbps

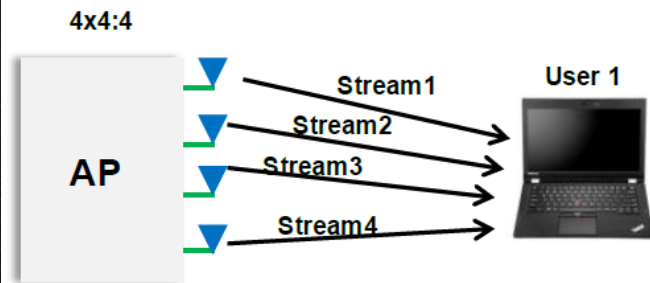
IEEE 802.11ac



IEEE 802.11ac

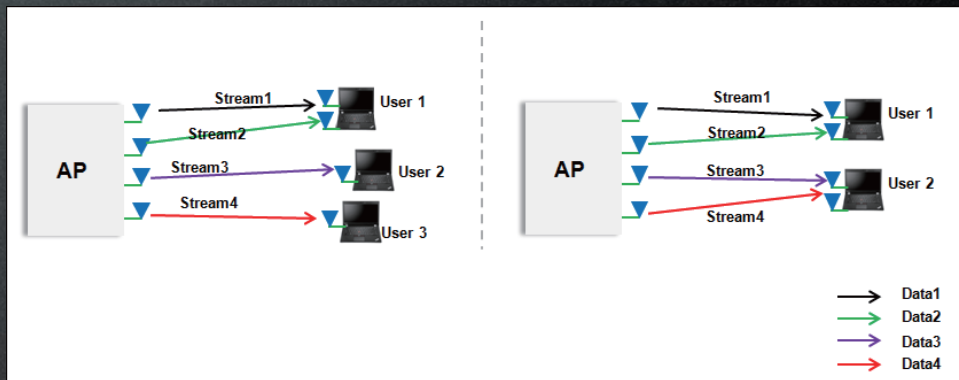
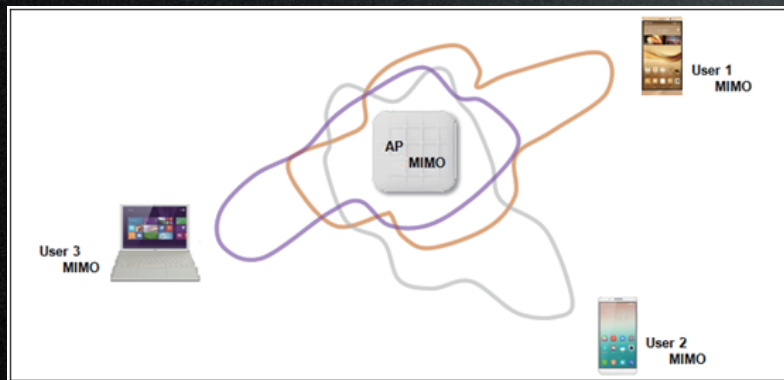
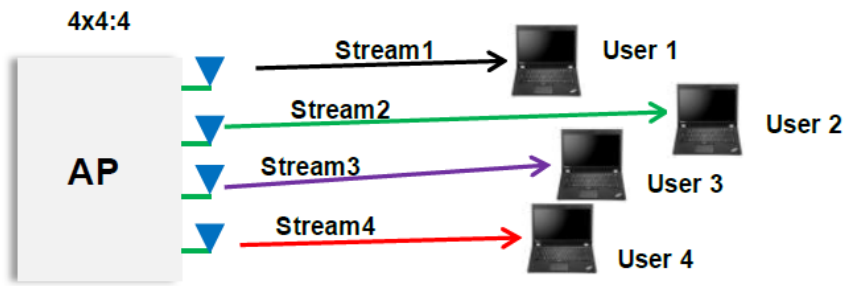
Single-user MIMO

Data can be sent to only one user at one time.



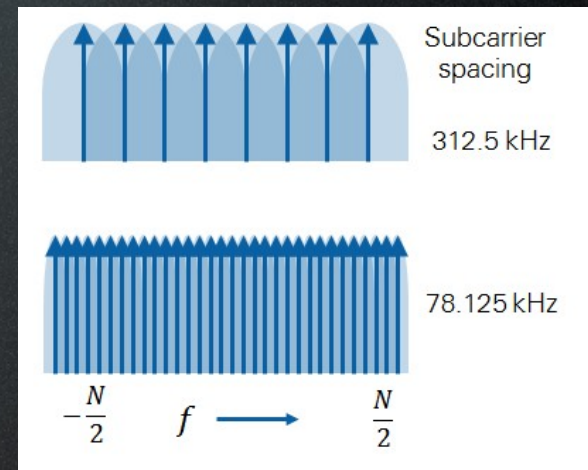
Multi-user MIMO

Data can be sent to four users simultaneously at one time.

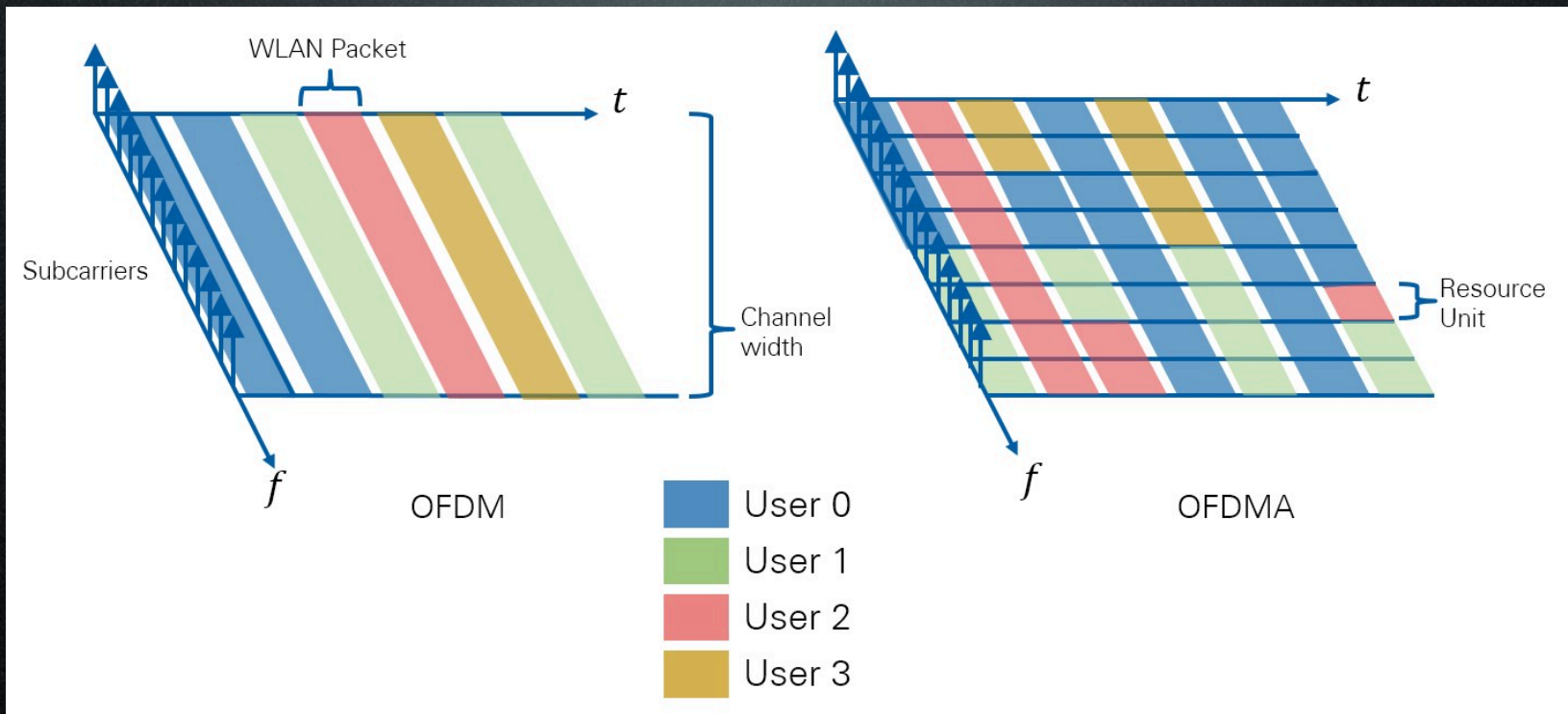


IEEE 802.11ax

	802.11ac	802.11ax
BANDS	5 GHz	2.4 GHz and 5 GHz
CHANNEL BANDWIDTH	20 MHz, 40 MHz, 80 MHz, 80+80 MHz & 160 MHz	20 MHz, 40 MHz, 80 MHz, 80+80 MHz & 160 MHz
FFT SIZES	64, 128, 256, 512	256, 512, 1024, 2048
SUBCARRIER SPACING	312.5 kHz	78.125 kHz
OFDM SYMBOL DURATION	3.2 us + 0.8/0.4 us CP	12.8 us + 0.8/1.6/3.2 us CP
HIGHEST MODULATION	256-QAM	1024-QAM
DATA RATES	433 Mbps (80 MHz, 1 SS) 6933 Mbps (160 MHz, 8 SS)	600.4 Mbps (80 MHz, 1 SS) 9607.8 Mbps (160 MHz, 8 SS)



IEEE 802.11ax



Rate Adaptation

Rate Adaptation Algorithms/Metrics:

- Probe Packets
 - ARF
 - AARF
 - SampleRate
- Consecutive successes/losses
 - ARF
 - AARF
 - Hybrid Algorithm
- Physical Layer metrics
 - Hybrid Algorithm
 - RBAR
 - OAR
- Long-term statistics
 - ONOE

ARF

Auto Rate Fall-back (ARF)

- Start data transmission at the highest bit-rate.
- If f consecutive packet transmissions fail at the current bit-rate, set the current rate to the next lower bit-rate.
- If s consecutive packet transmissions succeed at the current bit-rate, set the current rate to the next higher bit-rate.
- Otherwise continue at the same bit-rate.

In the current implementations of ARF $s = 10$, $f = 2$.

AARF

Implements a binary-exponential back-off procedure.

- Transmits a probe packet at the next higher bit-rate after encountering a (threshold number) of consecutive successful packet transmissions s at the current bit-rate.
- If the probe packet transmission fails, the number of consecutive successful packet transmissions required at the current bit-rate before the next probe packet is sent is doubled, up to a (maximum value)
- If the probe packet transmission is successful, the current bit-rate is set to the bit-rate at which the probe was sent.
- If f consecutive packet transmissions fail at the current bit-rate, set the current bit-rate to the next lower bit-rate.

In the current implementation s (initial) = 10, f = 2 and $s(\text{max})=50$.