Communication Systems
Wi-Fi (IEEE 802.11 WLAN) Part 2

WS 2025/2026@THI

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WS 2025/2026 Wi-Fi Lecture Topics

Part 1 (2025-11-25):
- Introduction
- Wi-Fi Architecture
- Wi-Fi Specifications
- Wi-Fi Spectrum
- Wireless Channel
- Wi-Fi PHY Evolution

Part 2 (2025-11-28):
- Wi-Fi PHY Layer
- Wi-Fi PHY Q&A

Part 3 (2025-12-02):
- Wi-Fi MAC Layer
- Wi-Fi MAC Layer Q&A
- Wi-Fi QoS

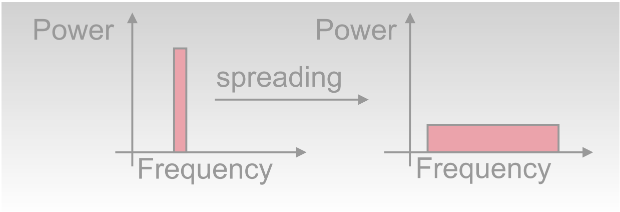
Part 4 (2025-12-05):
- Wi-Fi Security
- Wi-Fi Security Q&A

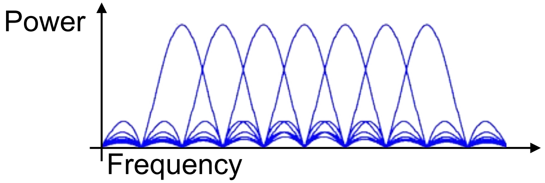
Key takeaways of the last lecture

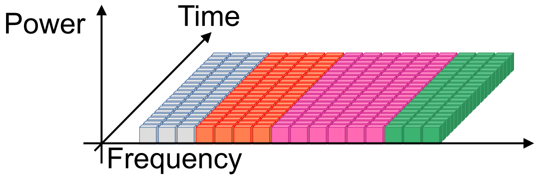
- Wi-Fi market:
  - ~ 4000 mio shipments per year, smartphones biggest segment, IoT most growing
- Specifications:
  - IEEE 802.11 (technical amendments) & Wi-Fi Alliance (compatibility, certification)
- Basic architectural terms:
  - STA, AP, BSS, BSSID, ESS, SSID, distribution system (DS)
- Generational notation of radio evolution:
  - Wi-Fi 4 … Wi-Fi 7, formerly through related IEEE 802.11 spec, e.g. ‘a’, ‘b’, ‘g’, ‘n’, ..
- Unlicensed spectrum:
  - 2.4 GHz, 5 GHz, 6 GHz; transmission power limits given in EIRP, device categories
- Radio signal propagation issues:
  - path-loss, reflection, diffraction, scattering
  - free-space path-loss model, delay spread, selective fading

IEEE802.11 PHY layer solutions for 2.4 GHz, 5 GHz, 6 GHz

- 2.4 GHz Direct Sequence Spread Spectrum (1997)
  - DBPSK/DQPSK providing 1/2 Mbps
  - Channel bandwidth: 22 MHz
- 2.4 GHz High Rate DSSS **(1999: 802.11b – Wi-Fi 1)**
  - CCK/DQPSK providing 5.5/11 Mbps
  - Channel bandwidth: 22 MHz
- 5 GHz Orthogonal Frequency Division Multiplex **(1999: 802.11a – Wi-Fi 2)**
  - OFDM providing 6/9/12/18/24/36/48/54 Mbps
  - Channel bandwidth: 20 MHz
- 2.4 GHz Extended Rate **(2003: 802.11g – Wi-Fi 3)**
  - DSSS providing 1/2/5.5/11 Mbps
  - OFDM providing 6/9/12/18/24/36/48/54 Mbps
  - Channel bandwidth: 22/20 MHz
- 2.4 GHz & 5 GHz High Throughput **(2009: 802.11n – Wi-Fi 4)**
  - OFDM with up to 4x4 MIMO providing up to 600 Mbps
  - Channel bandwidth: 20 MHz & 40 MHz
- 5 GHz Very High Throughput **(2013: 802.11ac – Wi-Fi 5)**
  - OFDM with up to 8x8 DL MU-MIMO providing up to 6900 Mbps (3460 Mbps to single STA)
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz
- 1 – 7.25 GHz High Efficiency **(2021: 802.11ax – Wi-Fi 6)**
  - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 9600 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz
- 1 – 7.25 GHz Extremely High Throughput **(2024: 802.11be – Wi-Fi 7)**
  - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 23 000 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz, 320 MHz

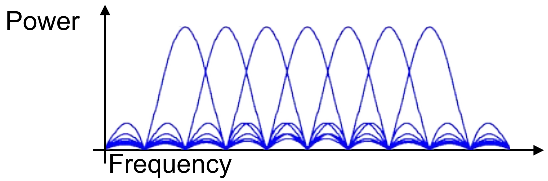




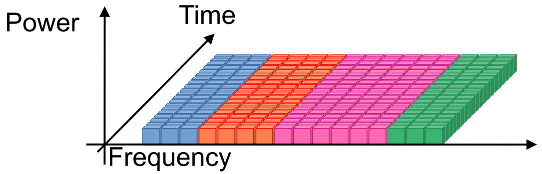


IEEE802.11 PHY layer solutions for 2.4 GHz, 5 GHz, 6 GHz

Step-wise evolution of features and performance



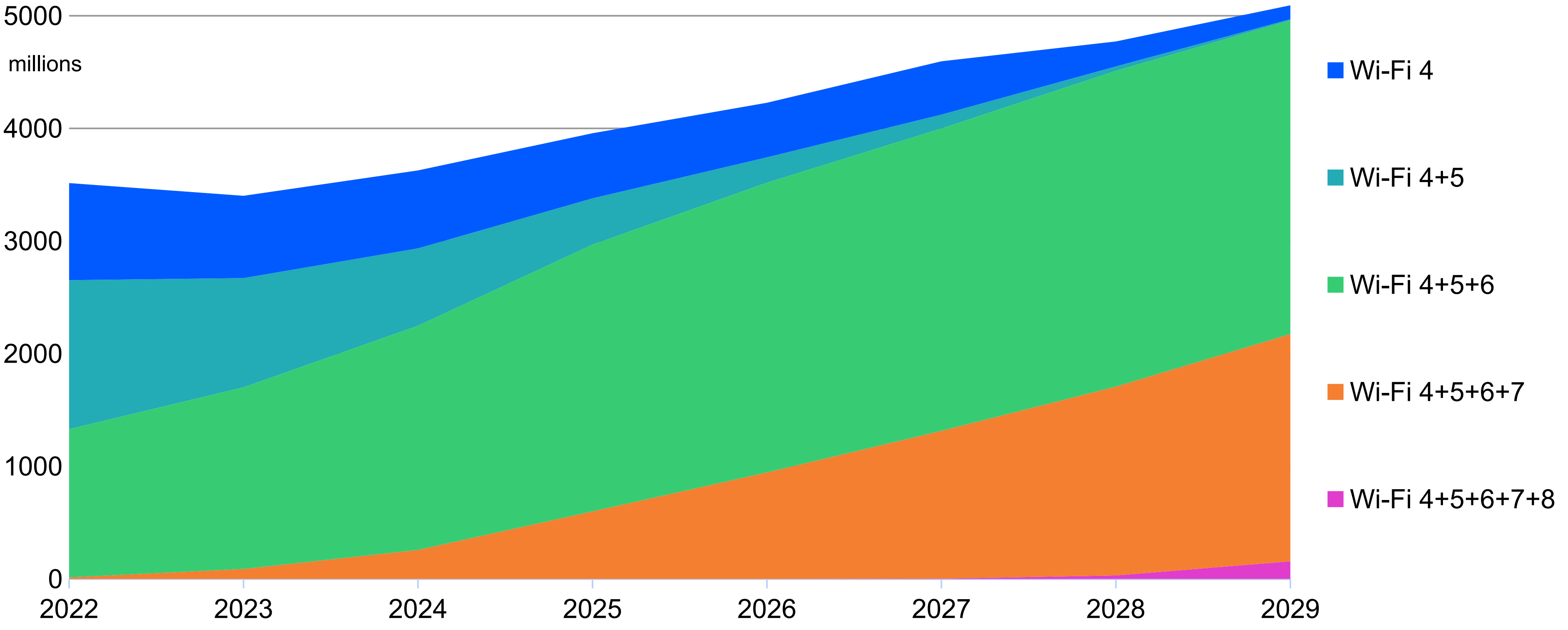
- 2.4 GHz & 5 GHz High Throughput (***802.11n – Wi-Fi 4***)
  - OFDM with up to **4x4 MIMO** providing up to 600 Mbps
  - Channel bandwidth: 20 MHz & **40 MHz**
- 5 GHz Very High Throughput (***802.11ac – Wi-Fi 5***)
  - OFDM with up to **8x8 DL MU-MIMO** providing up to 6900 Mbps (3460 Mbps to single STA)
  - Channel bandwidth: 20 MHz, 40 MHz, **80 MHz, 160 MHz**



- 1 – 7.25 GHz High Efficiency (***802.11ax – Wi-Fi 6***)
  - OFDM/**OFDMA** with up to **8x8 MU-MIMO** providing up to 9600 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz
- 1 – 7.25 GHz Extremely High Throughput (***802.11be – Wi-Fi 7***)
  - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 23 000 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz, **320 MHz**

Wi-Fi growth is driven by backward compatible generations

Yearly Wi-Fi chipset shipments, world market



Source: ABIresearch Q3/2024

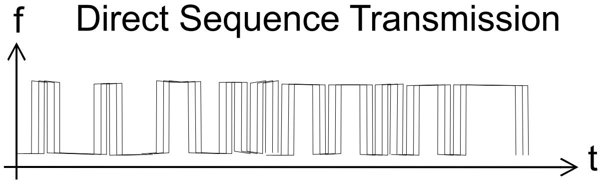
Wi-Fi PHY Layer

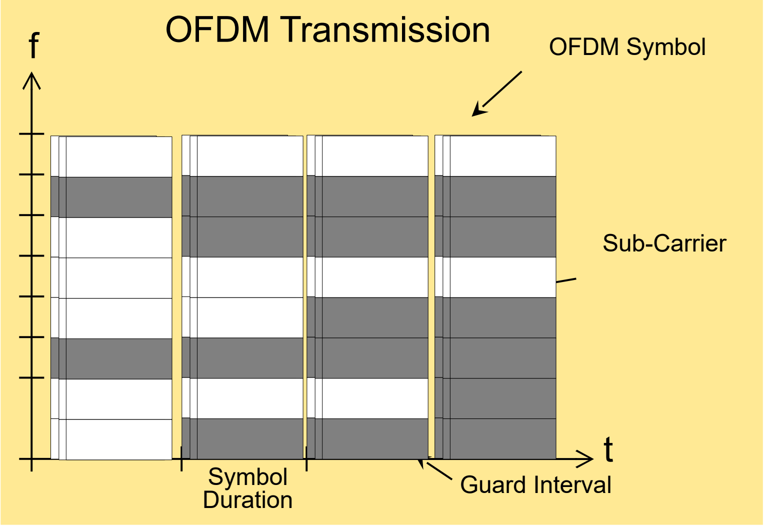
OFDM - ORTHOGONAL FREQUENCY DIVISION MULTIPLEX

Mitigating Delay Spread Channels

- More robust transmission by transformation of high speed bit sequences into a slower sequence of complex symbols

	D	e	m	o
ASCII	68	101	109	111
128	0	0	0	0
64	1	1	1	1
32	0	1	1	1
16	0	0	0	0
8	0	0	1	1
4	1	1	1	1
2	0	0	0	1
1	0	1	1	1

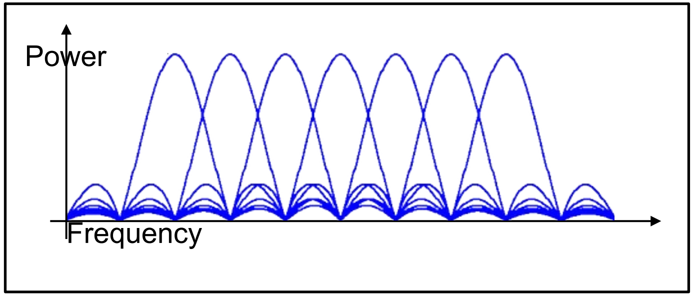




Wi-Fi PHY Layer

OFDM FOUNDATION

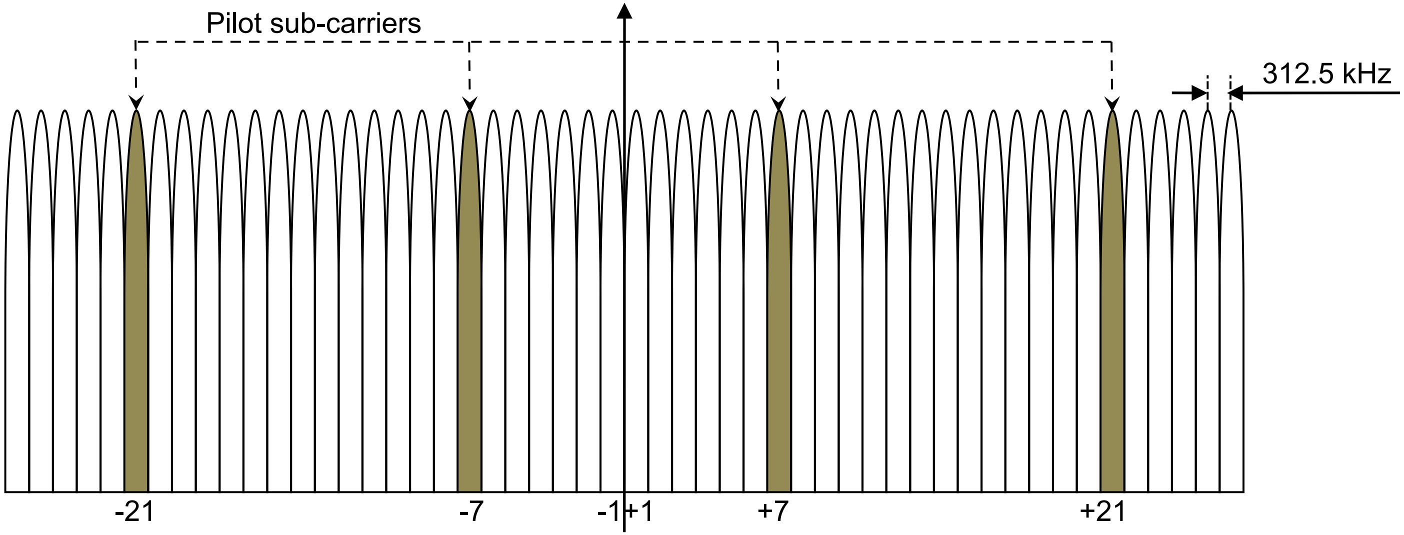
Orthogonal Frequency Division Multiplex (OFDM)



- Introduction through IEEE 802.11a-1999
  - Developed in cooperation with ETSI
- Group of bits is represented by a ‘sound’
  - Sound: lasting set of frequencies
  - Defines one OFDM symbol
- One OFDM symbol of a duration of 3.2 μs is sent every 4 μs
  - 250 kSymbols/s
  - 0.8 μs guard interval between symbols enable orthogonality of subsequent symbols
- OFDM transforms set of frequencies into time domain sequence, and vice-versa
  - Generation/separation by FFT-64
    - IFFT/FFT used for coding/decoding
- Robust against reflections and multi-path propagation through symbol duration and guard interval

OFDM Foundation: Time and frequency

- 52 sub-carriers of FFT-64 are used
  - 20 MHz channel bandwidth / 64 = 312.5 kHz sub-carrier spacing,
  - 48 data sub-carriers and 4 pilot sub-carriers
  - Total bandwidth: 16.25 MHz
- Pilot sub-carriers are required as reference for automatic gain control
  - Setting the right decoding thresholds

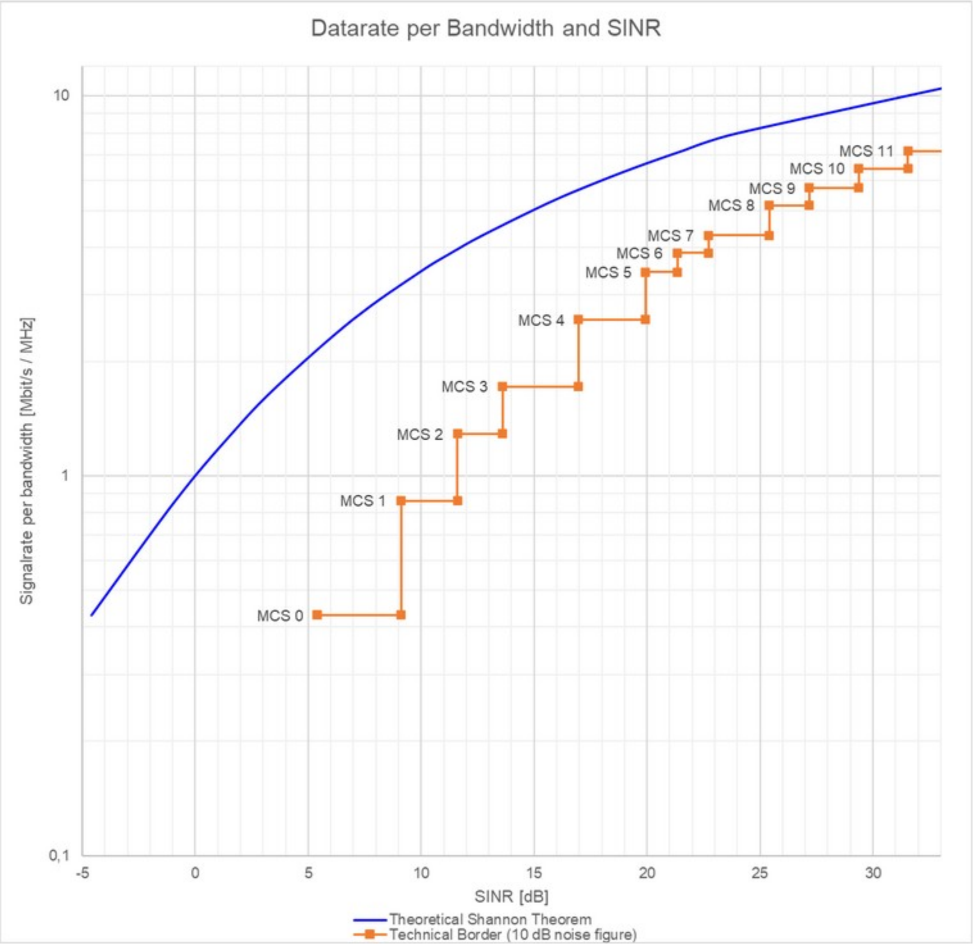


OFDM Modulation and Coding Schemes (MCS)

- OFDM spreads data transmission in time domain.
- Depending on Signal-Noise-Ratio, each tone can carry a varying amount of information.
- Limit is set through Shannon-Hartley theorem:

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

  - C: channel capacity [bps]
  - B: bandwidth [Hz]
  - S/N: signal-noise-ratio
- Real systems have noise figures of 6..10 dB.



OFDM Throughput calculations

$$\text{Maximum physical data rate} = \frac{N_{SD} \bullet N_{CBPS} \bullet R \bullet N_{SS}}{T_{SYM}}$$

With:

- N_{SD}: Number of data sub-carriers
- N_{CBPS}: Number of coded bits per OFDM symbol
- R: Code rate of forward error correction (1/2, 2/3, 3/4, 5/6)
- N_{SS}: Number of spatial streams
- T_{SYM}: OFDM symbol duration including guard time

	BPSK	**QPSK**	**16QAM**	**64QAM**	**256QAM**	**1024QAM**	**4096QAM**
N_{CBPS}	1 bit	2 bit	4 bit	6 bit	8 bit	10 bit	12 bit

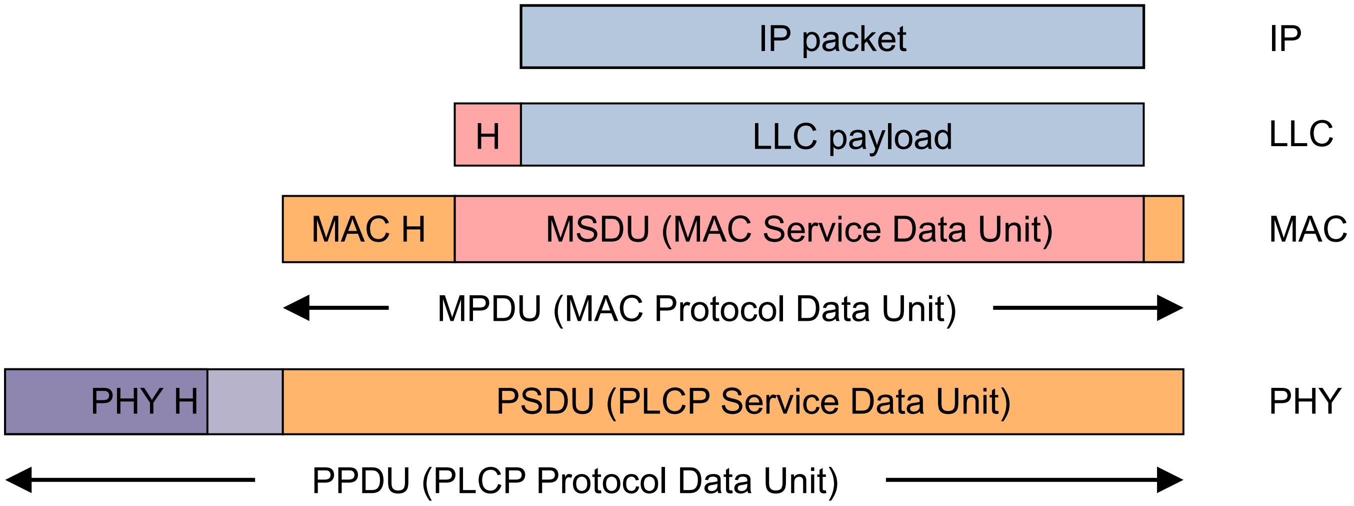
OFDM Foundation - Coding and Modulation

- 48 Data sub-carriers
- Sub-carrier modulation:
  - BPSK, QPSK, 16QAM, 64QAM
- Bit interleaved convolutional FEC coding
  - R=1/2, 2/3, 3/4
- Data rates:
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbps

Data Rate (Mbps)	Modulation	Coding Rate	Coded bits per subcarrier	Coded bits per OFDM symbol	Data bits per OFDM symbol	Receive sensitivity	$SINR_{min}$ (technical)
6	BPSK	1/2	1	48	24	- 82 dBm	3 dB
9	BPSK	3/4	1	48	36	- 81 dBm	4 dB
12	QPSK	1/2	2	96	48	- 79 dBm	6 dB
18	QPSK	3/4	2	96	72	- 77 dBm	9 dB
24	16-QAM	1/2	4	192	96	- 74 dBm	11 dB
36	16-QAM	3/4	4	192	144	- 70 dBm	14 dB
48	64-QAM	2/3	6	288	192	- 66 dBm	17 dB
54	64-QAM	3/4	6	288	216	- 65 dBm	19 dB

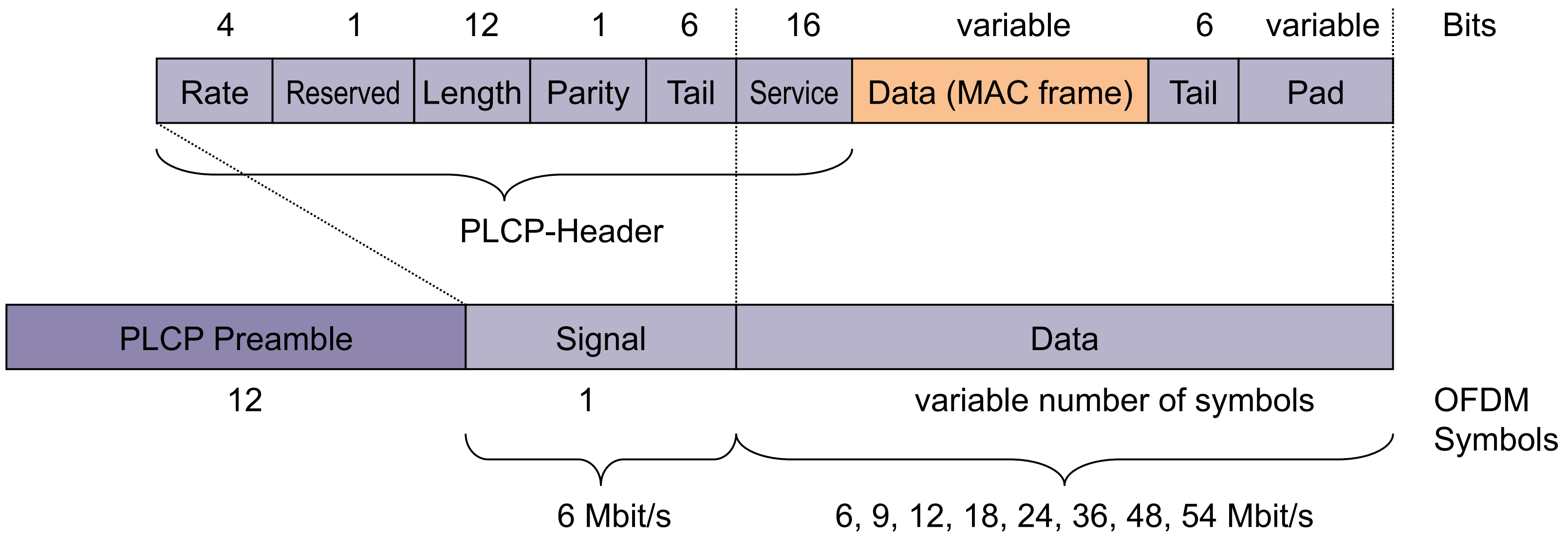
IEEE 802.11 Frame structure overview

- Each protocol layer deploys its own header for conveying the protocol information between peers



- IEEE 802.11 PHY header carries the information for setting up the reception of radio frames
- Physical Layer Convergence Protocol (PLCP) provides a PHY independent Service Access Point (SAP) for higher layers

OFDM Foundation - PHY Frame Format



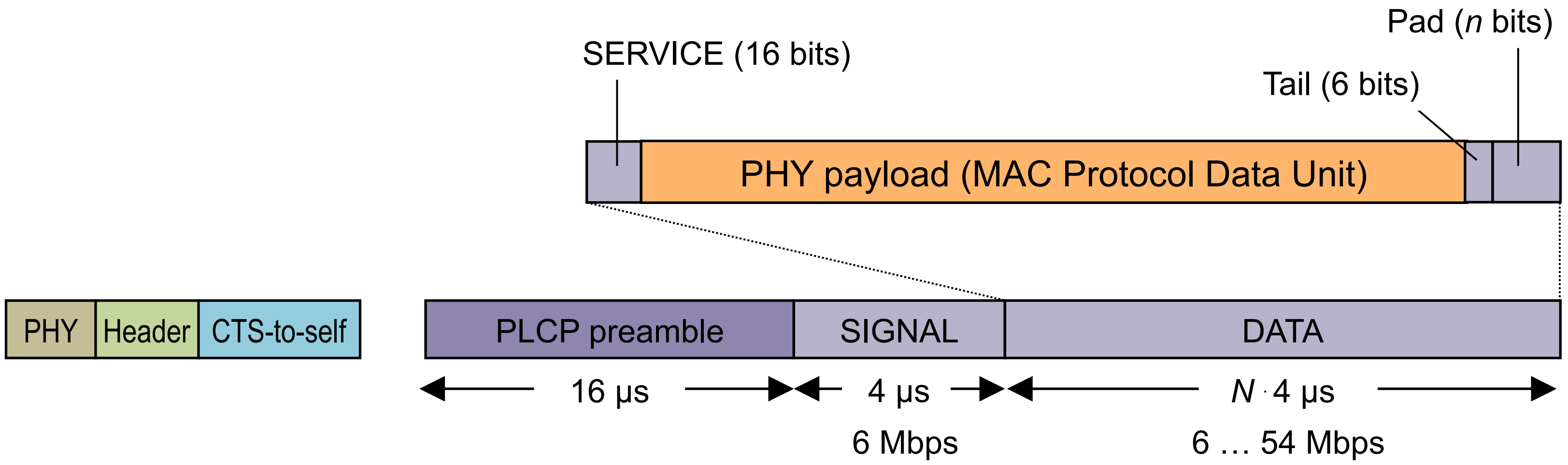
- OFDM PHY Preamble with 12 symbols takes 16 µs
  - 10 short training symbols without guard periods
    - Timing synchronization, antenna selection and locking to the signal
  - 2 long training symbols with guard periods for fine tuning
- Signal is one OFDM symbol with 24 data bits which takes 4 µs

Wi-Fi Legacy: Extended Rate PHY (802.11g)

- Introduced by IEEE 802.11g – 2003
  - Deploys OFDM according to 802.11a in the 2.4 GHz band
    - Backward compatibility with HR/DSSS added
- Uses same transmission channels as HR/DSSS
  - 18 MHz OFDM easily fits in 22 MHz HR/DSSS channel
- Support of data rates above 11 Mbps
  - Data rates like 802.11a: 6 Mbps up to 54 Mbps
- Advantages of OFDM in the 2.4 GHz band:
  - worldwide harmonized license-exempt frequency band
  - lower attenuation than in the 5GHz band
    - less transmission power required
- MAC layer extensions for backward compatibility to HR/DSSS

ERP – PHY frame (OFDM native)

- Without strict backward compatibility, ERP deploys the same PHY frame as OFDM (802.11a) for better efficiency.



- HR/DSSS systems are not able to decode OFDM PHY frames
  - For coexistence an additional protection methods like CTS-to-self or RTS/CTS may be required

Wi-Fi PHY Layer

WI-FI 4: HIGH THROUGHPUT

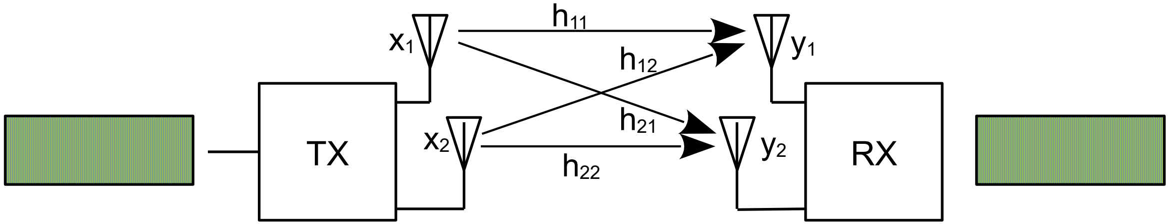
Wi-Fi 4: High Throughput (IEEE 802.11n)

- Major enhancement to IEEE 802.11a (5 GHz) and IEEE 802.11g (2.4 GHz)
  - From max. 54 Mbps to up to max. 600 Mbps in either band

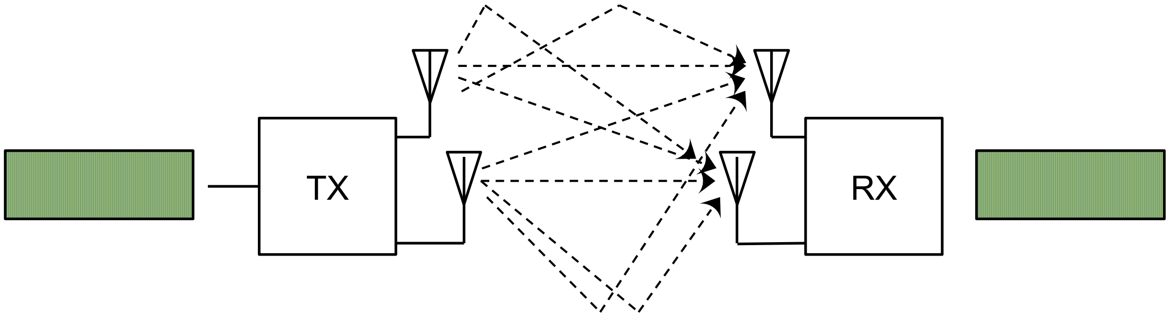
- Main techniques deployed to increase of bitrate:
  - <u>**Up to 4 parallel streams using MIMO (Multiple Input Multiple Output)**</u>
  - **Channel bonding of two adjacent channels to 40 MHz channels**
  - Enhancements to OFDM bandwidth, modulation scheme, and timing
  - MAC frame aggregation
    - A-MPDU as well as A-MSDU
  - Block acknowledgments

MIMO (Multiple Input Multiple Output)

- Mathematical model

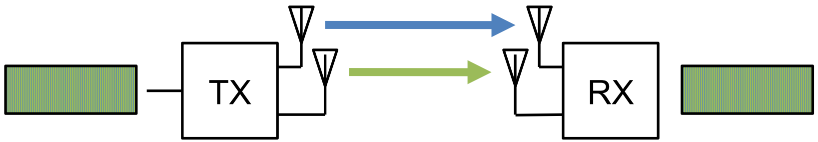


- Higher throughput can be achieved when channel matrix can be inverted.
  - Requires a multipath fading environment, as usual in indoor deployments.



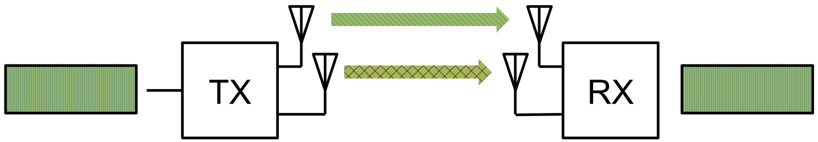
HT MIMO (Multiple Input Multiple Output) versions

- Spatial Multiplexing (SM)



  - Subdivides an outgoing signal stream into multiple pieces, transmitted through different antennas.
  - When individual streams are received with sufficiently distinct spatial signatures, an SM enabled receiver can reassemble the multiple pieces back into one stream
  - Maximizes data rate.

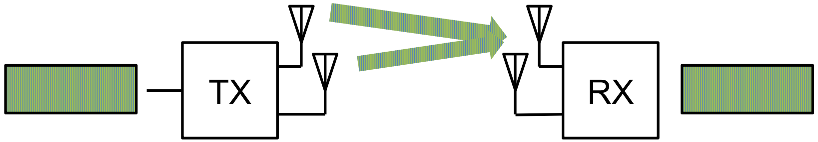
- Space-Time Block Coding (STBC)



  - Sends an outgoing signal stream redundantly, using different coding for each of the transmit antennas
  - Receiver has a better chance of accurately decoding the original signal stream in the presence of RF interference and distortion.
  - STBC improves reliability by reducing the error rate and may be combined with SM.

HT MIMO versions, cont.

- Transmit Beamforming (TxBF)

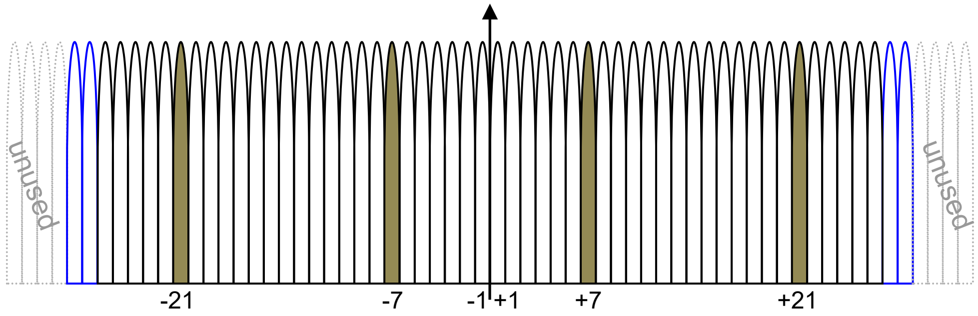


  - Steers signal stream towards the intended receiver by concentrating transmitted RF energy in a given direction.
  - Leverages signal reflection and multipath to improve received signal strength and sustain higher data rates.
  - Required channel knowledge can be obtained implicitly or explicitly by obtaining feedback from the receiver

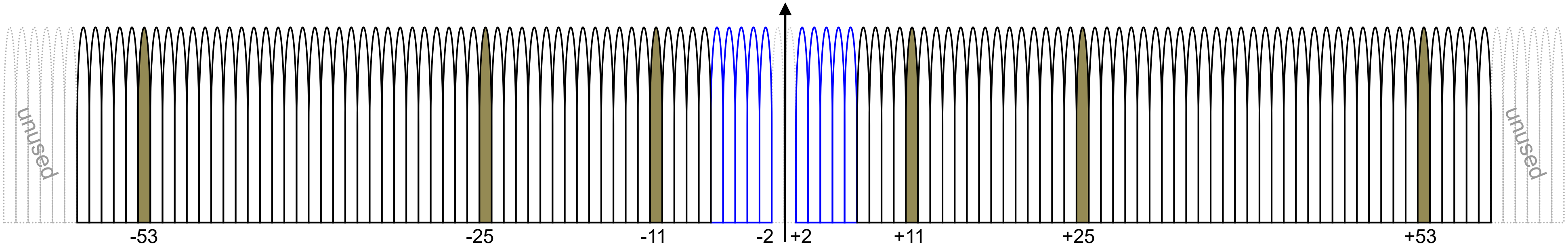
- Availability in Wi-Fi 4 products:
  - Only Spatial Multiplexing is part of Wi-Fi certification for Wi-Fi 4 out of the three different MIMO techniques specified in the High Throughput standard IEEE 802.11n.

HT Sub-carrier arrangement and channel bonding

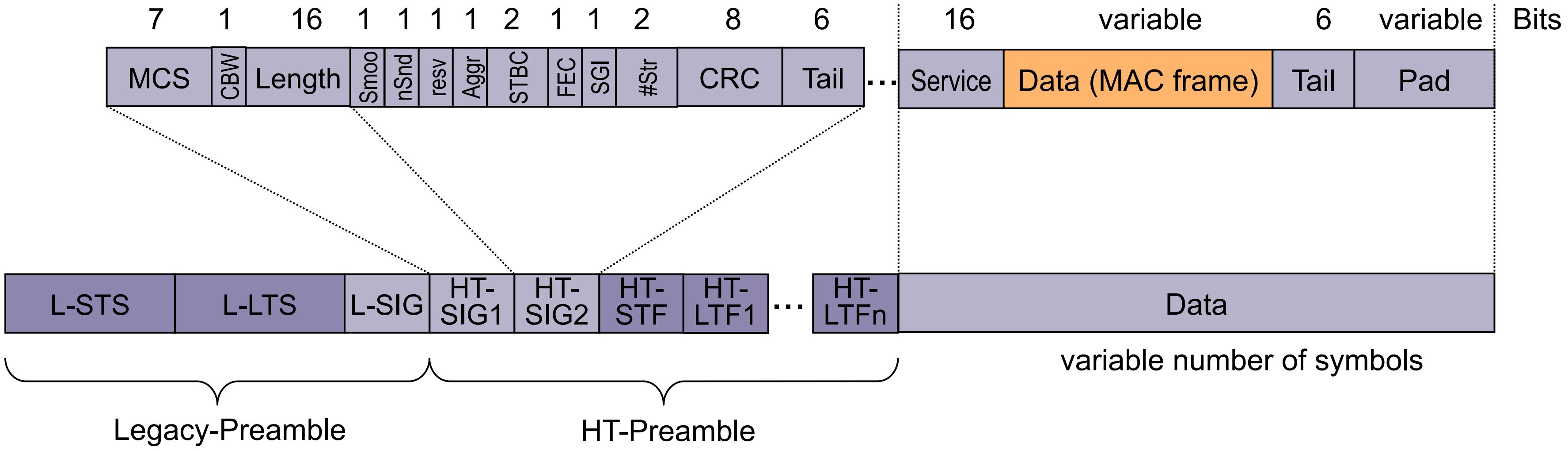
- Four more sub-carriers of OFDM-64 are used for data transmission (HT-20)
  - 52 data sub-carriers and 4 pilot sub-carriers



- Channel bonding of two 20 MHz channels to one 40 MHz channel (HT-40)
  - 108 data sub-carriers and 6 pilot sub-carriers



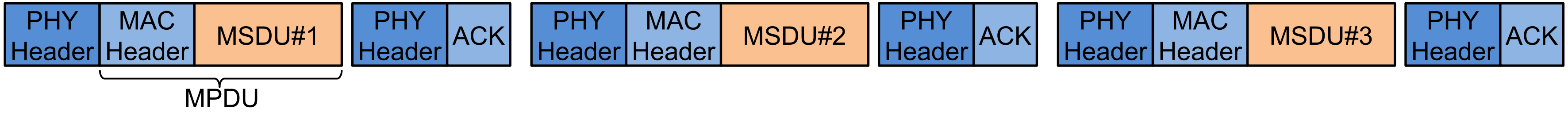
HT - PHY Frame Format



- Legacy OFDM PHY Preamble takes 20 µs
- HT Preamble takes 20 µs for two spatial streams
- HT-SIG1 and HT-SIG2 contain in total 48bits for PHY control information

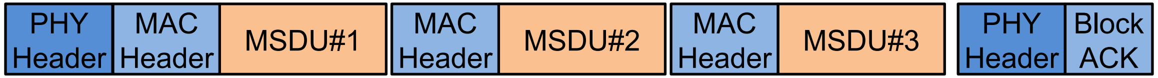
HT MAC Protocol Data Unit Aggregation

- MAC efficiency suffers when transferring sequence of smaller frames



  - Frame aggregation increases the payload that can be carried within a single 802.11 physical layer frame

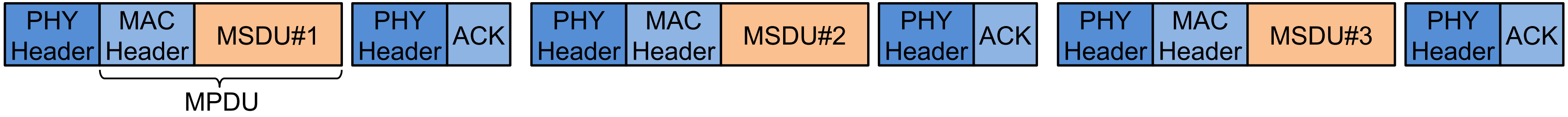
- MAC Protocol Data Unit Aggregation (A-MPDU) groups multiple MPDU sub-frames each with its own MAC header into one PSDU with up to 65535 bytes.



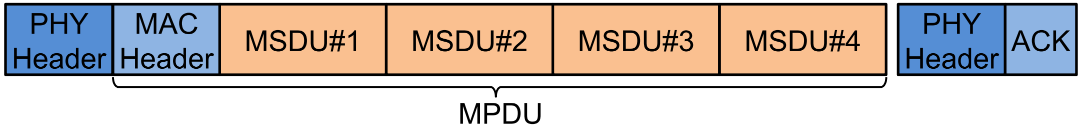
  - Reduced Interframe Space (RIFS) of 2µs used as delimiter between MPDUs
  - Block Acknowledgement for reduction of ACKs to one per multiple MPDU transmission
  - Selective retransmission of a single MPDU possible in the case that one of the aggregated MPDUs gets impacted.

HT MAC Service Data Unit Aggregation

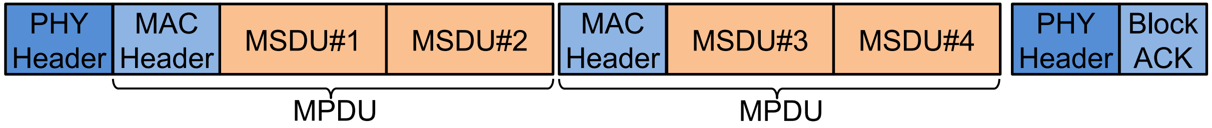
- MAC efficiency suffers when transferring sequence of smaller frames



- MAC Service Data Unit Aggregation (A-MSDU) groups multiple MSDUs into a single PSDU with a MAC header and up to 7935 data bytes.
  - All MSDUs with the same SA, DA and 802.11e QoS profile
  - High sensitivity against transmission errors; in the case of a single bit error the whole A-MSDU hast to be re-transmitted



- Higher resilience against transmission errors by a combination of MAC Service Data Unit aggregation and MAC Protocol Data Unit aggregation



  - Only erroneous MPDU has to be retransmitted.

Wi-Fi 4: High Throughput (802.11n) PHY improvements

- OFDM (54 -> 58.5 Mbps)
  - 52 data sub-carriers instead of 48 (4 pilot tones)
- Forward Error Correction (58.5 -> 65 Mbps)
  - 5/6 coding rate in addition to 3/4
- Short Guard Interval (65 -> 72.2 Mbps)
  - 0.4 µs down from 0.8 µs
- Channel Bonding (72.2 -> 150 Mbps)
  - 40 MHz by combining two 20 MHz (108 data sub-carriers, 6 pilot tones)
- MIMO (150 -> 600 Mbps)
  - Up to 4 parallel streams

Wi-Fi PHY Layer

WI-FI 5: VERY HIGH THROUGHPUT

Wi-Fi 5 (IEEE 802.11ac) Very High Throughput (VHT)

Extension to Wi-Fi 4 – High Throughput in 5GHz only through:

- Wider channel bandwidths
  - 80 MHz and 160 MHz channels in addition to 40 MHz and 20 MHz
- More MIMO spatial streams
  - Support for up to 8 spatial streams
- Downlink Multi-user MIMO (DL MU-MIMO)
  - Multiple STAs, each with one or more antennas, can receive data concurrently.
  - Max. 4 streams to a single STA
- New MCS 8, 9
  - 256-QAM, rate 3/4 and 5/6, added as optional modes in addition to modes available in HT
- Single sounding and feedback format for beamforming and MU-MIMO
  - Instead of multiple methods in HT – to make certification happen.
- Coexistence mechanisms for 20/40/80/160 MHz channels
  - Dynamic spectrum allocation among 11ac and 11a/n devices
- Minor MAC modifications (mostly to support above changes)

Wi-Fi 5 – VHT MCS Options for single stream

Wi-Fi 4 (802.11n)

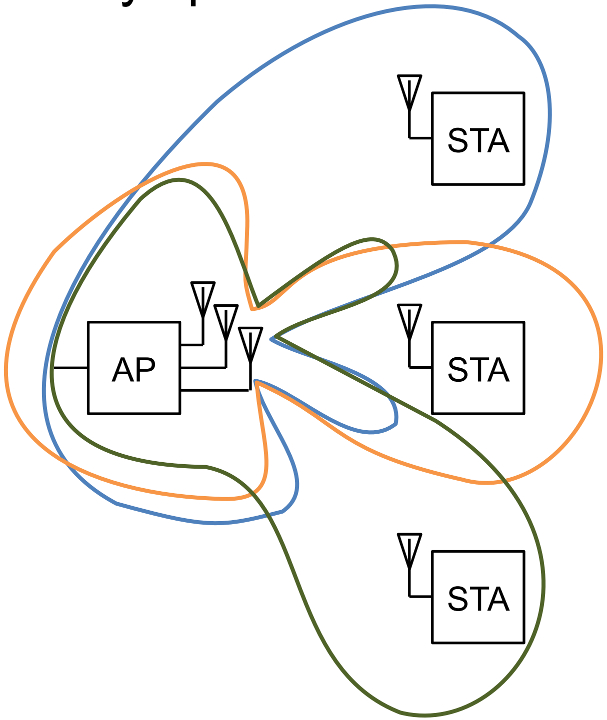
MCS index	Spatial Streams	Modulation type	Coding rate	Data rate [Mbps]							
				20 MHz [52 dsc]		40 MHz [108 dsc]		80 MHz [234 dsc]		160 MHz [468 dsc]	
				0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI
0	1	BPSK	1/2	6.5	7.2	13.5	15.0	29.3	32.5	58.5	65.0
1	1	QPSK	1/2	13.0	14.4	27.0	30.0	58.5	65.0	117.0	130.0
2	1	QPSK	3/4	19.5	21.7	40.5	45.0	87.8	97.5	175.5	195.0
3	1	16-QAM	1/2	26.0	28.9	54.0	60.0	117.0	130.0	234.0	260.0
4	1	16-QAM	3/4	39.0	43.3	81.0	90.0	175.5	195.0	351.0	390.0
5	1	64-QAM	2/3	52.0	57.8	108.0	120.0	234	260.0	468.0	520.0
6	1	64-QAM	3/4	58.5	65.0	121.5	135.0	263.3	292.5	526.5	585.0
7	1	64-QAM	5/6	65.0	72.2	135.0	150.0	292.5	325.0	585.0	650.0
8	1	256-QAM	3/4	78.0	86.7	162.0	180.0	351.0	390.0	702.0	780.0
9	1	256-QAM	5/6	N/A	N/A	180.0	200.0	390.0	433.3	780.0	866.7

- For multiple streams multiply numbers in table by number of streams.

dsc = data sub-carrier

Multi-User DL MIMO and Beamforming

- An VHT AP is able to use its antennas to transmit multiple frames to different clients, all at the same time and over the same frequency spectrum.
- To send data to a particular user, the AP forms a strong beam toward that user
  - Minimizing at the same time the signal strength in the direction of the other users (**“null steering”**)
  - Each of the users receives a strong signal of the desired data that is only slightly degraded by interference from data for the other users.
- AP has to know about the channel conditions to all connected terminals, detected
  - either detected **implicitly** out of the received signal, or
  - **explicitly** by the 802.11ac sounding protocol.
- By serving clients in parallel DL MU-MIMO allows to deliver more data in sum to clients being limited to a single or dual antenna.



MU- MIMO with combination of Beamforming and Null Steering

Wi-Fi PHY Layer

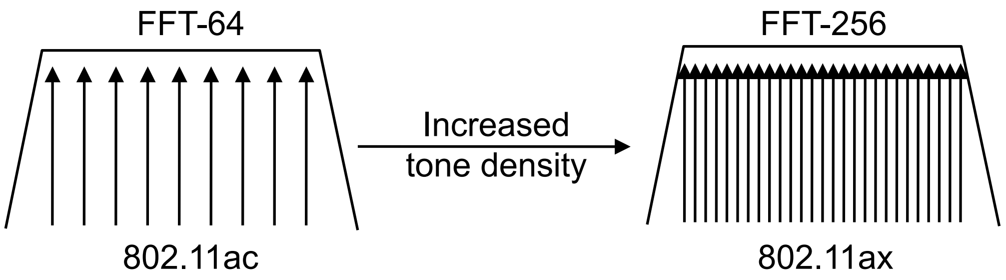
WI-FI 6: HIGH EFFICIENCY

Wi-Fi 6 (802.11ax) High Efficiency (HE)

- No aim to increase peak data rates far beyond what was already available through Wi-Fi 5 (VHT)
- Main focus was on increasing performance of 802.11 in uncoordinated high density scenarios
- Three key focus points:
  - (1) To improve efficiency in dense networks with large number of STAs
  - (2) To improve efficiency in dense heterogeneous networks with large number of APs
  - (3) To improve efficiency in outdoor deployments
- The aim is to achieve a substantial increase in the real-world throughput
  - Creating an instantly recognizable improvement in QoE (cell edge behavior)
  - Generating spatial capacity increase (area throughput)

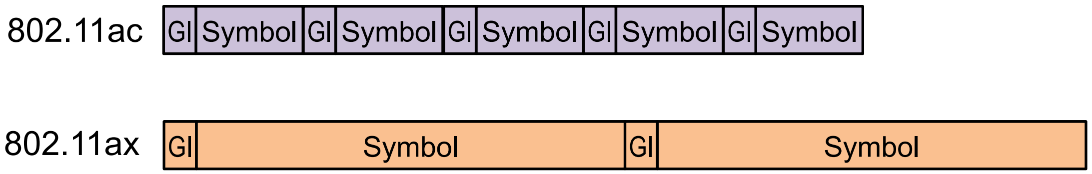
Wi-Fi 6 (802.11ax) HE increased link efficiency/speed

Frequency domain
(~ 5% gain)



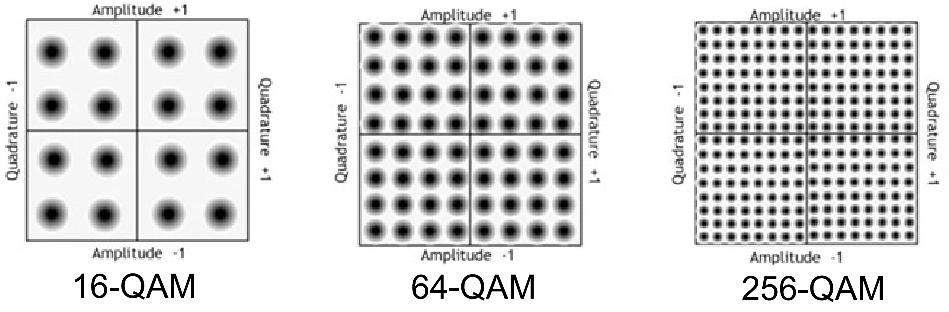
Squeeze more tones in at the channel edge

Time domain
(~ 15% gain)



Guard Interval (GI) overhead reduced

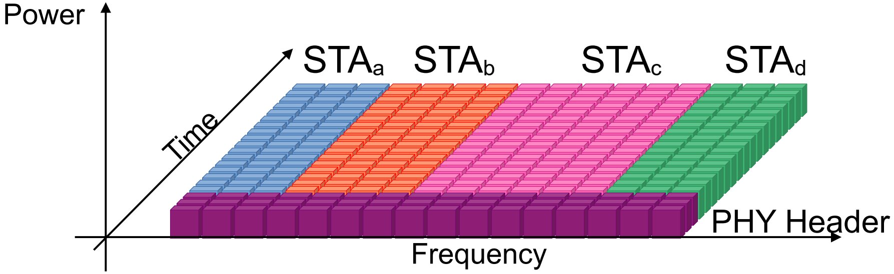
Modulation
(~ 25% gain)

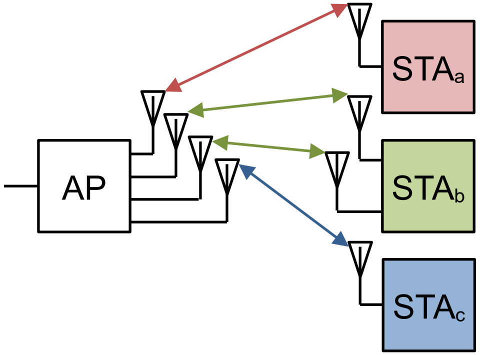


+ 1024-QAM
(802.11ax only)

Wi-Fi 6 – High Efficiency (HE) technical highlights

- Higher efficiency through multiplexing users in both frequency and space
  - Uplink and downlink OFDMA and MU-MIMO
  - OFDMA allows for much more fine-grain radio resource management than MU-MIMO





- Increase link efficiency with longer OFDM symbol (256-FFT) and high order modulation (1024-QAM)
- Improved support for outdoor operation (optional longer guard interval)
- Increase spatial reuse through BSS coloring, Spatial Reuse Groups, and dynamic clear channel assessment (CCA)
  - More details in next part

Wi-Fi 6: OFDM and OFDMA arrangements

Radio Unit arrangements

CBW				20	40	80	160
RU	**26**	**52**	**106**	**242**	**484**	**996**	**1992**
Data	24	48	102	234	468	980	1960
Pilot	2	4	4	8	16	16	32
RU-26				9	18	37	74
RU-52				4	8	16	32
RU-106				2	4	8	16
RU-242				1	2	4	8
RU-484					1	2	4
RU-996						1	2

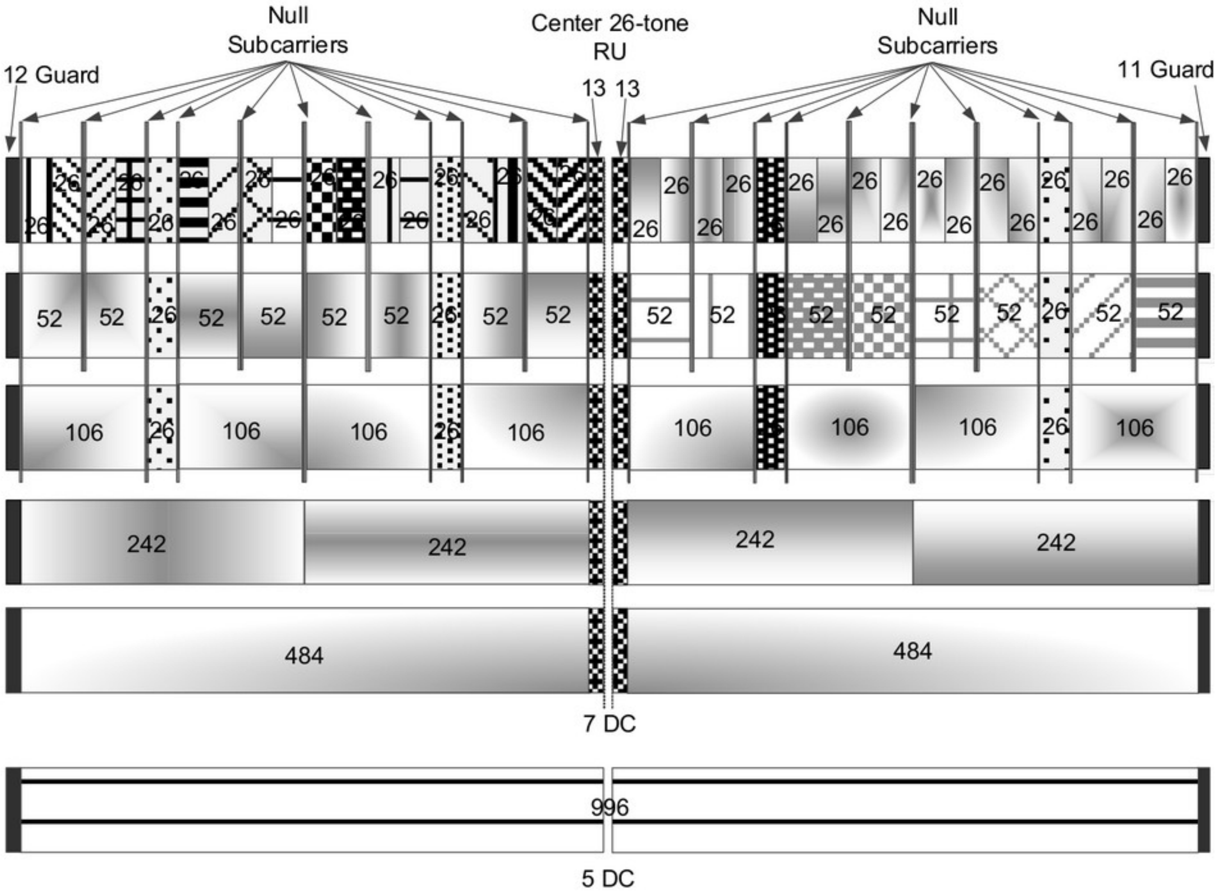
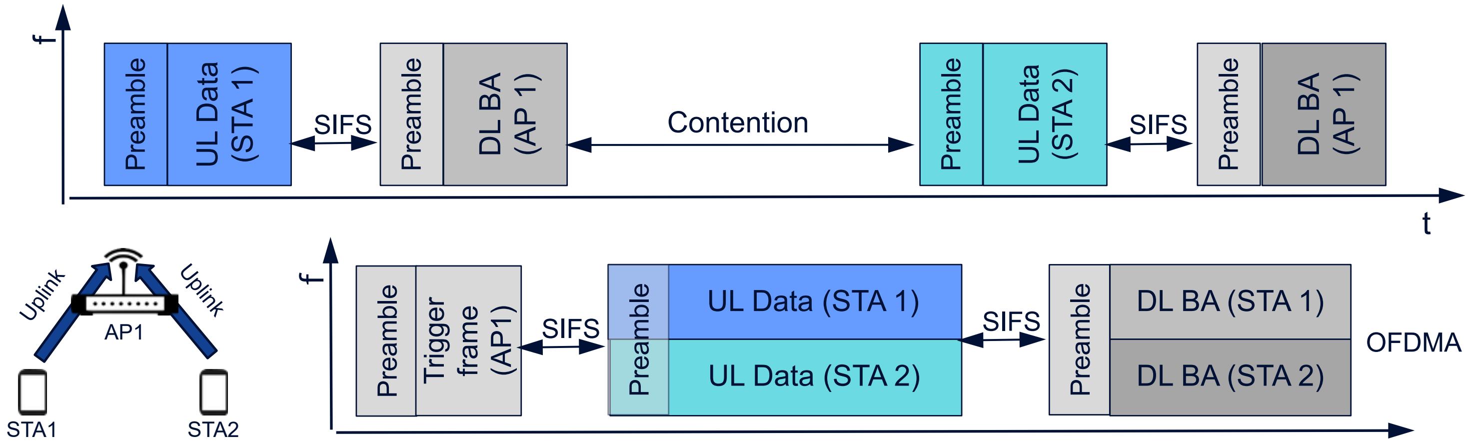


Figure 27-7—RU locations in an 80 MHz HE PPDU

OFDMA TBT reduces access overhead compared to OFDM



- OFDMA enables APs to further split channel usage to various parallel streams for concurrent access of multiple STAs
- Uplink OFDMA **Trigger Based Transmission (TBT)** starts with trigger frame directly followed by responses of STAs within their assigned resource units
  - Flexible arrangements of resource units to accommodate high variety of throughput demands
  - Leads to increased efficiency for frequent short data frames, in particular in the uplink
- Overall, OFDMA results in shorter transmission delays and less jitter.

Wi-Fi 6: PHY rates, minimum sensitivity, and required SINR

			20 MHz			40 MHz			80 MHz			
MCS	Modulation	Coding	RSSI	1x1 Rate	2x2 Rate	RSSI	1x1 Rate	2x2 Rate	RSSI	1x1 Rate	2x2 Rate	SINR*
0	BPSK	1/2	-82	8.6	17.2	-79	17.2	34.4	-76	36	72	2
1	QPSK	1/2	-79	17.2	34.4	-76	34.4	68.8	-73	72	144	6
2	QPSK	3/4	-77	25.8	51.6	-74	51.6	103.2	-71	108	216	9
3	16-QAM	1/2	-74	34.4	68.8	-71	68.8	137.6	-68	144	288	11
4	16-QAM	3/4	-70	51.6	103.2	-67	103.2	206.5	-64	216	432	14
5	64-QAM	1/2	-66	68.8	137.6	-63	137.6	275.3	-60	288	576	17
6	64-QAM	3/4	-65	77.4	154.8	-62	154.9	309.7	-59	324	649	19
7	64-QAM	5/6	-64	86.0	172.0	-61	172.1	344.1	-58	360	721	20
8	256-QAM	3/4	-59	103.2	206.5	-56	206.5	412.9	-53	432	865	23
9	256-QAM	5/6	-57	114.7	229.4	-54	229.4	458.8	-51	480	961	25
10	1024-QAM	3/4	-54	129.0	258.0	-51	258.1	516.2	-48	540	1081	27
11	1024-QAM	5/6	-52	143.4	286.8	-49	286.8	573.5	-46	600	1201	30
			dBm	Mbps	Mbps	dBm	Mbps	Mbps	dBm	Mbps	Mbps	dB

*technical, i.e. usual real systems

Wi-Fi 6 enhancements compared to Wi-Fi 5

Feature	Wi-Fi 5	Wi-Fi 6
OFDMA	Not available	Centrally controlled medium access with dynamic assignment of 26, 52, 106, 242, 484, or 996 tones per station. Each tone consists of a single subcarrier of 78.125 kHz bandwidth. Therefore, bandwidth occupied by a single OFDMA transmission is between 2.03125 MHz and ca. 80 MHz bandwidth.
Multi-user MIMO (MU-MIMO)	Available in downlink direction	Available in downlink and uplink direction
Trigger-based Transmissions	Not available	Allows performing multiple UL OFDMA transmissions by stations without contention for the medium
Spatial frequency reuse	Not available	Coloring enables devices to differentiate transmissions in their own network from transmissions in neighboring networks. Adaptive Power and Sensitivity Thresholds allows dynamically adjusting transmit power and signal detection threshold to increase spatial reuse.
Target Wait Time (TWT)	Not available	TWT reduces power consumption and medium access contention.
Guard Interval duration	0.4 μs or 0.8 μs	0.8 μs, 1.6 μs or 3.2 μs
Symbol duration	3.2 μs	3.2 μs, 6.4 μs, or 12.8 μs

Wi-Fi PHY Layer

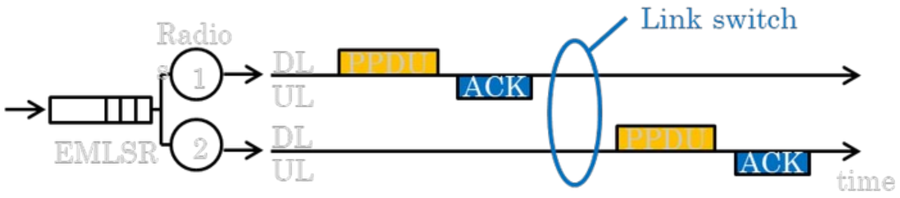
WI-FI 7: EXTREMELY HIGH THROUGHPUT

Wi-Fi 7 – Extremely High Throughput (802.11be)

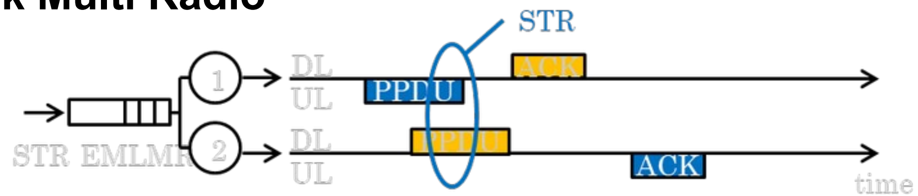
- Carrier frequencies between 1 and 7.125 GHz.
- Maximum MAC throughput of 36 Gbps/AP
  - ~ 4x compared to Wi-Fi 6
- Wider bandwidth (320 MHz)
- QAM-4096 coding and modulation
- Better efficiency through puncturing and new header structures
- **Technical highlight: Multi Link Operation**
- Backward compatibility and coexistence with legacy Wi-Fi devices in the 2.4 GHz, 5 GHz and 6 GHz bands.

Multi-Link Operation (MLO)

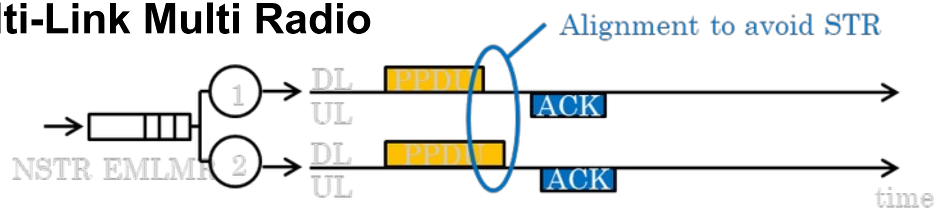
- MLO allows devices to have connectivity on multiple links, enabling a STA multi-link device (MLD) to discover, authenticate, associate, and set up multiple links with an AP MLD.
- Defined modes of operation:
  - **Enhanced Multi-Link Single Radio**
    - Allows quickly to choose the best link with single radio and multiple reduced function radios to monitor the links



  - **Simultaneous Transmit and Receive Multi-Link Multi Radio**
    - Most flexible mode allowing to aggregate multiple links for improved throughput and reduced latency and jitter when MLDs can tolerate interference between the links



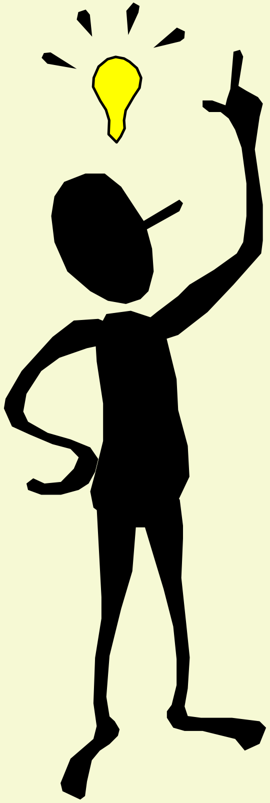
  - **Non-Simultaneous Transmit and Receive Multi-Link Multi Radio**
    - Concurrent transmissions on multiple links are synchronized in a way to avoid harmful interference between the links of an MLD



Wi-Fi Improvements from Wi-Fi 4 to Wi-Fi 7

Parameter	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 7	Benefits of Wi-Fi 7
Bands	2.4 GHz 5 GHz	5 GHz	2.4 GHz 5 GHz 6 GHz	2.4 GHz 5 GHz 6 GHz	Designed for 6 GHz from the ground up, including MLO across two or more bands
Channel Widths	20 MHz 40 MHz	20 MHz 40 MHz 80 MHz 160 MHz	20 MHz 40 MHz 80 MHz 160 MHz	20 MHz 40 MHz 80 MHz 160 MHz 320MHz	Doubles the size of the widest Wi-Fi 6 channel and makes 160 MHz mandatory to support high-speed use cases
Highest Modulation	64-QAM	256-QAM	1024-QAM	4096-QAM	20% higher transmission rate than Wi-Fi 6
Multi-Link Operation (MLO)	N	N	N	Y	Increased throughput, lower latency, reduced interference, reduced intra-AP roaming time
Max Data Rate	600 Mbps	3.5 Gbps	9.6 Gbps	23 Gbps 36 Gbps (w/MLO)	More than three times higher throughput than Wi-Fi 6
Max Spatial Streams	4	4	8	8	Max streams per STA
Uplink Channel Access	EDCA	EDCA	EDCA Triggered access	EDCA Optimized triggered access	More predictable latency with lower overheads

Questions and answers



Wi-Fi radio questions...

1) Which of the IEEE 802.11 radio standards support operation in 2.4 GHz?
2) Which IEEE 802.11 radio standards only support operation in 5 GHz?
3) What does OFDM stand for?
4) What is the purpose of guard intervals in OFDM?
5) Which symbol rate is used by OFDM as introduced by IEEE 802.11a?
6) How much [in %] does the OFDM symbol rate change in 802.11n and 802.11ac through shortening the guard interval compared to 802.11a and 802.11g?
7) Which MIMO methods are specified in 802.11n, and which is mandatory for certification?
8) What are the **_two_** main techniques deployed by Wi-Fi 4 (802.11n) to increase the maximum bitrate from 54 Mbit/s to 600 Mbit/s?
9) What is the benefit of MAC Protocol Data Unit aggregation compared to MAC Service Data Unit aggregation?

Wi-Fi radio questions, cont.

10) What are the **_two_** main techniques deployed by Wi-Fi 5 (802.11ac) provide higher bitrates compared to Wi-Fi 4 (802.11n)?
11) What is the difference between explicit beam-forming and implicit beam-forming?
12) What is the benefit of deploying a FFT-256 instead of a FFT-64?
13) What is the benefit of trigger based transmissions in Wi-Fi 6 and Wi-Fi 7?
14) Through which method up to 9 stations can be served in parallel in a 20 MHz channel?
15) What is the maximum channel bandwidth of Wi-Fi 7?
16) What is the throughput enhancement through QAM-4096 compared to Wi-Fi 6?
17) How can 36 Gbps throughput achieved in Wi-Fi 7?

End of part 2

Questions and remarks