Advanced Mobile Networks
Wi-Fi (IEEE 802.11 WLAN) Part 2b

WS 2024/2025 Lecture

Max Riegel
(max.riegel@ieee.org)

WS 2024/2025 Wi-Fi Lecture topics overview

Part 0:
- Introduction and overview

Part 1:
- Wi-Fi Deployments
- Wi-Fi Network architecture
- Wi-Fi Stds & Certification
- Wi-Fi Spectrum
- Wireless Channel

Part 2:
- Wi-Fi PHY Layer
- Wi-Fi PHY Q&A

\+ PHY Exercises

Part 3:
- Wi-Fi MAC Layer
- Wi-Fi QoS
- Wi-Fi MAC Q&A

\+ MAC Exercises

Part 4:
- Wi-Fi Security
- Wi-Fi Mobility
- Wi-Fi Security Q&A

AMN – Wi-Fi Lecture dates and content (tentative)

Thu, Nov. 28	Part 0	Thu, Jan 17th	Part 3
Tue, Dec. 10th	Part 1	Tue, Jan 21st	||
Thu, Dec 12th	||	Thu, Jan 23rd	||
Thu, Dec 19th	Part 2	Thu, Jan 30th	||
Tue, Jan 7th	||	Tue, Feb 4th	Part 4
Thu, Jan 9th	||	Thu, Feb 6th	||(partial)

Advanced Mobile Networks – Wi-Fi

IEEE 802.11 STANDARDS REFERENCE

IEEE Std 802.11™-2024 + amendment 802.11be™-2024

- *Can be downloaded at no charge through the IEEE Get Program*
  - *https://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68*
- *No all the features specified in the standard are available in real Wi-Fi products*
- *This lecture presents behavior of real Wi-Fi products as specified by Wi-Fi Alliance in its certification programs*
  - *https://www.wi-fi.org/discover-wi-fi/specifications*

IEEE Standard for Information technology

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

- Revision of IEEE Std 802.11-2020
  - Revision of IEEE Std 802.11-2016
    - Revision of IEEE Std 802.11-2012
      - Revision of IEEE Std 802.11-2007
        - Revision of IEEE Std 802.11-1999
          - First IEEE 802.11 standard release in 1997
- Comprises initial IEEE Std 802.11-1999 and all amendments IEEE 802.11a-1999 … IEEE 802.11bd-2022
  - *i.e.:* a, b, d, e, g, h, I, j, k, n, p, r, s, u, v, w, y, z, aa, ac, ad, ae, af, ah, ai, aj, ak, aq, ax, ay, az, ba, bb, bc, bd

Amendment standard IEEE Std 802.11be-2024

- Amendment 8: Enhancements for extremely high throughput (EHT)

IEEE 802.11 radio standards evolution

Std	Release	Freq. (GHz)	Bandwidth (MHz)	Data rate per stream (Mbit/s)	Allowable MIMO streams	Modulation	Approximate indoor range (m)	Approximate outdoor range (m)
	Jun 1997	2.4	20	1, 2	1	DSSS	40	150
a	Sep 1999	5	20**	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM	40	150
b	Sep 1999	2.4	20	5.5, 11	1	DSSS	40	150
g	Jun 2003	2.4	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM (DSSS)	40	150
n	Oct 2009	2.4 5	20/40	up to 72.2/150	4	OFDM	60 40	200 150
y	Nov 2008	3.7	5/10/20	up to 13.5/27/54	1	OFDM	-	5 000
ac	Dec 2013	5	20/40/80/160	up to 87/200/433/867	8	OFDM	40	150
ad	Oct 2012	60	2160	up to 6 700	1	SC // OFDM	line of sight	line of sight
af	Dec 2013	TV WS	1,2,4x 6/7/8	up to 1,2,4x 26.7/26.7/35.5	4	OFDM	100	1000
ah	Dec 2016	< 1	1/2/4/8/16	0.15 … up to 4.4/9/20/43/87	4	OFDM	100	1000
ax	Feb 2021	1...7.2	[2]/[4]/[8]/20/ 40/80/160	up to [15]/[30]/[63]/143/287/600/1201	8	OFDMA	80	300
ay	Mar 2021	60	1..4 x 2160	N_{cb}x 8.6 // 8.3/18.2/28.1/37.9 Gbps	8	SC // OFDM	line of sight	line of sight
be	Sep 2024	1...7.2	[2]/[4]/[8]/20/ 40/80/160/320	up to [18]/[36]/[75]/172/344/720/1441/2882	8	OFDMA	80	300

* Preliminary information; specifications still in early phases of development.
** Half-clocked and quarter clocked variants available for 10 MHz and 5 MHz channel bandwidth, as used by IEEE 802.11p
IEEE 802.11y-2008 is only licensed in the United States by the FCC; licensed spectrum allows for higher TX power

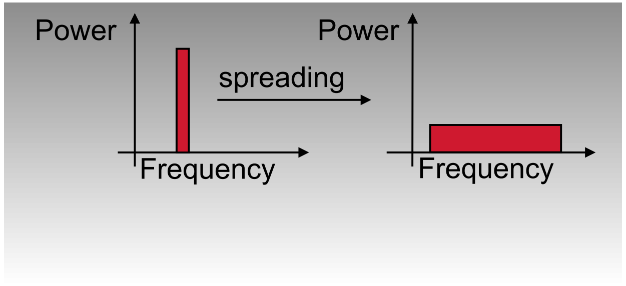
Advanced Mobile Networks

WI-FI PHY LAYER

Advanced Mobile Networks – Wi-Fi PHY Layer

DIRECT SEQUENCE SPREAD SPECTRUM (DSSS)

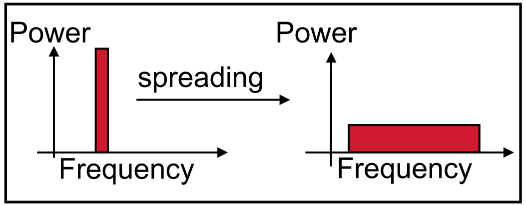
Legacy IEEE802.11 PHY layer solutions for 2.4 GHz

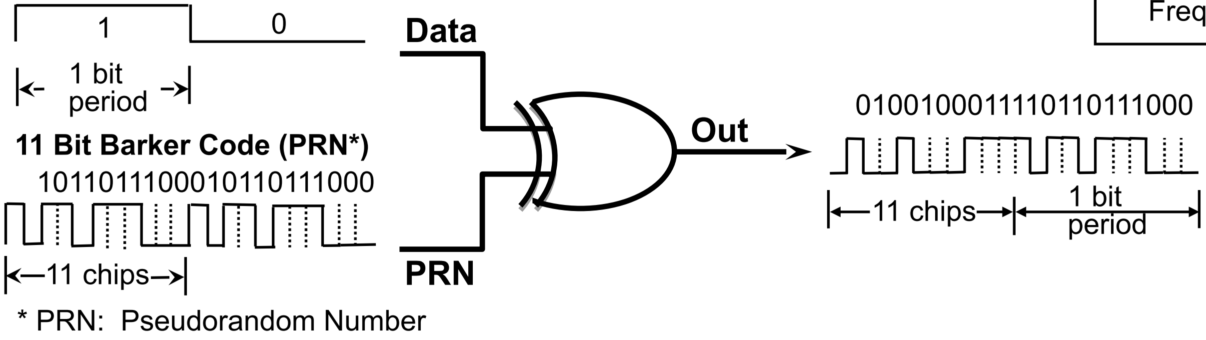


- 2.4 GHz Direct Sequence Spread Spectrum
  - DBPSK/DQPSK providing 1/2 Mbps
  - Channel bandwidth: 22 MHz
- 2.4 GHz High Rate DSSS **(802.11b – Wi-Fi 1)**
  - CCK/DQPSK providing 5.5/11 Mbps
  - Channel bandwidth: 22 MHz

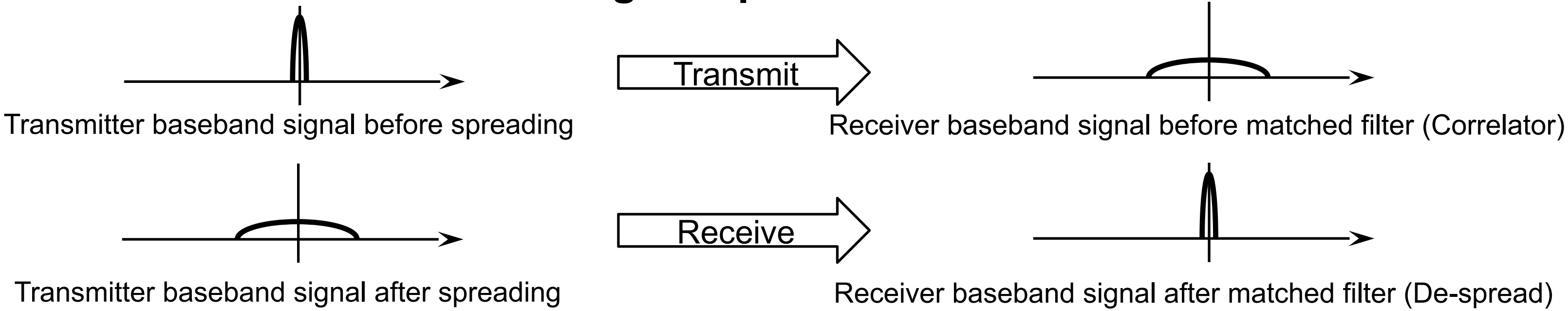
Direct Sequence Spread Spectrum

RF energy is spread by XOR of data with PRN sequence



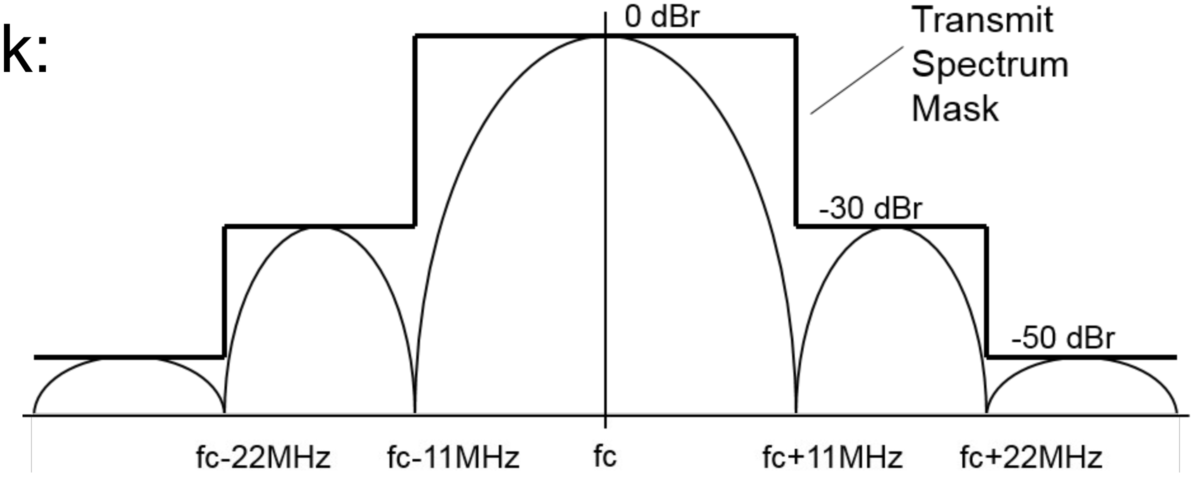


Signal Spectrum



HR/DSSS Summary and Spectrum

- Maximum data rate: 11 Mbps
  - intermediate steps: 1, 2, 5.5, 11 Mbps
- Modulation: BPSK, DQPSK, CCK
  - CCK = Complementary Code Keying
    - High data rate DSSS coding with inherent spreading
- Channel bandwidth: 22 MHz
- HR/DSSS Spectrum Mask:

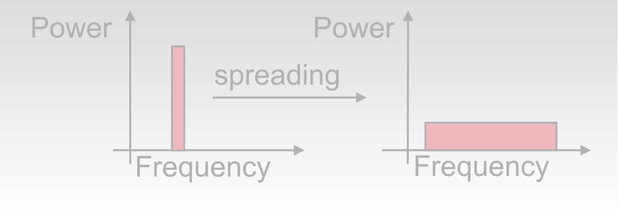


Advanced Mobile Networks – Wi-Fi PHY Layer

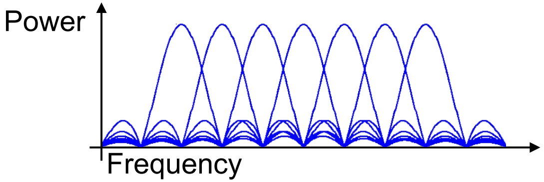
OFDM - ORTHOGONAL FREQUENCY DIVISION MULTIPLEX

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

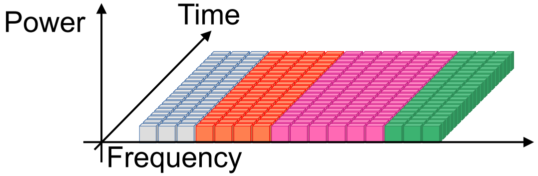
- 2.4 GHz Direct Sequence Spread Spectrum
  - DBPSK/DQPSK providing 1/2 Mbps
  - Channel bandwidth: 22 MHz
- 2.4 GHz High Rate DSSS **(802.11b – Wi-Fi 1)**
  - CCK/DQPSK providing 5.5/11 Mbps
  - Channel bandwidth: 22 MHz



- 5 GHz Orthogonal Frequency Division Multiplex **(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 **(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 **(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



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
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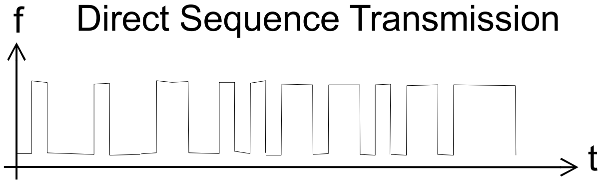
Direct Sequence Transmission



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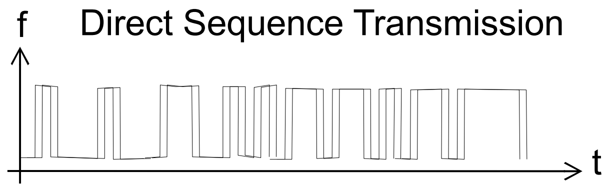

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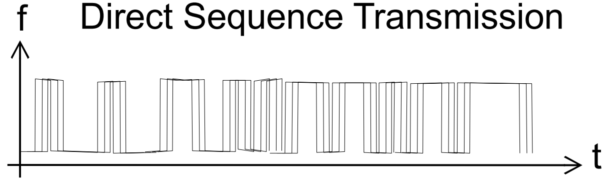

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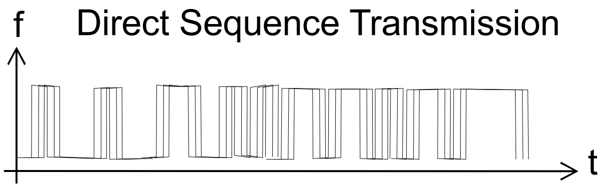

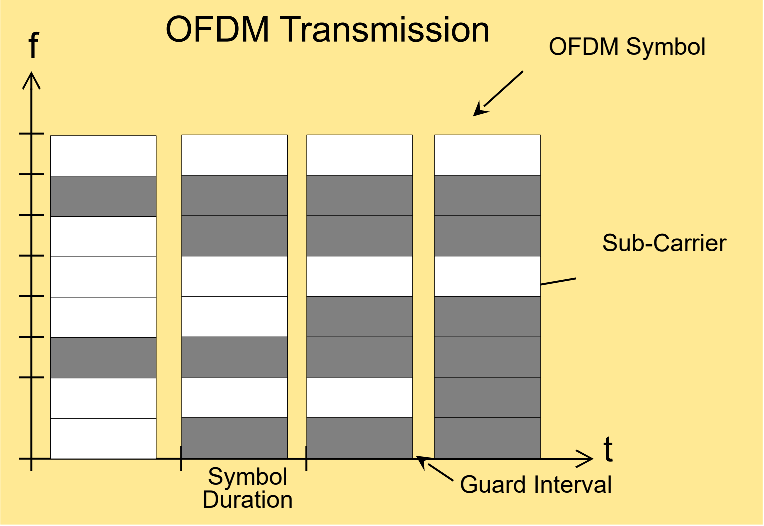

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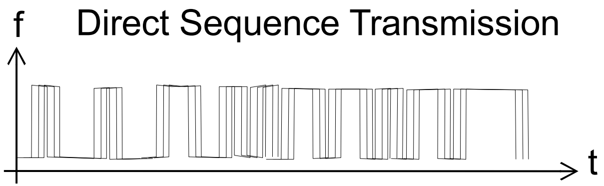

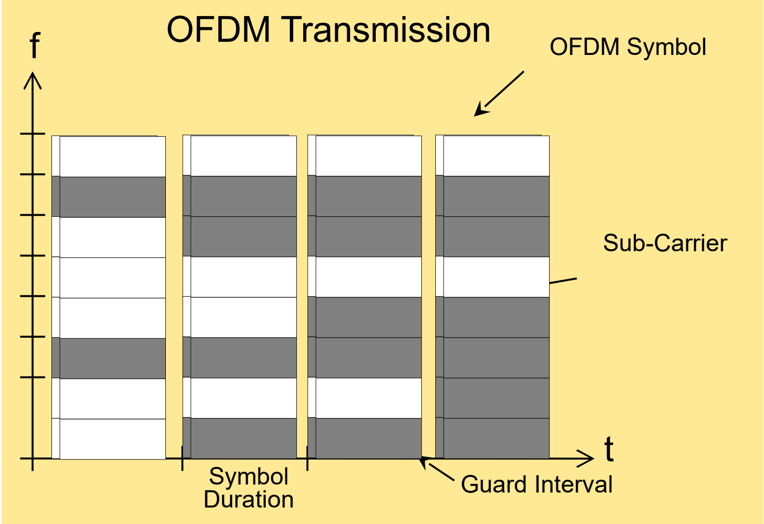

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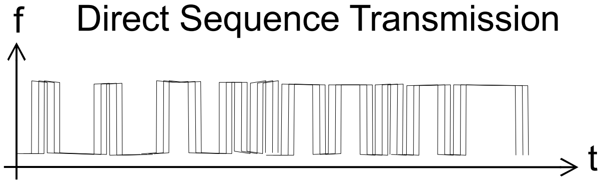
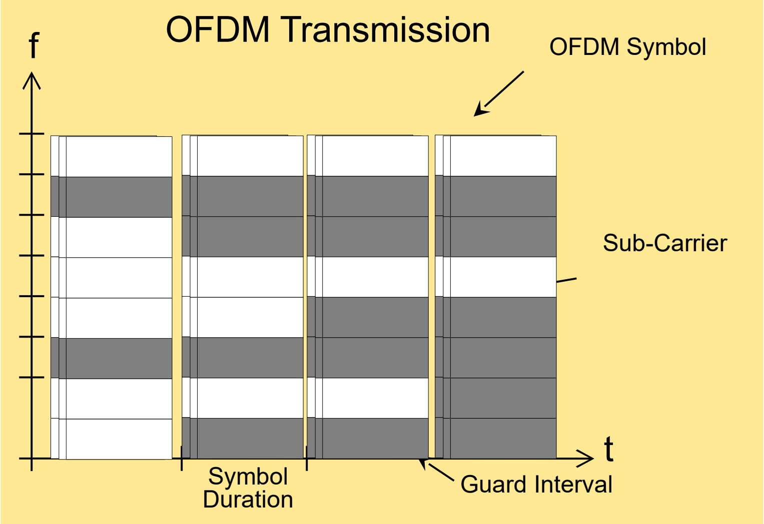
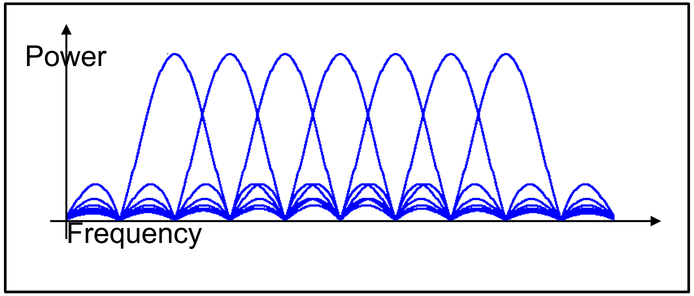




Advanced Mobile Networks – Wi-Fi PHY Layer

WI-FI 2: OFDM

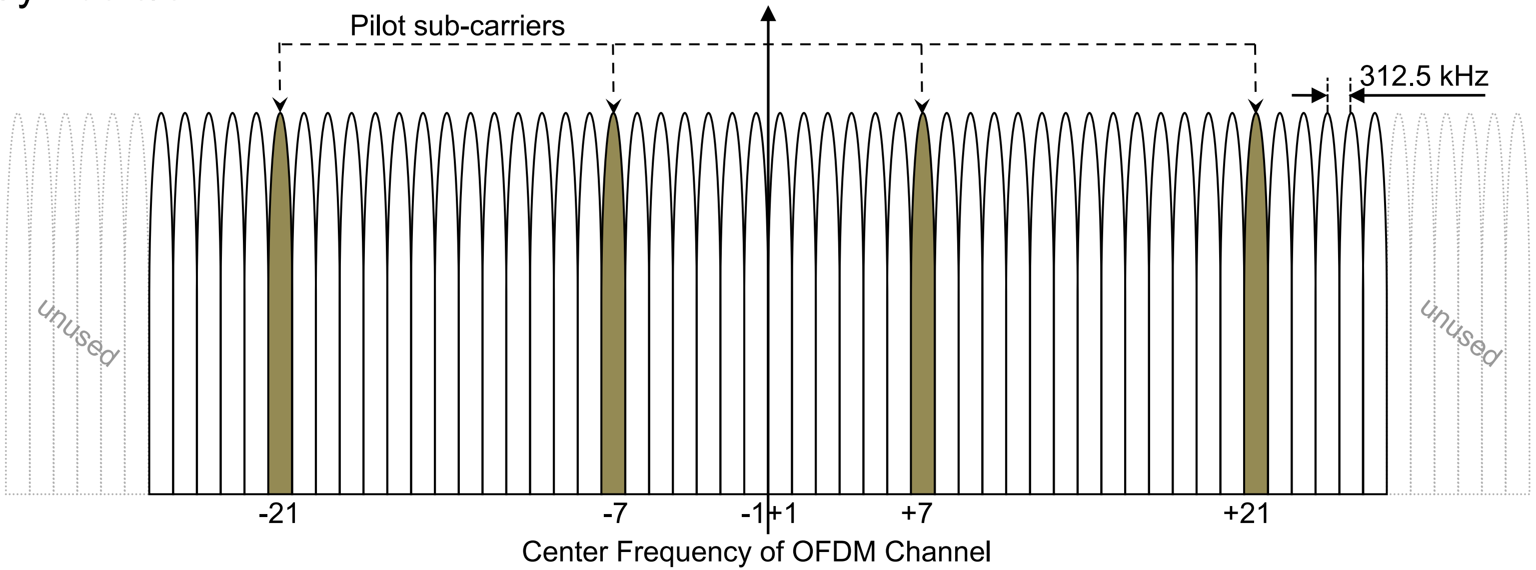
Wi-Fi 2: Orthogonal Frequency Division Multiplex (OFDM)



- Introduction through IEEE Std 802.11a-1999
  - Cooperation with ETSI
- Transforms time domain signals into set of frequencies
  - Generation/separation by FFT-64
    - IFFT/FFT used for coding/decoding
  - Serial data into a set of orthogonal signals denoted symbol
  - Each symbol is build through a combination of ‘tones’
- 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
- Robust against reflections and multi-path propagation through symbol duration and guard interval

OFDM: Time and frequency

- 52 sub-carriers of OFDM-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
- One OFDM symbol of a duration of 3.2 μs is sent every 4 μs
  - 250 kSymbols/s

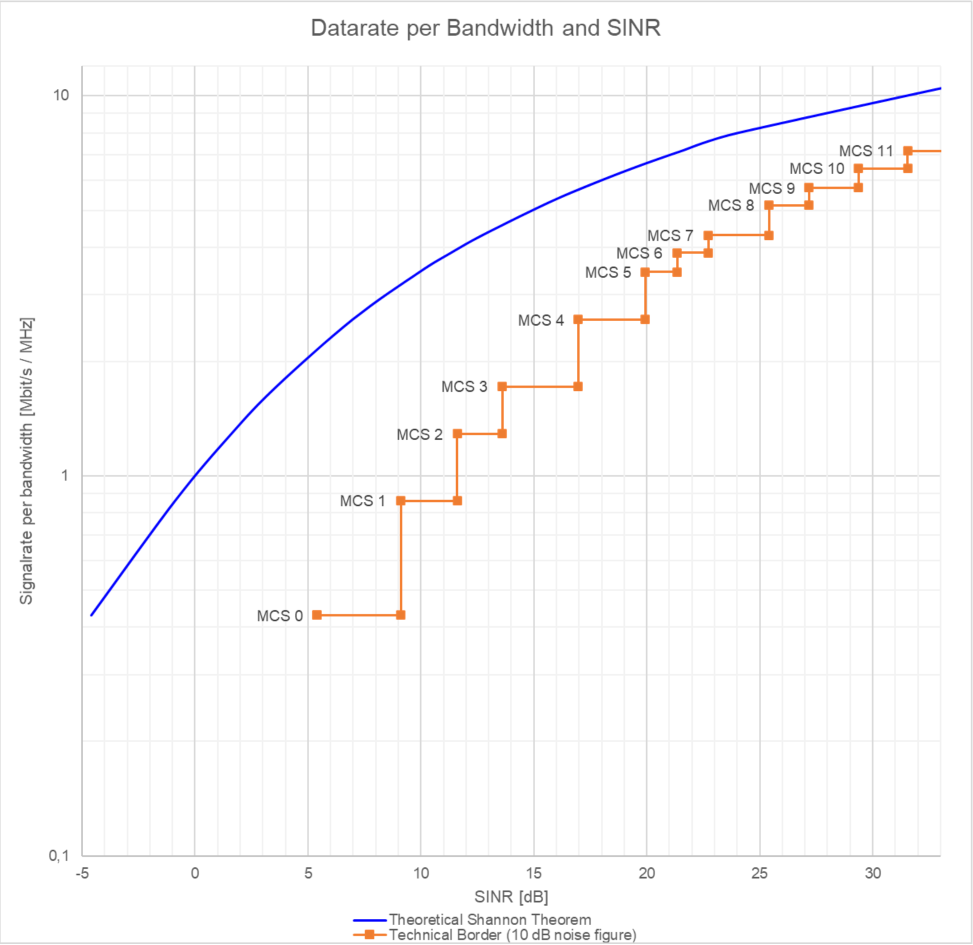


OFDM Modulation and Coding Schemes

- OFDM spreads data transmission across a frequency band
- 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 - 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

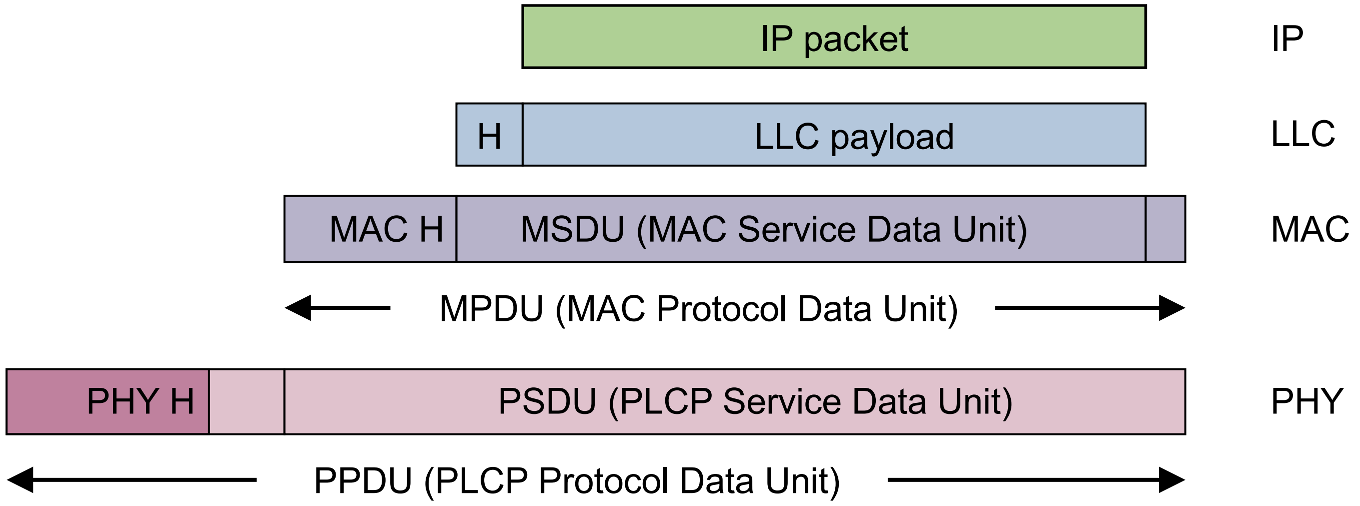
Data Rate (Mbps)	Modulation	Coding Rate	Coded bits per subcarrier	Coded bits per OFDM symbol	Data bits per OFDM symbol	Receive sensitivity	$SINR_{min}$ (technical)
6	BPSK	1/2	1	48	24	- 82 dBm	3 dB
9	BPSK	3/4	1	48	36	- 81 dBm	4 dB
12	QPSK	1/2	2	96	48	- 79 dBm	6 dB
18	QPSK	3/4	2	96	72	- 77 dBm	9 dB
24	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

Advanced Mobile Networks – Wi-Fi PHY Layer

FRAME STRUCTURE

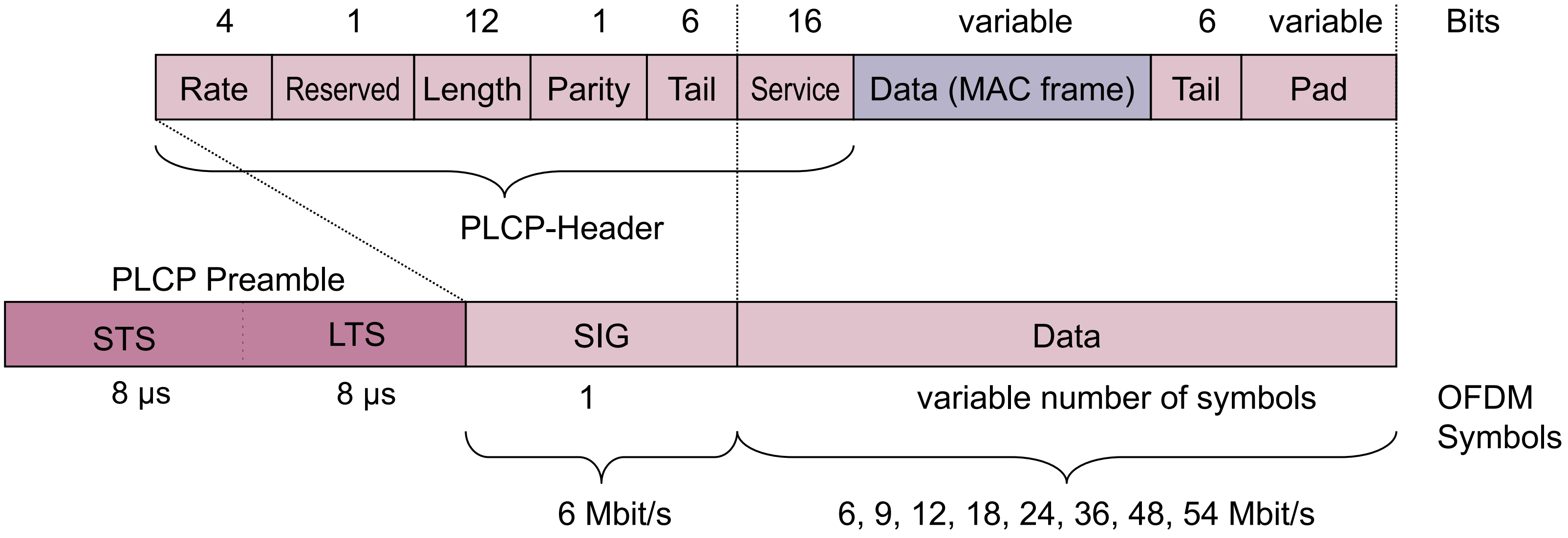
IEEE 802.11 Frame structure overview

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



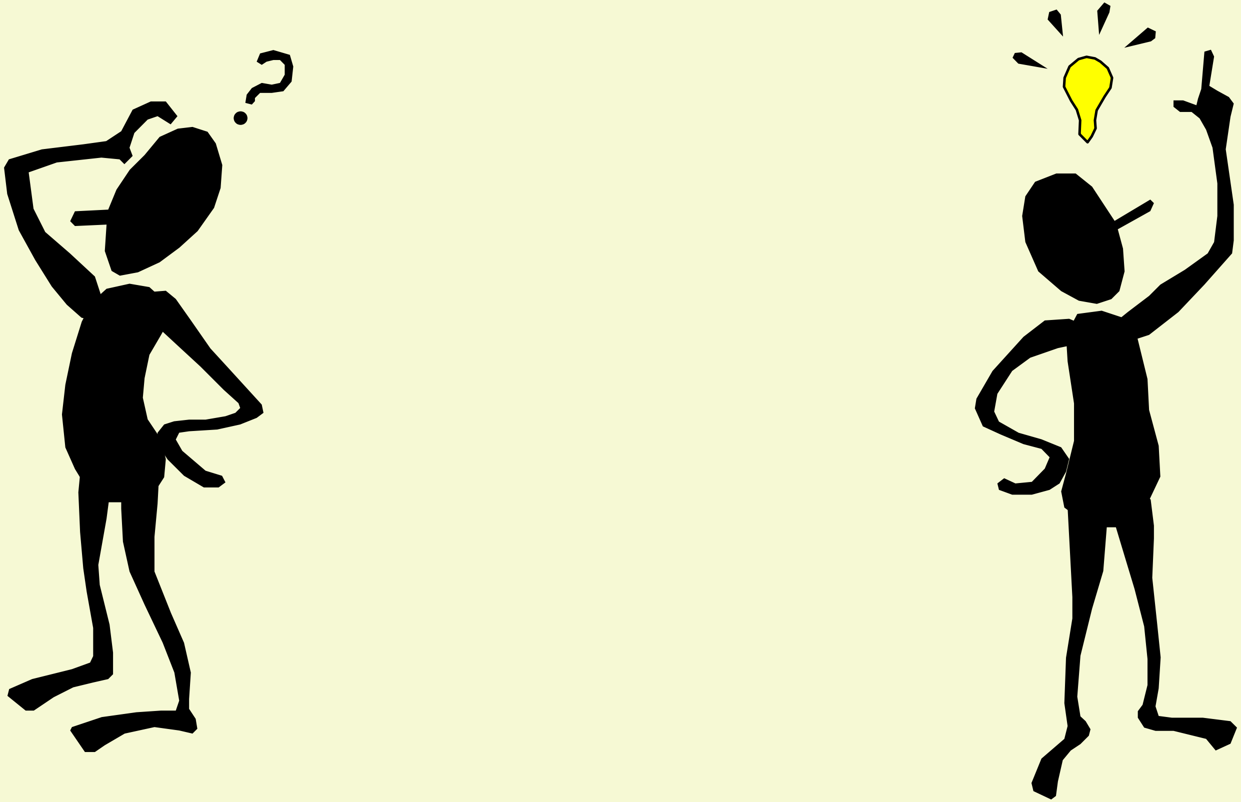
- IEEE 802.11 PHY header carries the information for setting up the reception of radio frames
- Physical Layer Convergence Protocol (PLCP) provides a PHY independent Service Access Point (SAP) for higher layers

OFDM - PHY Frame Format

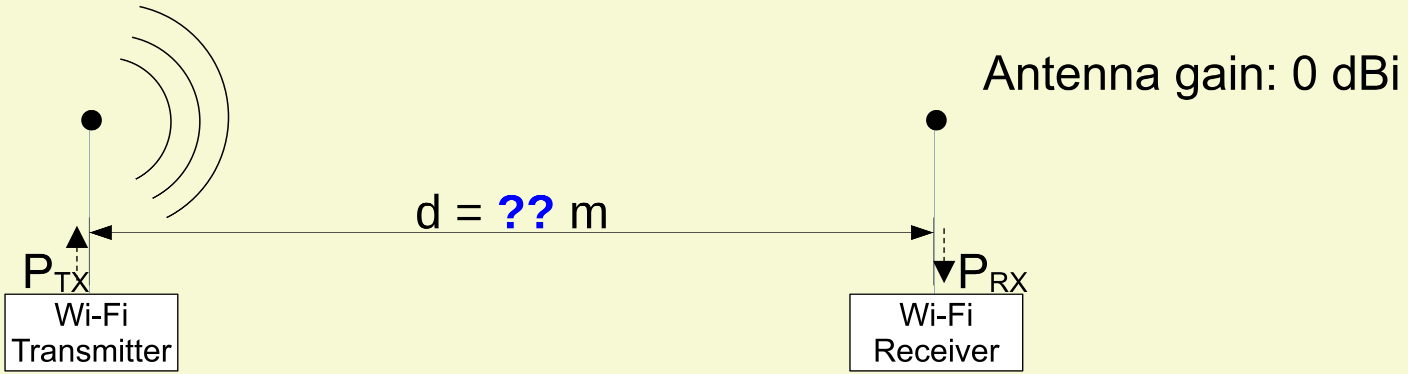


- OFDM PHY Preamble with 12 symbols takes 16 µs
  - 10 short training symbols (STS), each 0.8µs without guard periods
    - Timing synchronization, antenna selection and locking to the signal
  - 2 long training symbols (LTS), each 3.2µs with 0.8µs guard periods for fine tuning
- Signal (SIG) is one OFDM symbol with 24 data bits which takes 4 µs

Exercise



Reach of Wi-Fi 2 in the 5 GHz band



OFDM can adapt to a wide range of transmission distances. How far in open area (η = 2) can Wi-Fi 2 reach at 6 Mbps, and how far at maximum speed (54 Mbps), when the transmitter with antenna exposes an EIRP of 100 mW towards the receiver at 5.5 GHz.

- Which reach can be achieved at 6 Mbps?
- Which reach can be achieved at 54 Mbps?

Advanced Mobile Networks – Wi-Fi PHY Layer

WI-FI 3: EXTENDED RATE PHY

Wi-Fi 3: Extended Rate PHY (802.11g)

- Introduced through IEEE Std 802.11g – 2003
  - Deploys OFDM according to 802.11a in the 2.4 GHz band
    - Backward compatibility with HR/DSSS added

- Support of data rates above 11 Mbps
  - Data rates like 802.11a: 6 Mbps up to 54 Mbps

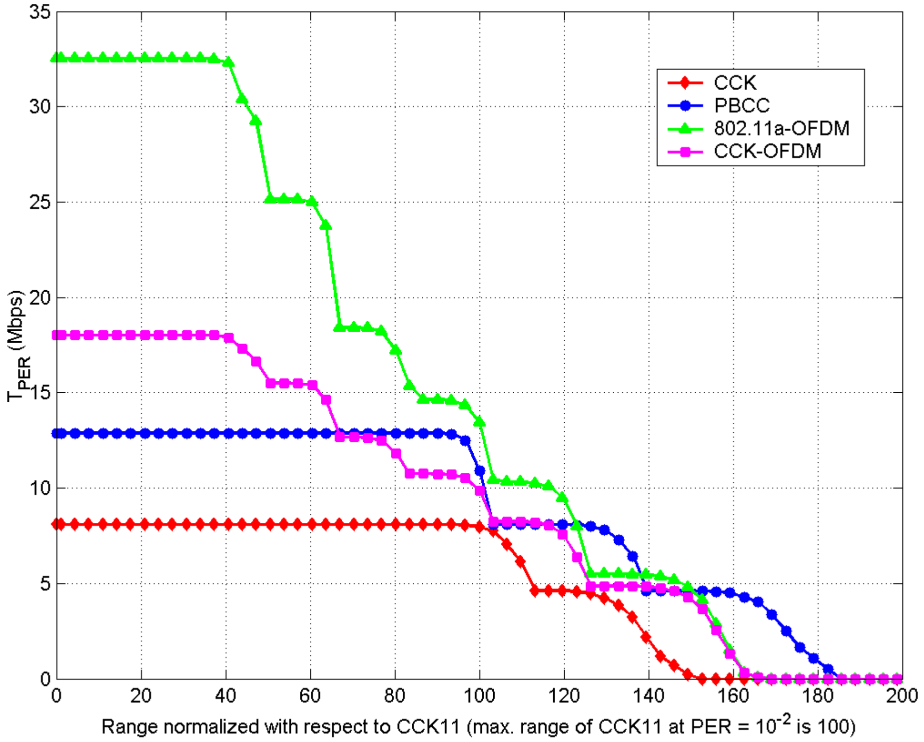
- Advantages of OFDM in the 2.4 GHz band:
  - worldwide harmonized license-exempt frequency band
  - lower attenuation than in the 5GHz band
    - less transmission power required

- MAC layer extensions for backward compatibility to HR/DSSS

- Uses same transmission channels as HR/DSSS
  - 18 MHz OFDM easily fits in 22 MHz HR/DSSS channel

IEEE 802.11 a/b/g – performance and efficiency values

Range vs. Rate



Batra, Shoemake; Texas Instruments;
(Doc: IEEE 802.11-01-286r2)

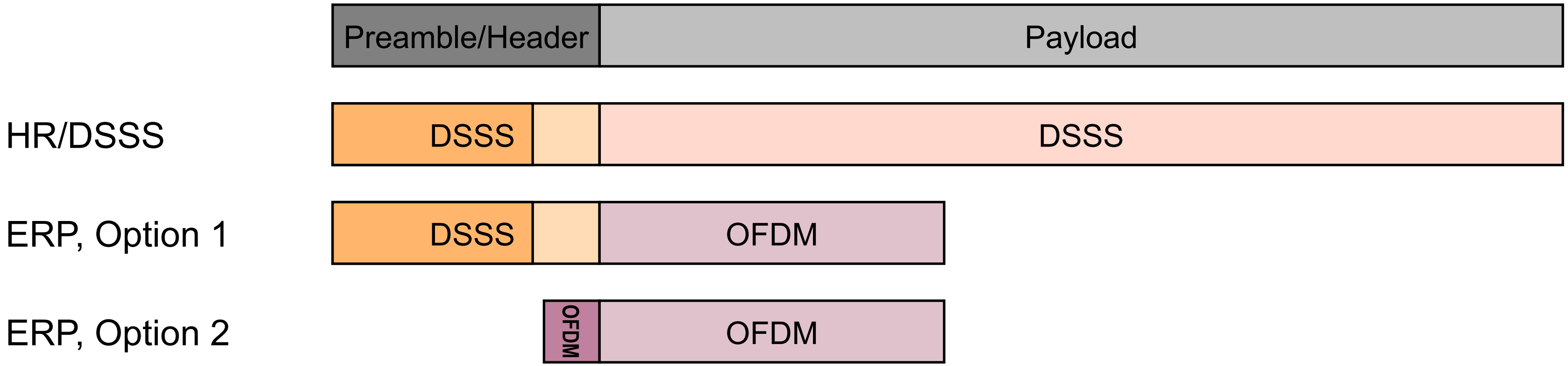
Efficiency

Mode	Mod.	Coding	Mbps	Mbps	%
OFDM	64-QAM	3/4	54	26.12	48%
OFDM	64-QAM	2/3	48	23.25	48%
OFDM	16-QAM	3/4	36	18.31	51%
OFDM	16-QAM	1/2	24	14.18	59%
OFDM	QPSK	3/4	18	11.50	64%
OFDM	QPSK	1/2	12	8.31	69%
OFDM	BPSK	3/4	9	6.55	73%
OFDM	BPSK	1/2	6	4.64	77%
HR	CCK		11	7.18	65%
HR	CCK		5.5	4.07	74%
DSSS	QPSK		2	1.58	79%
DSSS	BPSK		1	0.81	81%

Huawei Quidway WA1006E Wireless Access Point
(http://www.sersat.com/descarga/quidway_wa1006e.pdf)

ERP – HR/DSSS Interworking

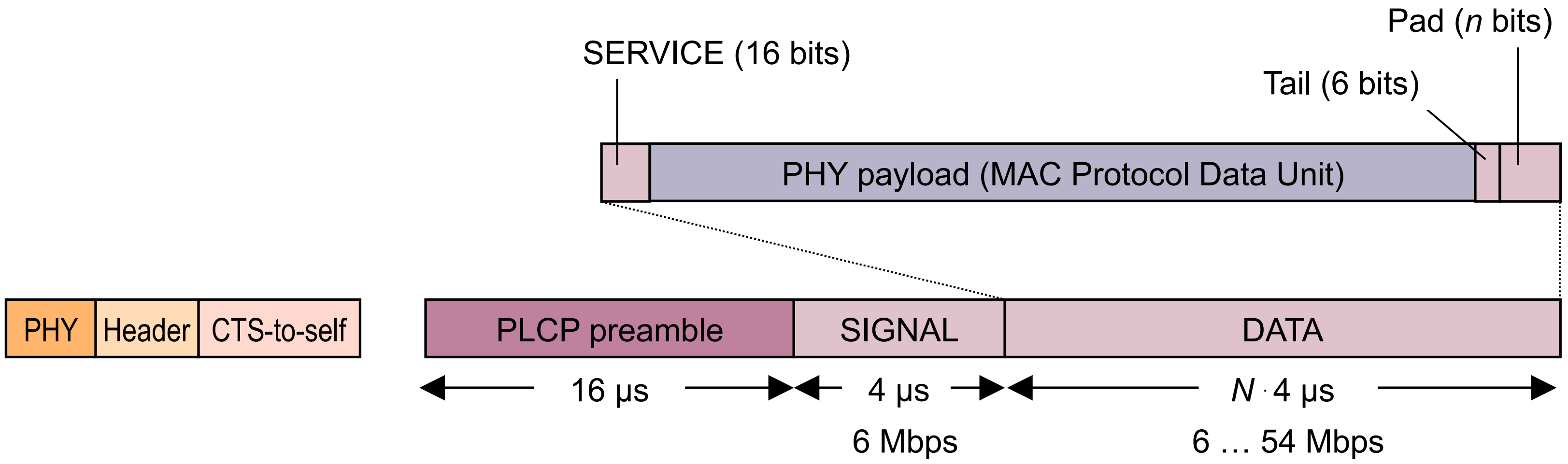
- ERP (802.11g) and HR/DSSS (802.11b) interworking is based on two alternatives regarding the ERP PHY frame structure:



- Option 1 enables HR/DSSS stations to decode the PHY header and keep off the medium according to the Length information
- Option 2 requires additional methods like CTS-to-self or RTS/CTS to provide information to HR/DSSS about other transmissions blocking the medium.

ERP – PHY frame (OFDM native)

- Without backward compatibility, ERP (802.11g) deploys the same PHY frame as OFDM (802.11a)
- 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

Advanced Mobile Networks – Wi-Fi PHY Layer

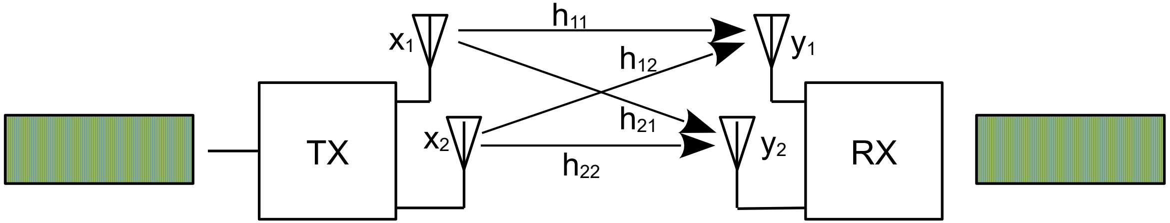
WI-FI 4: HIGH THROUGHPUT

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

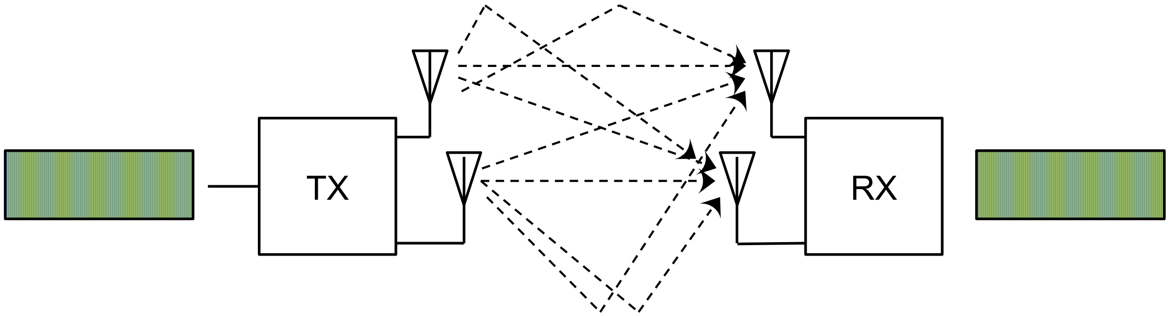
- Introduced through IEEE Std 802.11n – 2009
  - After about 6 years of standards development
- Enhancement to OFDM (5 GHz) and ERP (2.4 GHz)
  - Up to 600 Mbps in either band
- Main techniques deployed to increase of bitrate:
  - <u>**Up to 4 parallel streams using MIMO (Multiple Input Multiple Output)**</u>
  - **Channel bonding of two adjacent channels to 40 MHz**
  - Enhancements to OFDM modulation scheme and timing
  - MAC frame aggregation
    - A-MPDU as well as A-MSDU
  - Block acknowledgments

MIMO (Multiple Input Multiple Output)

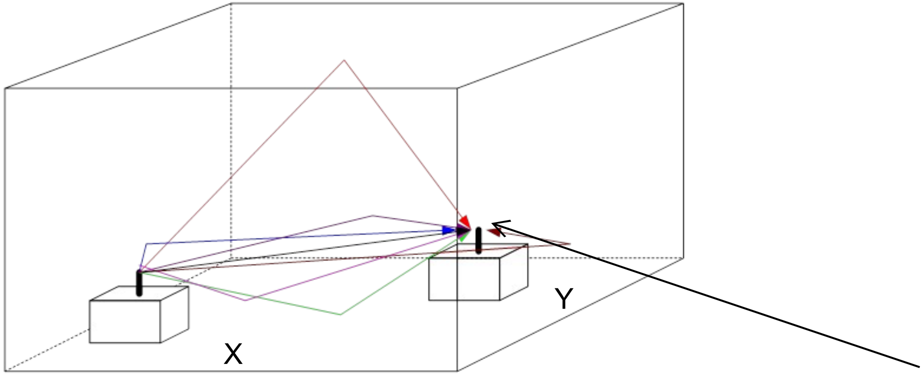
- Mathematical model

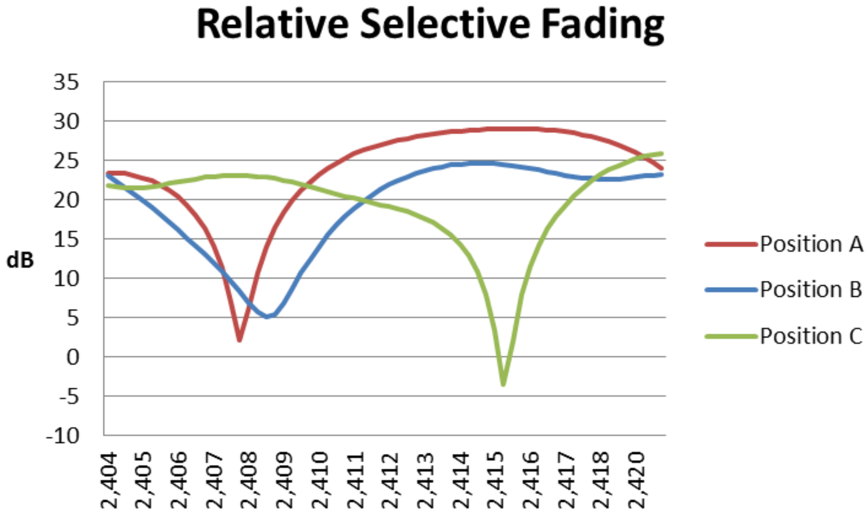


- Higher throughput can be achieved when channel matrix can be inverted.
  - Requires a multipath fading environment, as usual in indoor deployments.



Example of multipath fading environment





Example of selective fading

- Reference doc.: IEEE 802.11-13/0416r5
- Use of ray tracing to estimate delays
- Scenario
  - Room 100 ft by 70 ft (x, y)
  - Ceiling 20 ft
  - RX position (65, 44 w/ 3ft off ground)
  - 10dB obstruction to direct and floor rays

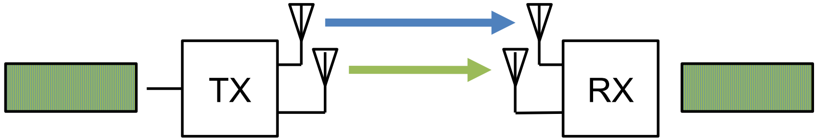
Transmission characteristics taken for

- Position A (21, 45) (delays 23 -100 ns)
- Position B (30, 45) (delays 27 - 102 ns)
- Position C (13, 45) (delays 21 - 99 ns)

Fades up to 25 dB!

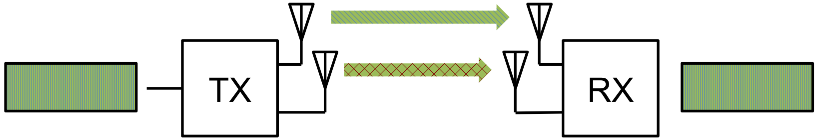
HT MIMO (Multiple Input Multiple Output) variations

- Spatial Multiplexing (SM) aka Space-division multiplexing (SDM)



  - 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.

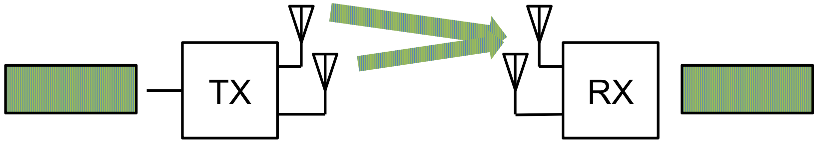
- Space-Time Block Coding (STBC)



  - 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 variations, cont.

- Transmit Beamforming (TxBF)

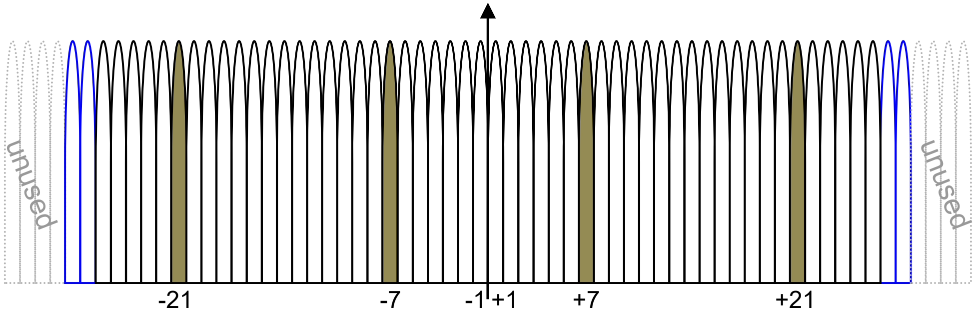


  - Steers signal stream towards the intended receiver by concentrating transmitted RF energy in a given direction.
  - Leverages signal reflection and multipath to improve signal strength at the receiver location, and thereby sustain higher data rates.
  - Required channel knowledge can be obtained implicitly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

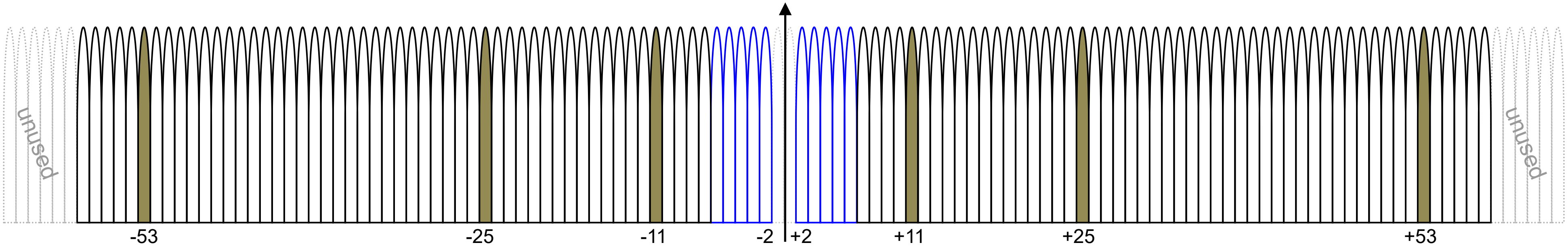
- Availability in HT products:
  - Only Spatial Multiplexing out of the three different MIMO techniques specified in the IEEE Std 802.11n is part of Wi-Fi 4 certification for HT.

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



High Throughput (802.11n) PHY improvements

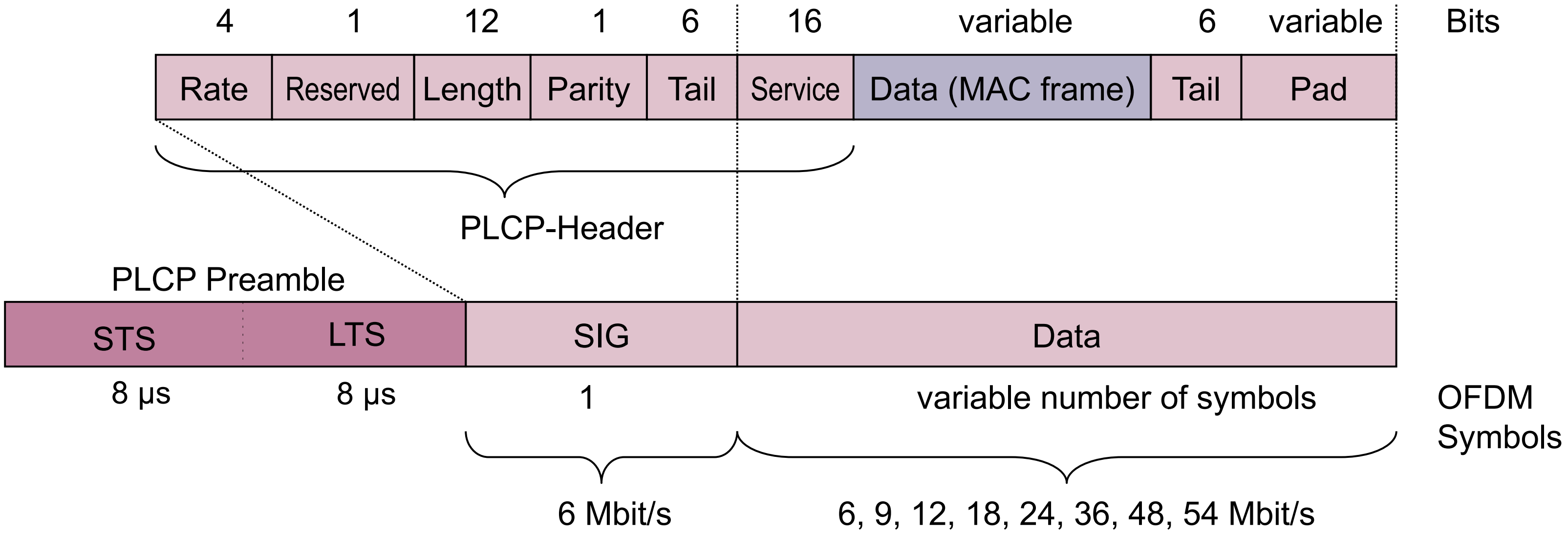
- OFDM *(54 -> 58.5 Mbps)*
  - 52 data sub-carriers instead of 48 (4 pilot tones)
- Forward Error Correction *(58.5 -> 65 Mbps)*
  - 5/6 coding rate in addition to 3/4
- Short Guard Interval *(65 -> 72.2 Mbps)*
  - 0.4 μs down from 0.8 μs
- Channel Bonding *(72.2 -> 150 Mbps)*
  - 40 MHz by combining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

Wi-Fi 4 – HT MCS Options for single stream

MCS Index	Spatial Streams	Modulation type	Coding rate	Data Rate [Mbps]			
				20MHz [52 data sub-carrier]		40 MHz [108 data sub-carrier]	
				0.8 µs GI	0.4 µs GI	0.8 µs GI	0.4 µs GI
0	1	BPSK	1/2	6.5	7.2	13.5	15.0
1	1	QPSK	1/2	13.0	14.4	27.0	30.0
2	1	QPSK	3/4	19.5	21.7	40.5	45.0
3	1	16-QAM	1/2	26.0	28.9	54.0	60.0
4	1	16-QAM	3/4	39.0	43.3	81.0	90.0
5	1	64-QAM	2/3	52.0	57.8	108.0	120.0
6	1	64-QAM	3/4	58.5	65.0	121.5	135.0
7	1	64-QAM	5/6	65.0	72.2	135.0	150.0

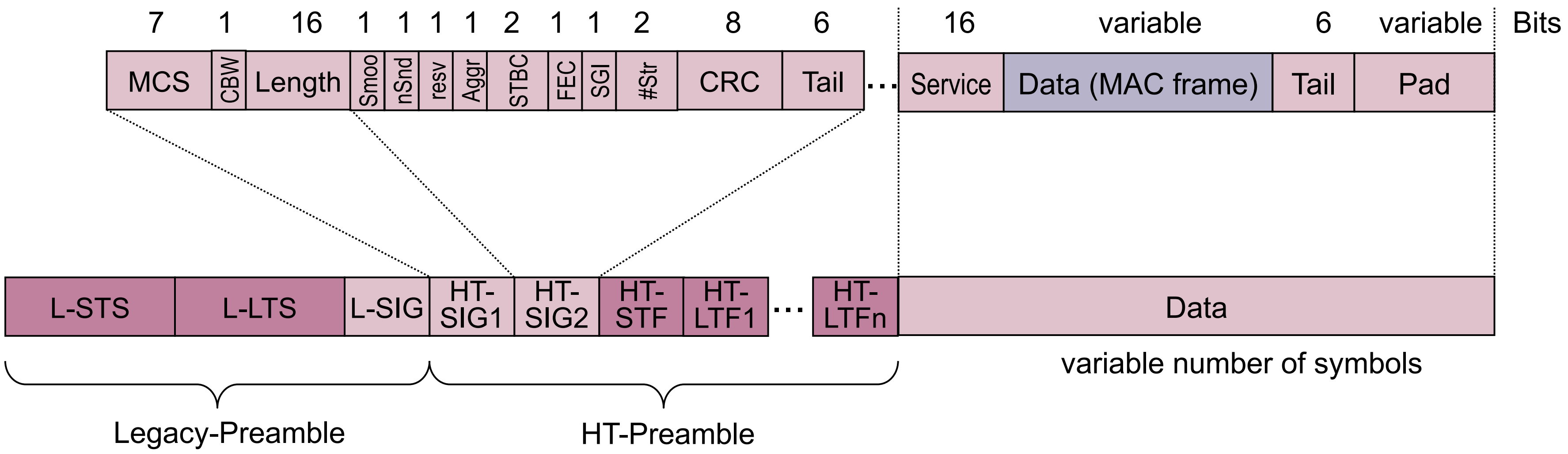
- For multiple streams through MIMO, multiply numbers in table by the number of streams.

Legacy OFDM - PHY Frame Format



- OFDM PHY Preamble with 12 symbols takes 16 µs
  - 10 short training symbols (STS), each 0.8µs without guard periods
    - Timing synchronization, antenna selection and locking to the signal
  - 2 long training symbols (LTS), each 3.2µs with 0.8µs guard periods for fine tuning
- Signal (SIG) is one OFDM symbol with 24 data bits which takes 4 µs

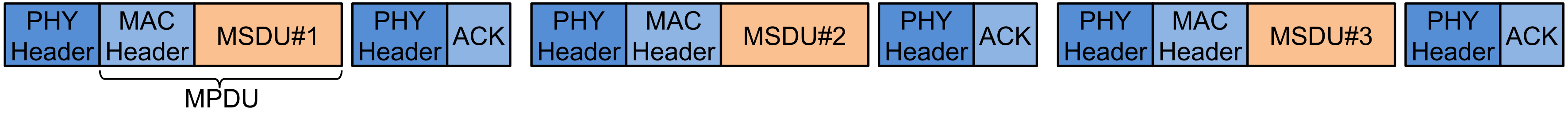
HT - PHY Frame Format



- 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

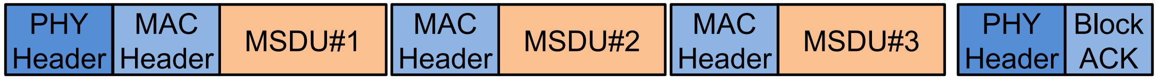
HT MAC Protocol Data Unit Aggregation

- 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

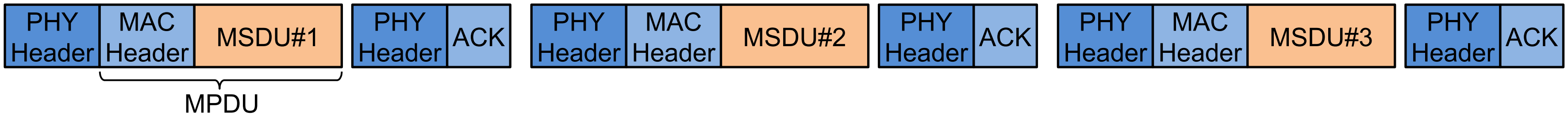
- MAC Protocol Data Unit Aggregation (A-MPDU) groups multiple MPDU sub-frames each with its own MAC header into one PSDU with up to 65535 bytes.



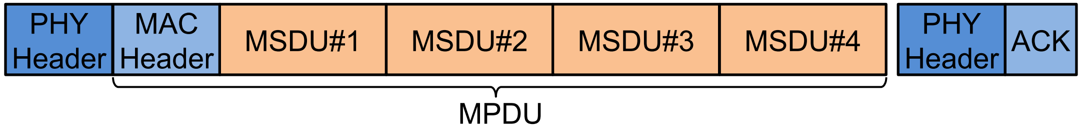
  - Reduced Interframe Space (RIFS) of 2µs used as delimiter between MPDUs
  - Block Acknowledgement for reduction of ACKs to one per multiple MPDU transmission
  - Selective retransmission of a single MPDU possible in the case that one of the aggregated MPDUs gets impacted.

HT MAC Service Data Unit Aggregation

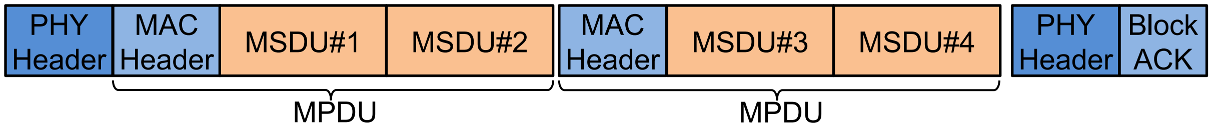
- MAC efficiency suffers when transferring sequence of smaller frames



- 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.

Advanced Mobile Networks – 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 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
- Multi-user MIMO (MU-MIMO)
  - Multiple STAs, each with one or more antennas, transmit or receive independent data streams simultaneously
  - 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
  - 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)

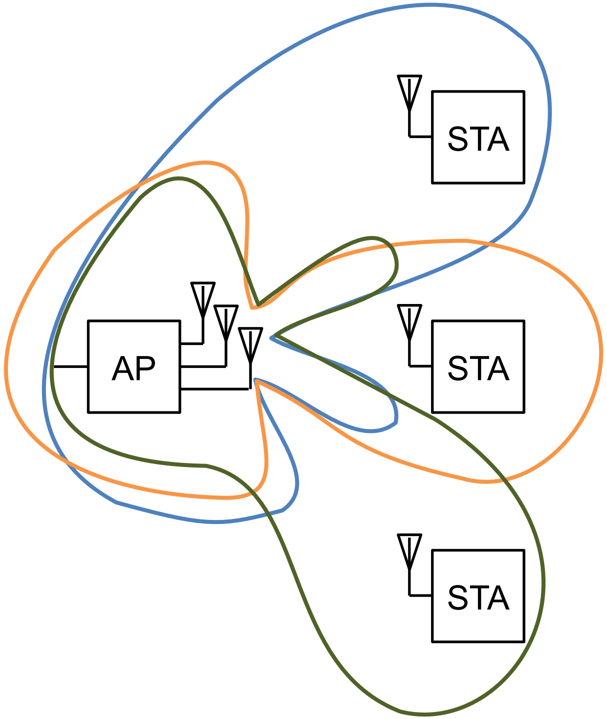
MCS index	Spatial Streams	Modulation type	Coding rate	Data rate [Mbps]							
				20 MHz [52 dsc]		40 MHz [108 dsc]		80 MHz [234 dsc]		160 MHz [468 dsc]	
				0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI
0	1	BPSK	1/2	6.5	7.2	13.5	15.0	29.3	32.5	58.5	65.0
1	1	QPSK	1/2	13.0	14.4	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 MIMO 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 antenna resources 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 5 – VHT (802.11ac) example configurations

Scenario	Typical Client Form Factor	PHY Link Rate	Aggregate Capacity
1-antenna AP, 1-antenna STA, 80 MHz	Handheld	433 Mbps	433 Mbps
2-antenna AP, 2-antenna STA, 80 MHz	Tablet, Laptop	867 Mbps	867 Mbps
1-antenna AP, 1-antenna STA, 160 MHz	Handheld	867 Mbps	867 Mbps
2-antenna AP, 2-antenna STA, 160 MHz	Tablet, Laptop	1.69 Gbps	1.69 Gbps
4-antenna AP, four 1-antenna STAs, 160 MHz (MU-MIMO)	Handheld	867 Mbps to each STA	3.39 Gbps
8-antenna AP, 160 MHz (MU-MIMO) -- one 4-antenna STA -- one 2-antenna STA -- two 1-antenna STAs	Set-top Box, Tablet, Laptop, PC, Handheld	3.39 Gbps to 4x STA 1.69 Gbps to 2x STA 867 Mbps to each 1x STA	6.77 Gbps
8-antenna AP, four 2-antenna STAs, 160 MHz (MU-MIMO)	Digital TV, PC, Tablet, Laptop,	1.69 Gbps to each STA	6.77 Gbps

- Wi-Fi 5 certification supports MU-MIMO, up to 4x4 MIMO and 160 MHz channels.

Advanced Mobile Networks – Wi-Fi PHY Layer

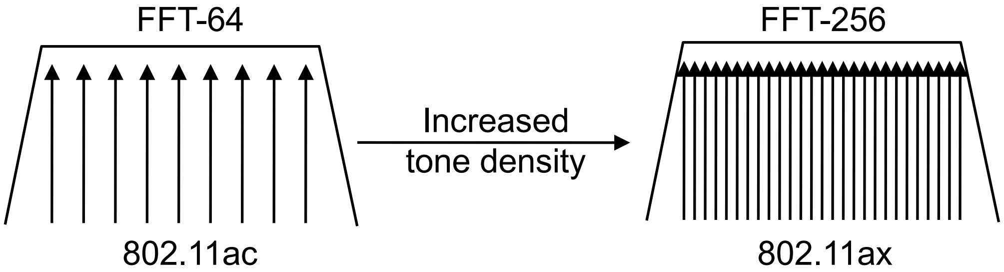
WI-FI 6: HIGH EFFICIENCY

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

- No aim to increase peak data rates far beyond what is already available by VHT
- Main focus of standards development was on increasing performance of Wi-Fi 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)
- Standards development of IEEE Std 802.11ax took more than 6 years due to the high complexity of the added enhancements while maintaining full backward compatibility.

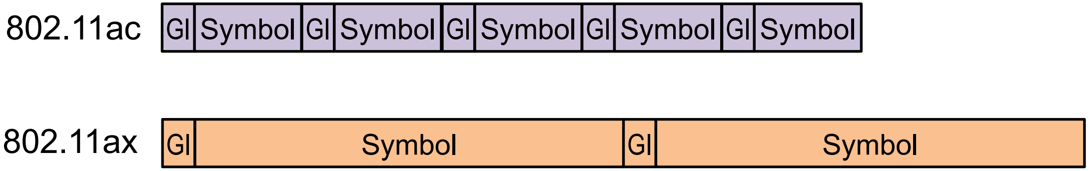
Wi-Fi 6 – HE (802.11ax) increased link efficiency

Frequency domain
(~ 5% gain)



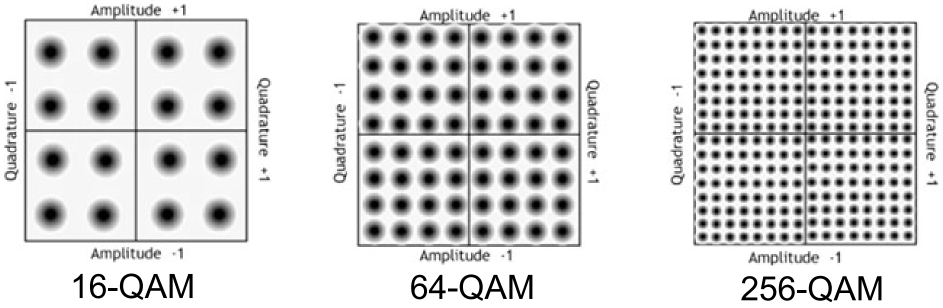
Squeeze more tones in at the channel edge

Time domain
(~ 15% gain)



Guard Interval (GI) overhead reduced

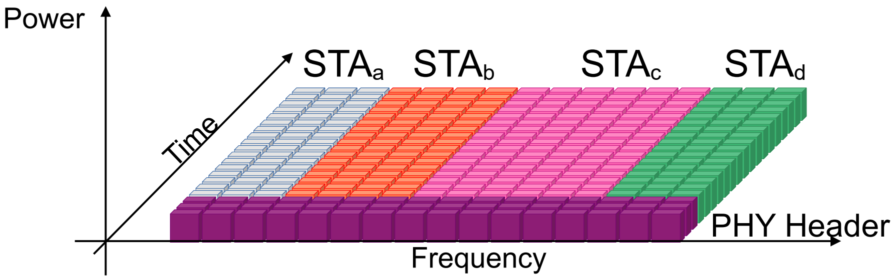
Modulation
(~ 25% gain)

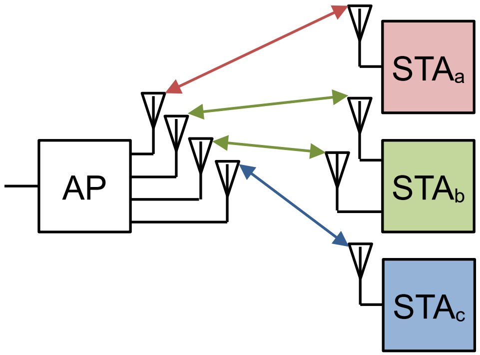


+ 1024-QAM
(802.11ax only)

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

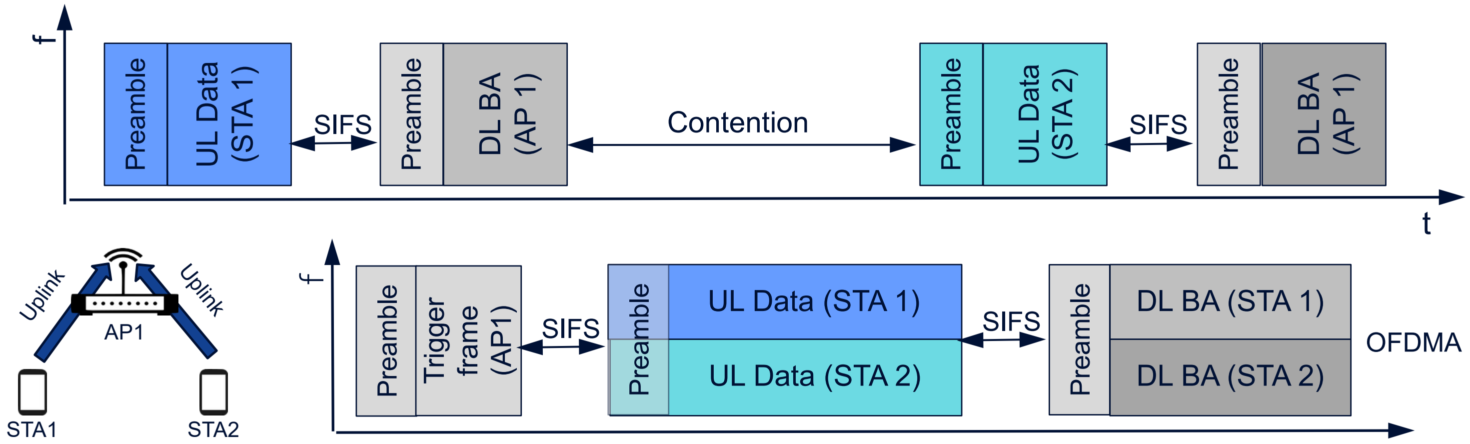
- Higher efficiency through multiplexing users in both frequency and space
  - Uplink and downlink OFDMA and MU-MIMO
    - OFDMA allows for much more fine-grain radio resource management than MU-MIMO





- 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)
  - Will be addressed in next section

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: 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

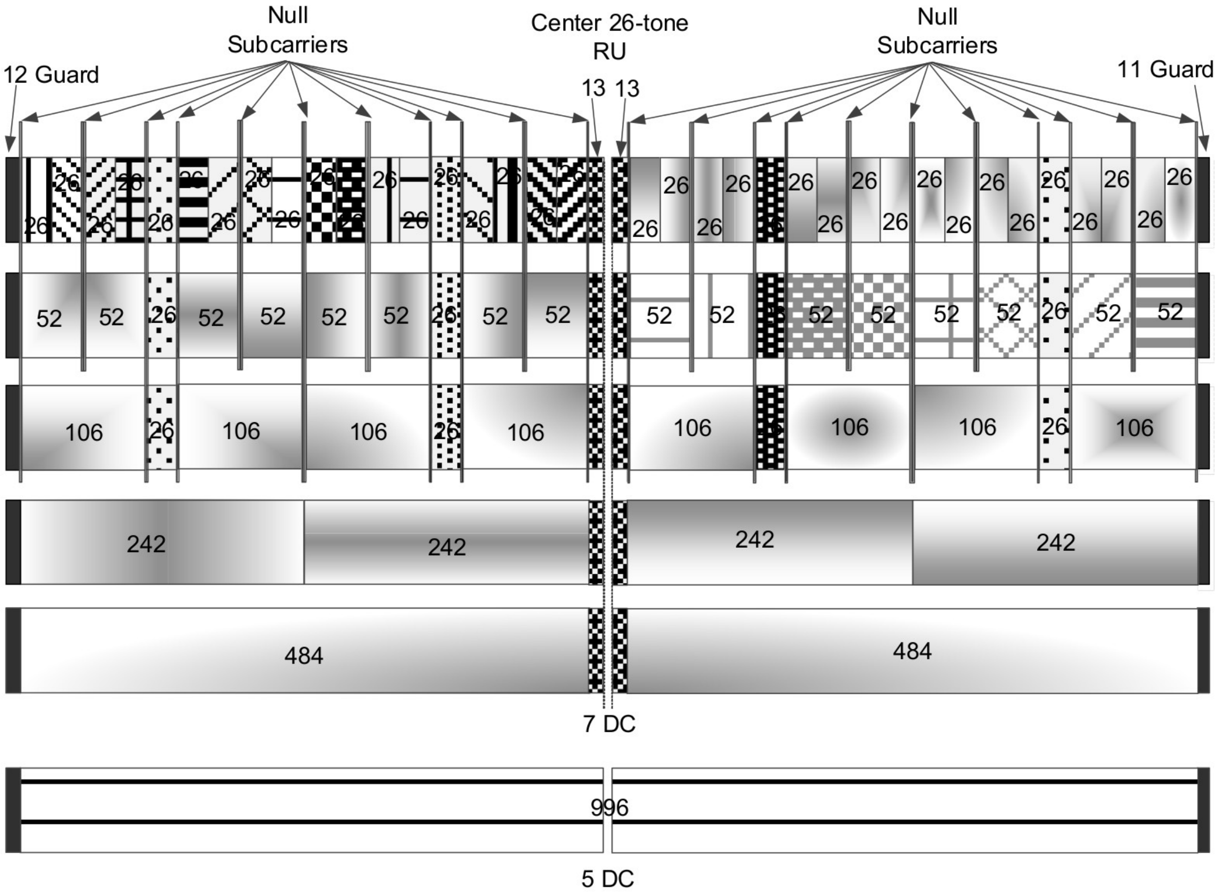


Figure 27-7—RU locations in an 80 MHz HE PPDU

Wi-Fi 6 – HE (802.11ax) MCSs for single spatial 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	8	8.6	16	17.2	34	36.0	68	72
1	QPSK	1/2	16	17.2	33	34.4	68	72.1	136	144
2	QPSK	3/4	24	25.8	49	51.6	102	108.1	204	216
3	16-QAM	1/2	33	34.4	65	68.8	136	144.1	272	282
4	16-QAM	3/4	49	51.6	98	103.2	204	216.2	408	432
5	64-QAM	2/3	65	68.8	130	137.6	272	288.2	544	576
6	64-QAM	3/4	73	77.4	146	154.9	306	324.4	613	649
7	64-QAM	5/6	81	86.0	163	172.1	340	360.3	681	721
8	256-QAM	3/4	98	103.2	195	206.5	408	432.4	817	865
9	256-QAM	5/6	108	114.7	217	229.4	453	480.4	907	961
10	1024-QAM	3/4	122	129.0	244	258.1	510	540.4	1021	1081
11	1024-QAM	5/6	135	143.4	271	286.8	567	600.5	1134	1201

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

Advanced Mobile Networks – Wi-Fi PHY Layer – OFDM

WI-FI 7: EXTREMELY HIGH THROUGHPUT

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

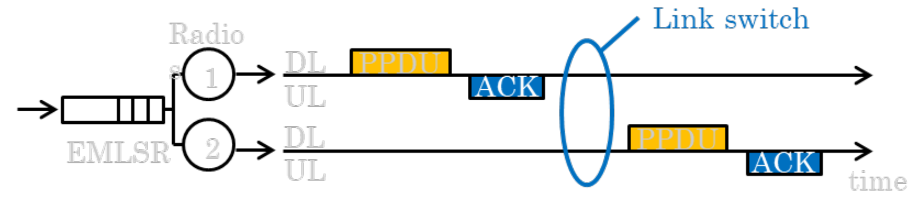
- Carrier frequencies between 1 and 7.125 GHz.
- Wider bandwidth (320 MHz)
- QAM-4096 coding and modulation
- Better efficiency through puncturing and new header structures
- Technical highlight: **Multi Link Operation**
- Maximum MAC throughput of 36 Gbps/AP
  - ~ 4x compared to Wi-Fi 6
  - acchieved through wider channel (2x), multi-link operation (~1.6x), and PHY enhancements
- Backward compatibility and coexistence with legacy Wi-Fi devices in the 2.4 GHz, 5 GHz and 6 GHz bands.
- Timeline
  - IEEE ratification in September 2024, certified products available since beginning of 2024

Main enhancements of Wi-Fi 7 (802.11be)

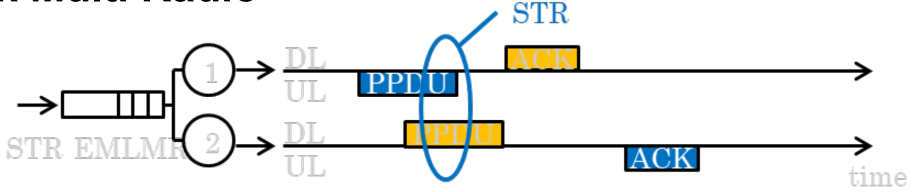
Feature	Benefit
320 MHz channels	• Two times higher throughput than Wi-Fi CERTIFIED 6® by doubling the widest channel size • Multigigabit Wi-Fi device speeds • Enables a higher number of simultaneous transmissions at the fastest possible speeds
4K QAM	• 20 percent higher transmission rates than Wi-Fi 6's 1024-QAM
Multiple RUs to a single STA	• Multiple RUs can be assigned to a single user and can combine RUs • It significantly improves flexibility for spectrum resource scheduling for increased efficiency.
Multi-link operation	• MLO enables devices to combine different channels across frequency bands together, allowing concurrent transmission and reception of data over multiple links • MLO allows more efficient load balancing of traffic among links to meet user needs, such as utilizing 5 GHz or 6 GHz for higher throughput and 2.4 GHz for range and selecting the most robust link in the presence of interference, resulting in increased throughput, lower latency, and improved reliability.
Triggered uplink access	• Optimizes Wi-Fi 6-defined triggered uplink access scheduling to accommodate uplink latency-sensitive streams • Satisfies uplink streams' QoS requirements and significantly improves uplink efficiency
Emergency Preparedness Communication Services	• Provides a seamless NSEP service experience to the users while maintaining the priority and quality of service in Wi-Fi access networks • Support for 5G offload to Wi-Fi access

Multi-Link Operation (MLO)

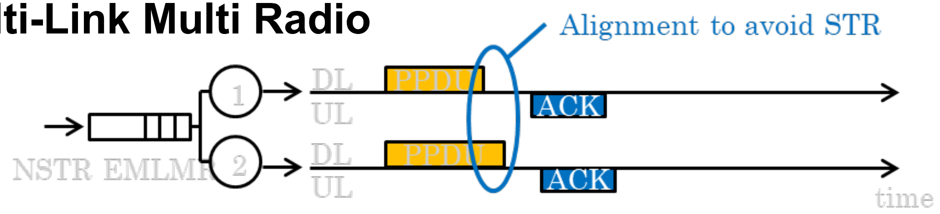
- MLO allows devices to have connectivity on multiple links, enabling a STA multi-link device (MLD) to discover, authenticate, associate, and set up multiple links with an AP MLD.
- Defined modes of operation:
  - **Enhanced Multi-Link Single Radio**
    - Allows quickly to choose the best link with 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 7 compared to Wi-Fi 6

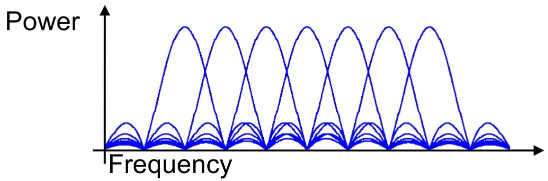
Feature	Wi-Fi 6 (802.11ax)	Wi-Fi 7 (802.11be)	Benefit
Bandwidth	20 MHz, 40 MHz, 80 MHz, 80+80 MHz and 160 MHz channels	Adds 320 MHz channels; removes support of non-contiguous arrangements such as 80+80 MHz	Increased data rate and lower complexity
Modulation	BPSK, QPSK, 16QAM, 64QAM, 256QAM, 1024QAM	BPSK, QPSK, 16QAM, 64QAM, 256QAM, 1024QAM, 4096QAM	Increased throughput
Resource units	Single resource unit (RU) per user	Adds support for multiple RU (MRU) assignments to a single user and changed allocation plan for ≥ 80 MHz	Efficient spectrum utilization and more scheduling flexibility
Compatibility	Backward compatibility in 2.4 GHz and 5 GHz band	Backward compatible to IEEE 802.11ax plus enhanced preamble for future extensibility	Easier/better coexistence with future Wi-Fi generations
Preamble puncturing	Supported	Enhancements to spectral emission masks when puncturing is used	More efficient spectrum utilization and better coexistence with other users
Multilink operation (MLD)	Not available	New feature	Improved spectral efficiency, load balancing, higher data throughput, lower latency
Restricted target wake time (TWT)	Not available	New feature	enables dedicated service period for low latency traffic

Advanced Mobile Networks – Wi-Fi PHY Layer

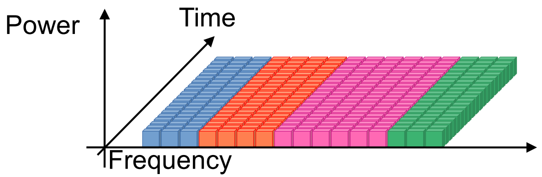
WI-FI 4 TO WI-FI 7 ENHANCEMENTS

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 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

Advanced Mobile Networks – Wi-Fi PHY Layer

LOOKING AHEAD: WI-FI 8

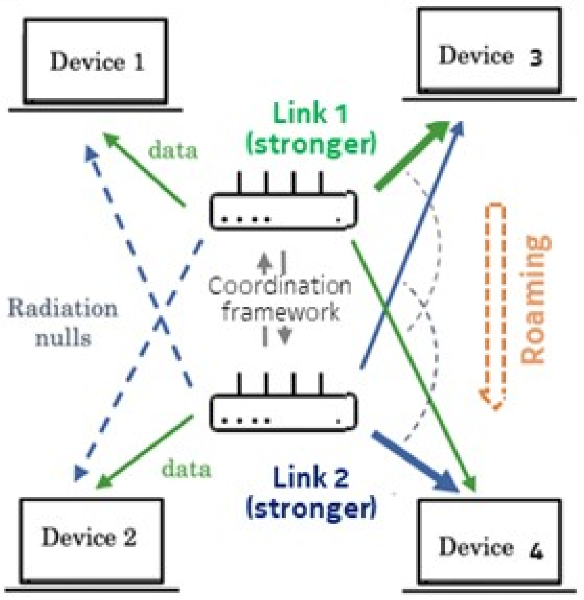
IEEE P802.11bn Ulta-High-Reliability

- The planned amendment will add an Ultra High Reliability capability to a Wireless Local Area Network (WLAN). The Ultra High Reliability capability is defined for both an isolated Basic Service Set (BSS) and overlapping BSSs:
  - At least one mode of operation capable of increasing throughput by 25%, as measured at the MAC data service Access Point, in at least one Signal to Interference and Noise Ratio (SINR) level (Rate-vs-Range), compared to the Extremely High Throughput MAC/PHY operation, and
  - At least one mode of operation capable of reducing latency by 25% for the 95th percentile of the latency distribution compared to the Extremely High Throughput MAC/PHY operation and
  - At least one mode of operation capable of reducing MAC Protocol Data Unit (MPDU) loss by 25% compared to the Extremely High Throughput MAC/PHY operation for a given scenario, especially for transitions between BSSs.
  - Power saving at the AP side and peer-to-peer operation.
- Wi-Fi 8 targeted for 2028 will be the first generation aiming to improve the Wi-Fi protocol's reliability, with a focus on service availability and delay guarantees.

Topics and approaches considered for P802.11bn

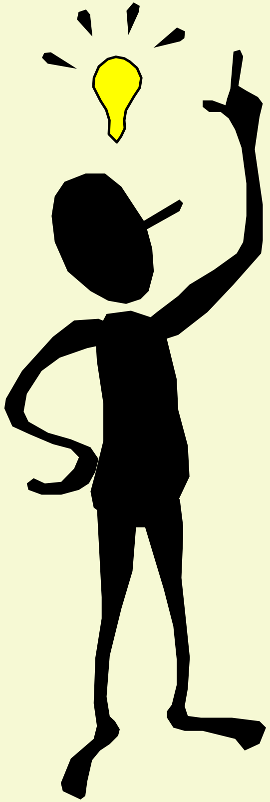
Distributed MLO and multi-AP coordination

- Devices roaming between APs is a major cause of Wi-Fi link unreliability. The MLO architecture of Wi-Fi 7 offers a high degree of flexibility and could improve mobility when AP MLO could stretch over multiple Aps.
- A new distributed MLO framework, where logical APs under the control of the same entity can create a distributed virtual cell where a device's mobility is handled by activating multiple links from different distributed APs. It ensures a moving device is always seamlessly connected to at least one link (make-before-break handover)
- Such distributed AP framework would also provide the base for coordination among adjacent APs to better control transmission through coordinated TDMA/OFDMA, coordinated Spatial Reuse, joint transmissions, coordinated beamforming, and other.



Distributed Multi-Link operation and AP-coordination

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 Wi-Fi 2/802.11a?
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