WLAN IEEE 802.11

aka Wi-Fi

Max Riegel

Lectures overview

- **June 25th**
  - Wi-Fi deployments
  - Standardization environment
  - Wi-Fi system architecture
  - Wi-Fi security
- **July 2nd**
  - Wi-Fi security
  - Medium access functions
- **July 9th**
  - MAC layer management frame formats
  - Quality of Service
  - Spectrum and wireless channel characteristics
- **July 16th**
  - Wi-Fi radio for 2.4 GHz and 5 GHz bands
  - (HaLow extension for below 1GHz bands - tbd)

Standards environments

STANDARD REFERENCE

IEEE Std 802.11™-2016 + amendment 802.11ah

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

IEEE Computer Society

- Can be downloaded at no charge by 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
- Where appropriate presentation adopts 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

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

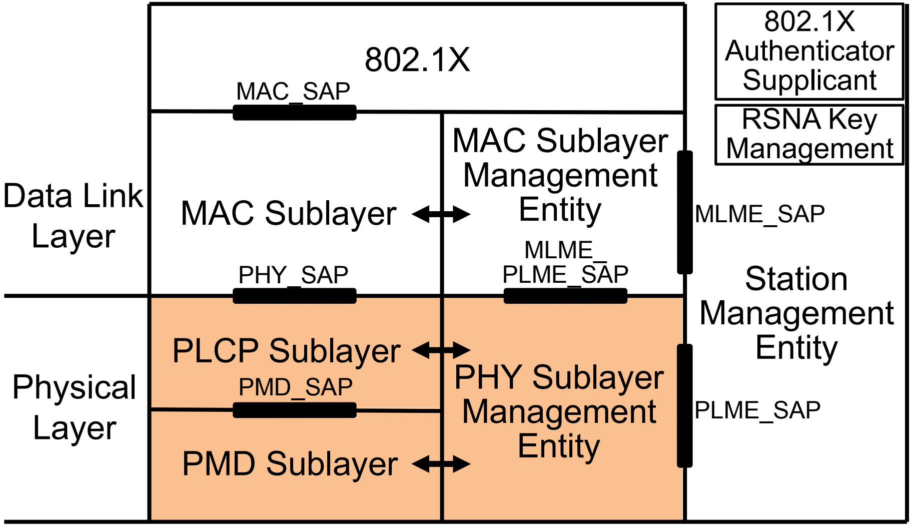
- Revision of IEEE Std 802.11-2012
  - Previous revisions: IEEE Std 802.11-2007 and IEEE Std 802.11-1999
  - Initial IEEE 802.11 standard release in 1997
- Comprises initial IEEE Std 802.11-1999 together with all amendments IEEE 802.11a-1999 … IEEE 802.11af-2013
  - i.e.: a, b, d, e, g, h, I, j, k, n, p, r, s, u, v, w, y, z, aa, ac, ad, ae, af

Amendment IEEE Std 802.11ah-2016

- Amendment 2: Sub 1 GHz License Exempt Operation

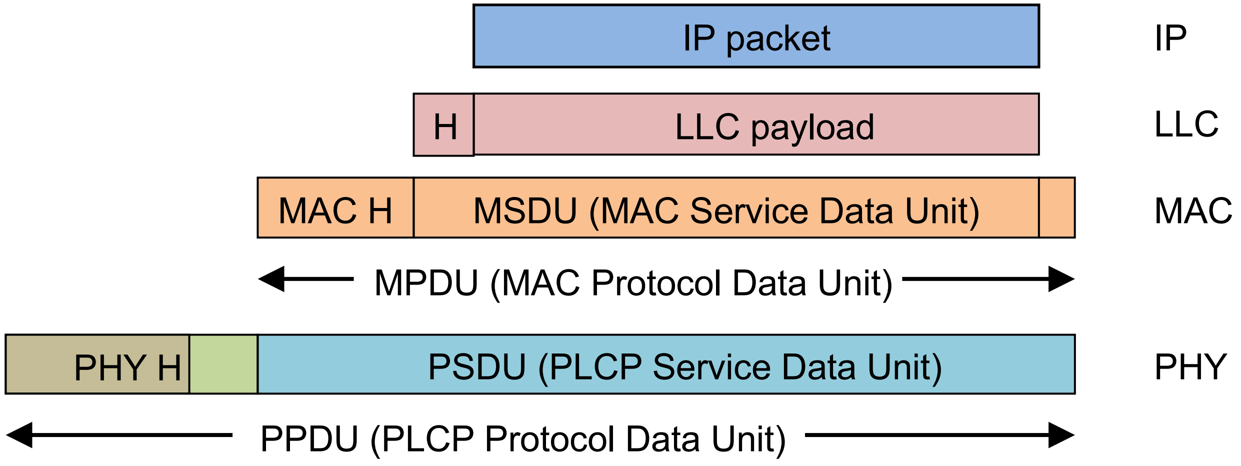
IEEE 802.11 Protocol architecture

- 802.1X
  - Port Access Entity
  - Authenticator/Supplicant
- RSNA Key Management
  - Generation of Pair-wise and Group Keys
- Station Management Entity (SME)
  - interacts with both MAC and PHY Management
- MAC Sublayer Management Entity (MLME)
  - synchronization
  - power management
  - scanning
  - authentication
  - association
  - MAC configuration and monitoring
- MAC Sublayer
  - basic access mechanism
  - fragmentation
  - encryption
- PHY Sublayer Management Entity (PLME)
  - channel tuning
  - PHY configuration and monitoring
- Physical Sublayer Convergence Protocol (PLCP)
  - PHY-specific, supports common PHY SAP
  - provides Clear Channel Assessment signal (carrier sense)
- Physical Medium Dependent Sublayer (PMD)
  - modulation and encoding



IEEE 802.11 Frame structure

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


IP packet
IP
H
LLC payload
LLC
MAC H
MSDU (MAC Service Data Unit)
MAC
MPDU (MAC Protocol Data Unit)
PHY H
PSDU (PLCP Service Data Unit)
PHY
PPDU (PLCP Protocol Data Unit)

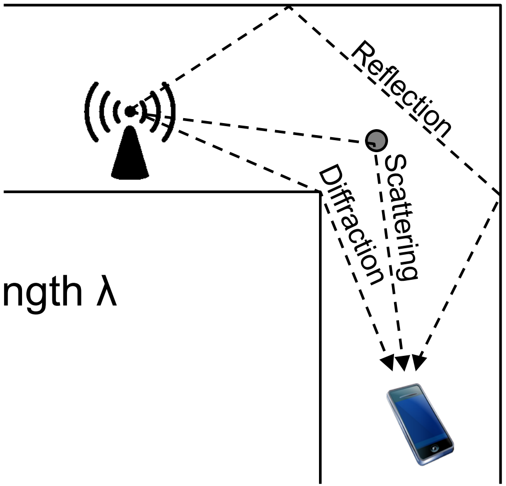
- IEEE 802.11 PHY header carries the information for setting up the reception of radio frames
- Physical Layer Convergence Protocol (PLCP) provides a PHY independent Service Access Point (SAP) for higher layers

WLAN IEEE 802.11

WIRELESS CHANNELS

Radio signal propagation issues

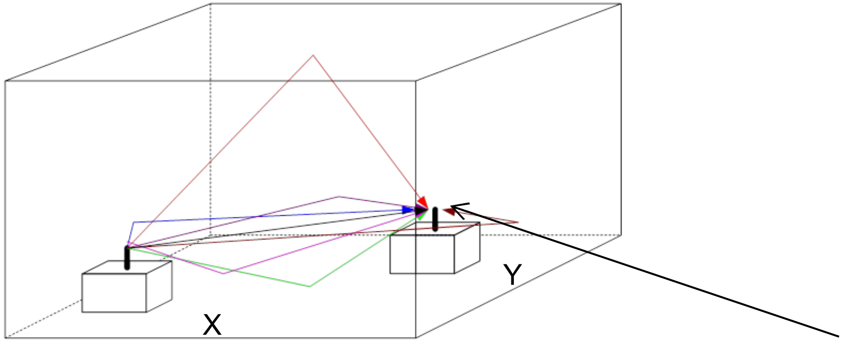
- Path loss
  - Attenuation due to distance and frequency
- Reflection
  - Surface large relative to wavelength λ of signal
- Diffraction
  - Edge of impenetrable body that is large relative to wavelength λ
- Scattering
  - Obstacle size in order of wavelength λ, e.g. lamp posts

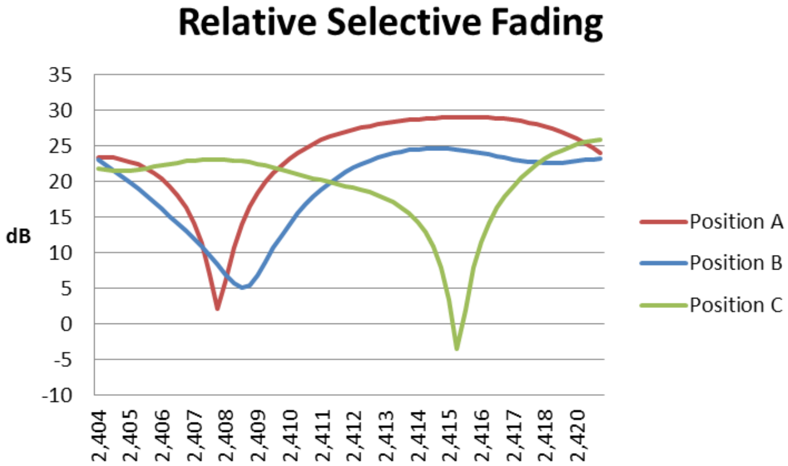


Main issues:

- Line-Of-Sight:
  - Reflected signals may cause major impact on signal
- non-Line-Of-Sight:
  - Diffraction and scattering are primary means of reception

WLAN channels with selective fading





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!

WLAN IEEE 802.11

WI-FI RADIO FOR 2.4 & 5 GHZ

Wi-Fi radio for 2.4 GHz and 5 GHz bands

- Unlicensed Spectrum
  - 2.4 GHz
  - 5 GHz
- IEEE 802.11 Radio modes for 2.4GHz & 5 GHz
  - DSSS
    - for up to 2 Mbps
  - CCK
    - for up to 11 Mbps
  - OFDM
    - for up to 54 Mbps
  - OFDM w/ 20/40MHz & MIMO
    - for up to 600 Mbps
  - OFDM w/ 20/40/80/160MHz & MU-MIMO in 5GHz
    - for up to 6 900 Mbps
  - Outlook: 802.11ax for ultra dense deployments

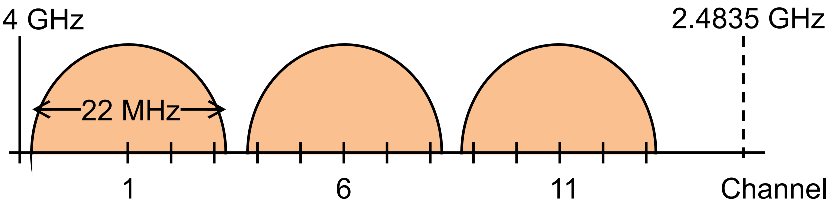
WLAN IEEE 802.11

UNLICENSED SPECTRUM

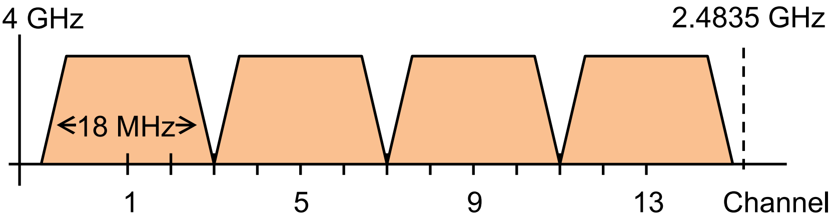
Wi-Fi in the 2.4 GHz ISM band

- Most of Wi-Fi today operate in the 2.4 GHz ISM band
  - IEEE 802.11b set the rule to deploy systems on channel
    1 – 6 – 11
  - Plain IEEE 802.11 g/n (OFDM) systems would not interfere
    when operation on channel
    1 – 5 – 9 – 13
- Avoid interference with two adjacent channels by configuration of channels in the middle.
- Regulatory requirements:
  - max TX power (EU): 100 mW EIRP
  - Use of spread spectrum coding
  - Specification: ETSI EN 300 328

DSSS/CCK (802.11b) channel bandwidth 22 MHz

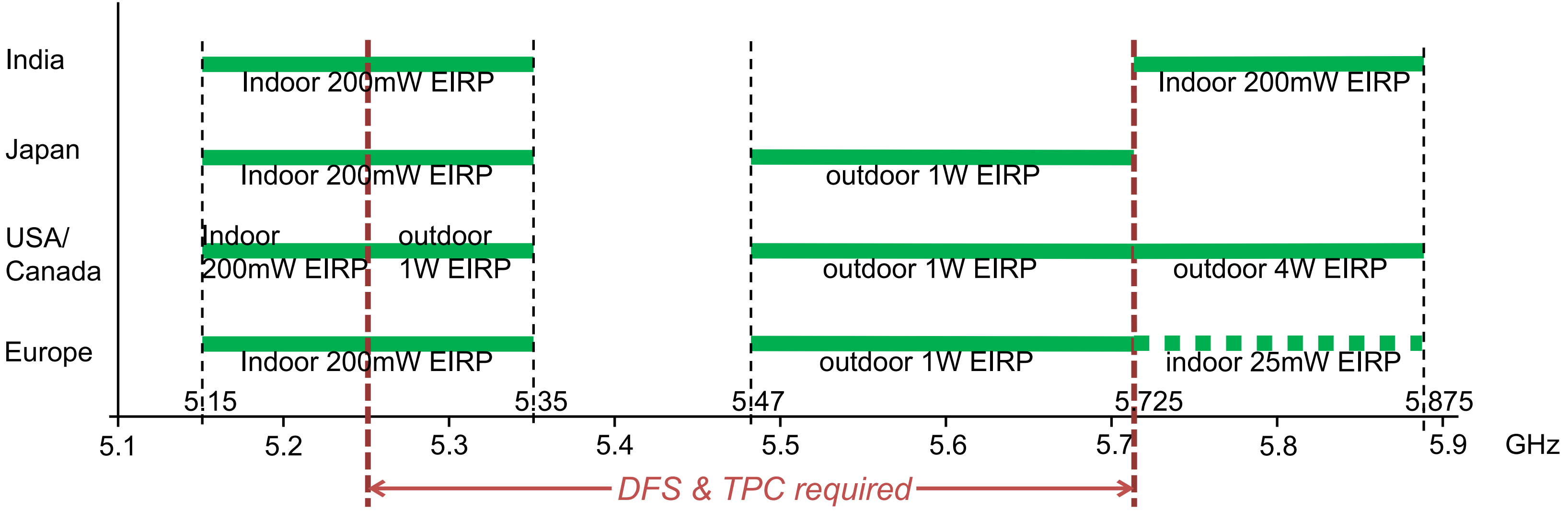


OFDM (802.11g/802.11n) 20 MHz channels



5 GHz Unlicensed Spectrum

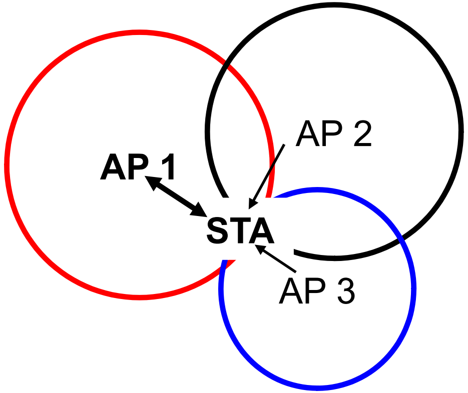
- 455 MHz of unlicensed spectrum available mostly worldwide
  - Wi-Fi is usually secondary user of that spectrum



- Dynamic Frequency Selection (DFS) and Transmission Power Control (TPC) are required for most of the 5 GHz spectrum to protect primary users (e.g. weather radars)
  - Specification: ETSI EN 301 893 (EN 300 440 for 5725-5875 MHz)

Spectrum management for the 5 GHz band

- DFS (Dynamic Frequency Selection)
  - APs dynamically select their operating channel after scanning for other users (e.g. weather radars)
  - STAs provide to APs detailed reports about spectrum usage at their locations.



- TPC (Transmission Power Control)
  - Supports interference minimization, power consumption reduction, range control and link robustness.
  - APs define and communicate regulatory and local transmit power constraints.
  - Stations select transmit powers for each frame according to local and regulatory constraints.

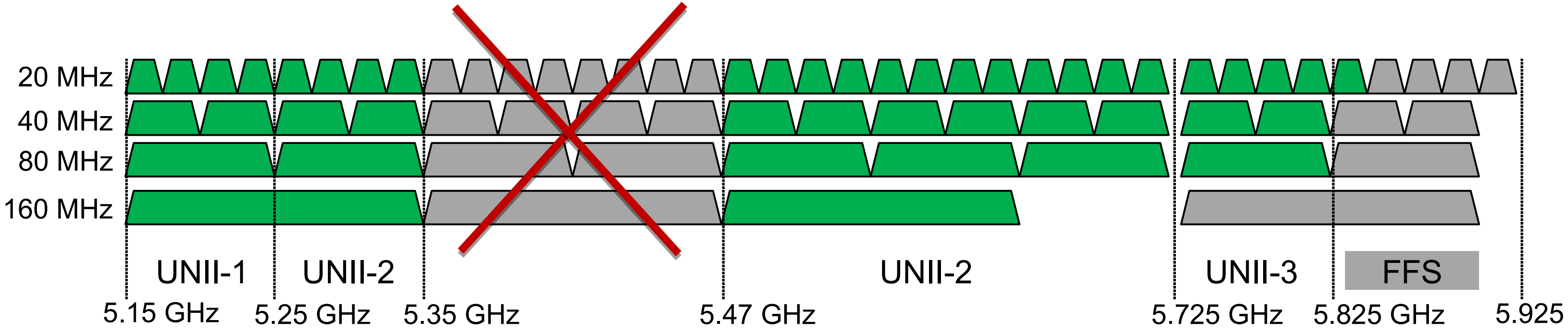
5 GHz spectrum evolution

Wide bandwidth channels desired to support high throughput requirements

- Non-overlapping channels to avoid co-channel interference desired for good QoS
- Current UNII spectrum allows only
  - **Six** (Europe: **five**) 80 MHz channels or **Two** 160 MHz channels
- Discussions regarding extension into 5.35-5.47 GHz did not materialize.
  - Worldwide harmonization of 5.725-5.875 GHz ongoing
  - 5.875-5.925 GHz reserved for car-to-car communications
- Current discussions in ITU-R potentially leading to global extension of 5 GHz band into 6 GHz range.

🟩 Available channels

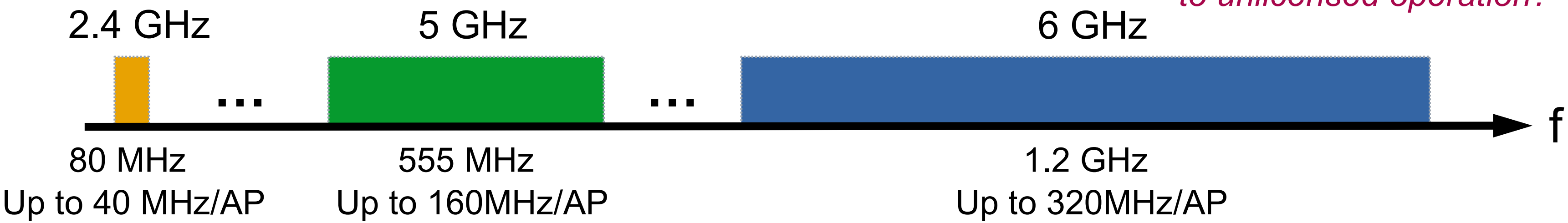
▨ New channels



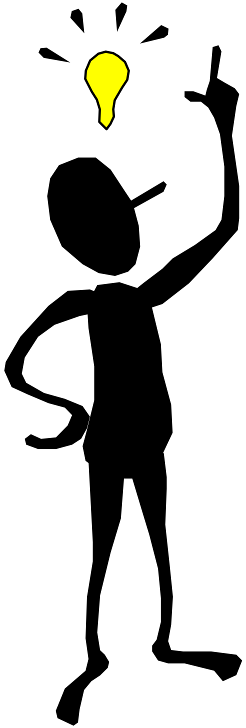
Unlicensed extension into 6 GHz

- New unlicensed spectrum in the 6 GHz band (5925-7125 MHz)
  - Potentially adding up to 1.2 GHz!
  - Up to 320 MHz channel bonding in the 6 GHz band
    - Definition of new channel access rules under discussion
  - Coexistence with incumbents needs to be managed
    - Wi-Fi nodes may require special protection procedures

Will all 1.2GHz be allocated to unlicensed operation?



Questions and answers



Wi-Fi spectrum questions

1) What is the optimal channel arrangement for a 802.11g/n-only system in Europe?
2) What is the channel bandwidth of 802.11b?
3) What are the frequencies for unlicensed operation in 5 GHz in Europe?
4) What is the purpose of DFS and TPC in the 5 GHz band?
5) For which frequencies is the support of DFS and TPC mandatory in Europe?
6) How many non-overlapping 80MHz channels can be arranged in the 5 GHz range in Europe?

WLAN IEEE 802.11

2.4 & 5 GHZ RADIO STANDARDS OVERVIEW

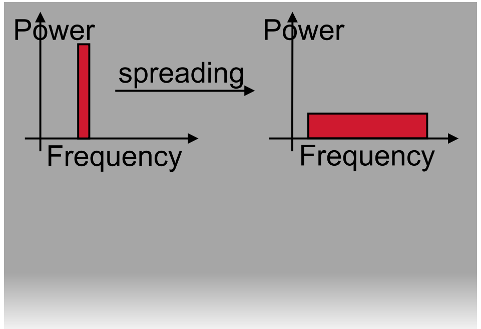
IEEE 802.11 radio standards evolution

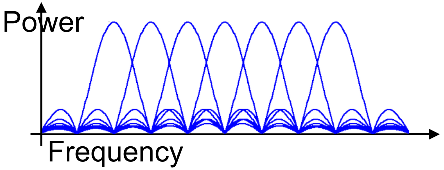
Std	Release	Freq. (GHz)	Bandwidth (MHz)	Data rate per stream (Mbit/s)	Allowable MIMO streams	Modulation	Approximate indoor range (m)	Approximate outdoor range (m)
	Jun 1997	2.4	20	1, 2	1	DSSS	40	150
a	Sep 1999	5	20**	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM	40	150
b	Sep 1999	2.4	20	5.5, 11	1	DSSS	40	150
g	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	~ 2020*	1...6	2.5/5/10/20/ 40/80/160	up to 15/30/63/143/287/600/1201	8	OFDMA	80	300
ay	~ 2020*	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

* 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

IEEE802.11 PHY layer solutions for 2.4 GHz & 5 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)**
  - CCK/DQPSK providing 5.5/11 Mbps
  - Channel bandwidth: 22 MHz
- 2.4 GHz Extended Rate **(802.11g)**
  - DSSS providing 1/2/5.5/11 Mbps
  - OFDM providing 6/9/12/18/24/36/48/54 Mbps
  - Channel bandwidth: 22/20 MHz
- 5 GHz Orthogonal Frequency Division Multiplex **(802.11a)**
  - OFDM providing 6/9/12/18/24/36/48/54 Mbps
  - Channel bandwidth: 20 MHz
- 2.4 GHz & 5 GHz High Throughput **(802.11n)**
  - OFDM with up to 4x4 MIMO providing up to 600 Mbps
  - Channel bandwidth: 20 MHz & 40 MHz
- 5 GHz Very High Throughput **(802.11ac)**
  - OFDM with up to 8x8 MU-MIMO providing up to 6900 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz



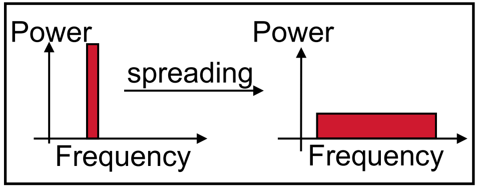


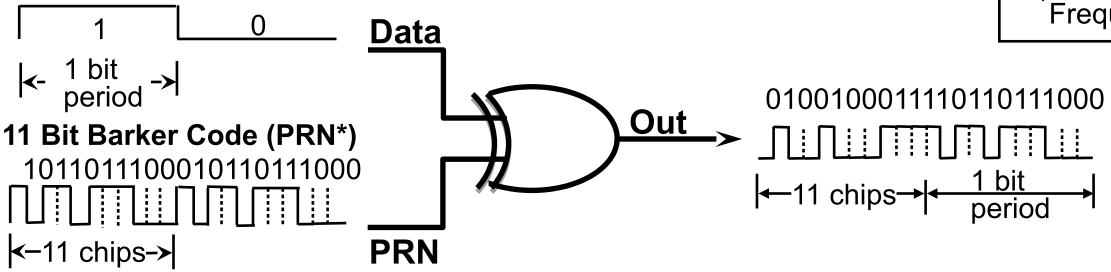
WLAN IEEE 802.11

DIRECT SEQUENCE SPREAD SPECTRUM (DSSS)

Direct Sequence Spread Spectrum

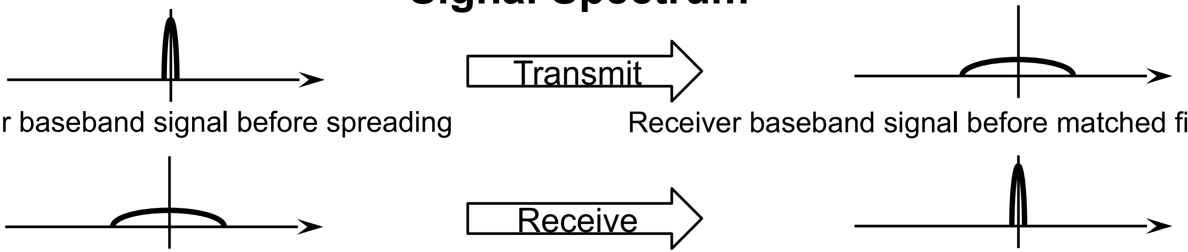
RF Energy is Spread by XOR of Data with PRN Sequence





* PRN: Pseudorandom Number

Signal Spectrum



Transmitter baseband signal before spreading

Receiver baseband signal before matched filter (Correlator)

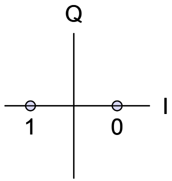
Transmitter baseband signal after spreading

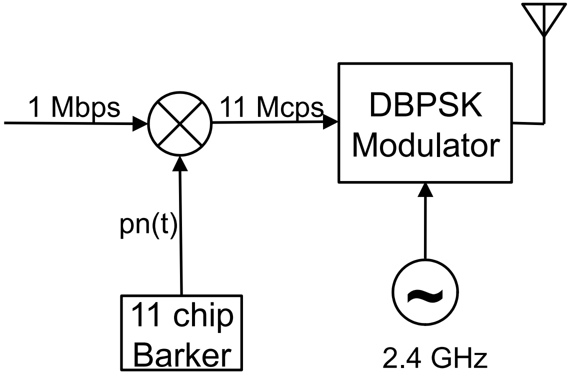
Receiver baseband signal after matched filter (De-spread)

DSSS - Modulation

1 Mbps by DBPSK

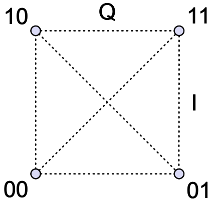
- Differential Binary Phase Shift Keying
  - 0 = 0
  - 1 = π

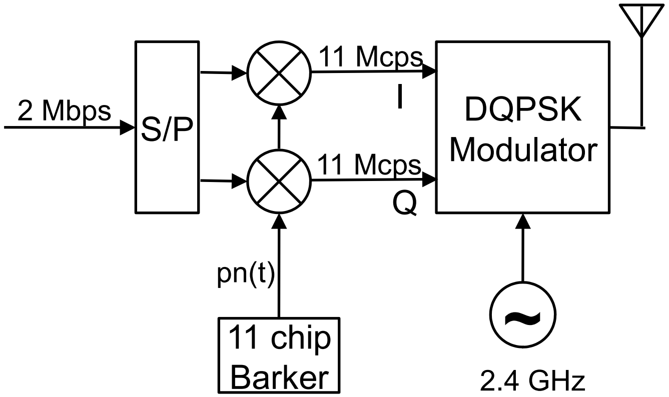




2 Mbps by DQPSK

- Differential Quadrature Phase Shift Keying
  - 00 = 0
  - 01 = π/2
  - 10 = -π/2
  - 11 = π





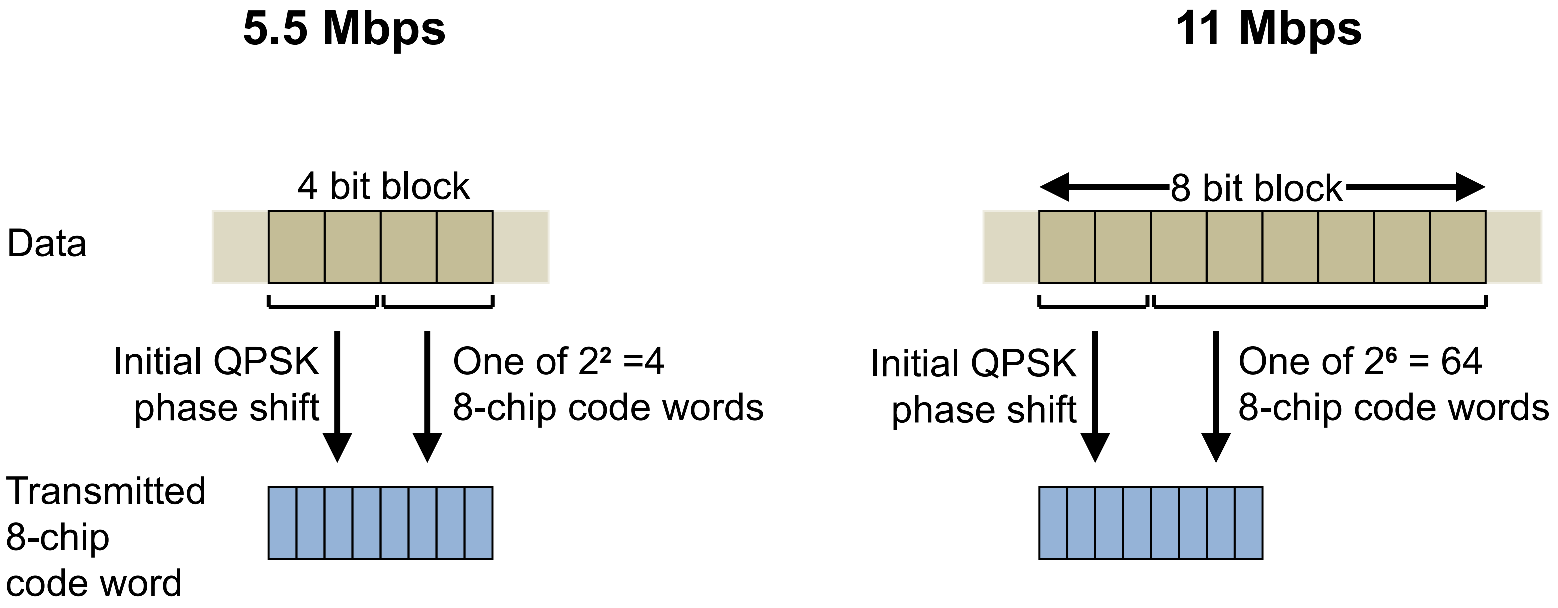
WLAN IEEE 802.11

HIGH RATE DIRECT SEQUENCE SPREAD SPECTRUM (HR/DSSS)

High Rate DSSS (802.11b) overview

- Efficient coding scheme using the same spectrum allocation of a 802.11 DSSS system
  - Introduced by IEEE 802.11b
- Basic idea:
  - Instead of transmitting a spreaded signal with a particular code sequence, different complex code sequences are used for spreading the transmitted signal
  - Each 8-bit word of the original signal is encoded with a complex chip word consisting of 8 symbols; the chip rate is 11 Mchip/s.
    - Complementary Code Keying (CCK)
  - Leads to practically the same spectrum allocation as a DSSS system

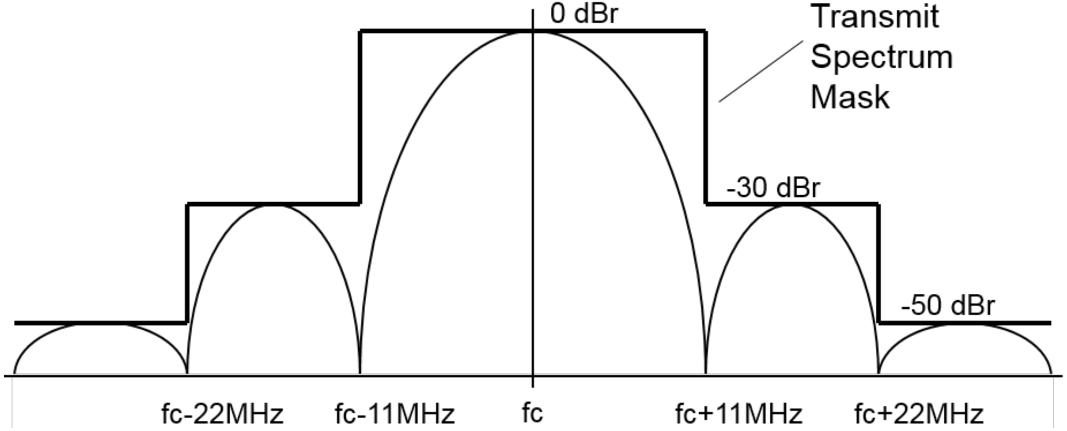
Complementary Code Keying (CCK)



Code word repetition rate = 1.375 Mwords/s

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:

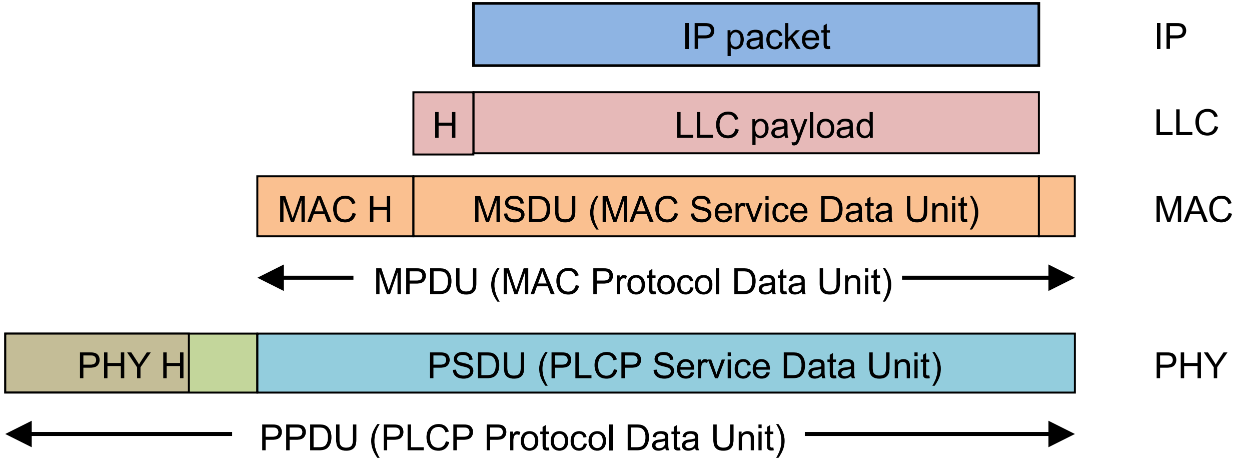


WLAN IEEE 802.11

HR/DSS PHY FRAMING

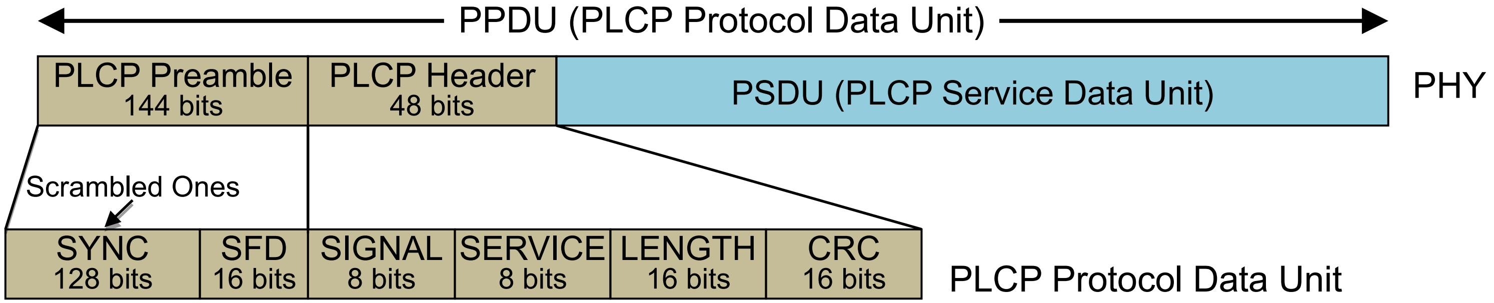
IEEE 802.11 Frame structure

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


IP packet
IP
H
LLC payload
LLC
MAC H
MSDU (MAC Service Data Unit)
MAC
MPDU (MAC Protocol Data Unit)
PHY H
PSDU (PLCP Service Data Unit)
PHY
PPDU (PLCP Protocol Data Unit)

- 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

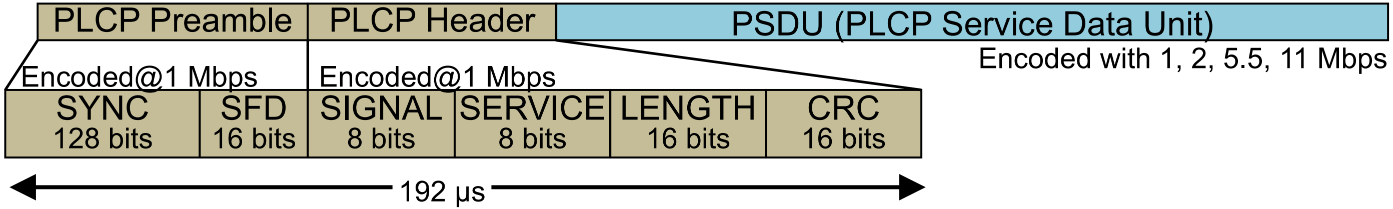
DSSS Physical Layer Convergence Protocol (PLCP)



- SYNC - gain setting, energy detection, antenna selection, frequency offset compensation
- SFD - Start Frame Delimiter “0000 1100 1011 1101”, bit synchronization
- SIGNAL - rate indication; (1, 2, 5.5, 11 Mbps)
- SERVICE – used to distinguish the coding schemes
- LENGTH - length of the PSDU part in µs
- CRC - CCITT CRC-16, protects signal, service, and length field
- Coding:
  - PLCP preamble is sent with minimum data rate (1 Mbps)
  - PLCP header is either send with 1 Mbps (long preample) or with 2 Mbps (short preample)

IEEE 802.11 DSSS Preambles

- The Preamble allows the receiver to acquire the wireless signal and synchronize itself with the transmitter.
- **Long Preamble:**



PLCP Preamble | PLCP Header | PSDU (PLCP Service Data Unit)

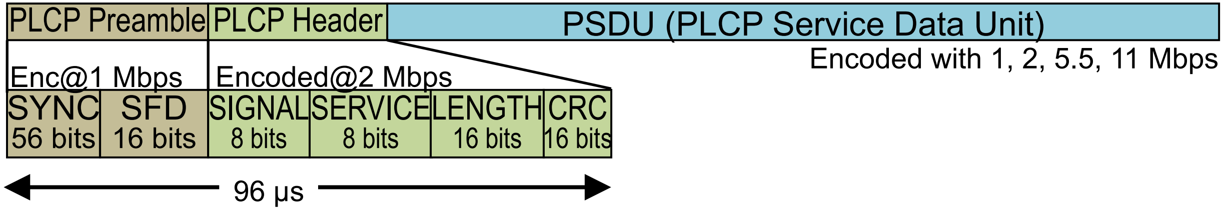
Encoded with 1, 2, 5.5, 11 Mbps

Encoded@1 Mbps | Encoded@1 Mbps

SYNC	SFD	SIGNAL	SERVICE	LENGTH	CRC
128 bits	16 bits	8 bits	8 bits	16 bits	16 bits

192 µs

  - Compatible with legacy IEEE 802.11 systems operating at 1 and 2 Mbps (Megabits per second)
  - PLCP with long preamble is transmitted at 1 Mbps regardless of transmit rate of data frames
  - Total Long Preamble transfer time is a constant at 192 µs
- **Short Preamble:**



PLCP Preamble | PLCP Header | PSDU (PLCP Service Data Unit)

Encoded with 1, 2, 5.5, 11 Mbps

Enc@1 Mbps | Encoded@2 Mbps

SYNC	SFD	SIGNAL	SERVICE	LENGTH	CRC
56 bits	16 bits	8 bits	8 bits	16 bits	16 bits

96 µs

  - Not compatible with legacy IEEE 802.11 systems operating at 1 and 2 Mbps
  - PLCP with short preamble: Preamble is transmitted at 1 Mbps and header at 2 Mbps
  - Total Long Preamble transfer time is a constant at 96 µs

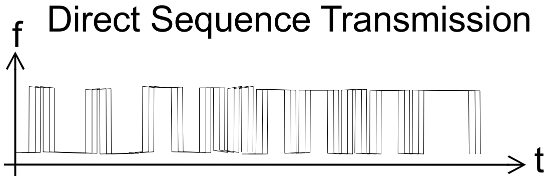
WLAN IEEE 802.11

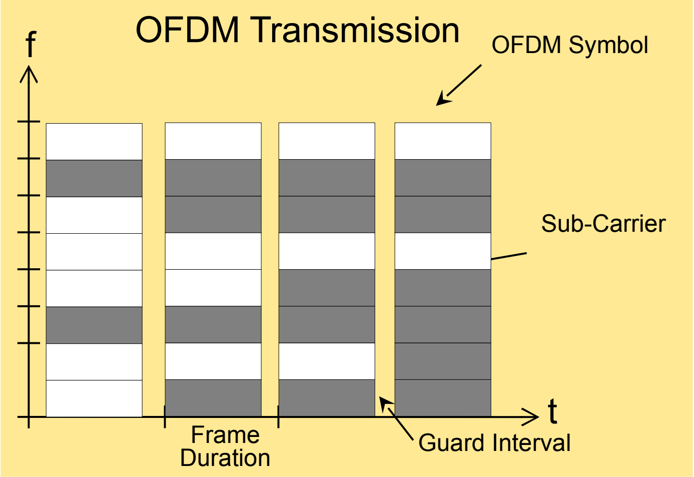
ORTHOGONAL FREQUENCY DIVISION MULTIPLEX (OFDM)

Transformation of transmission symbols

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

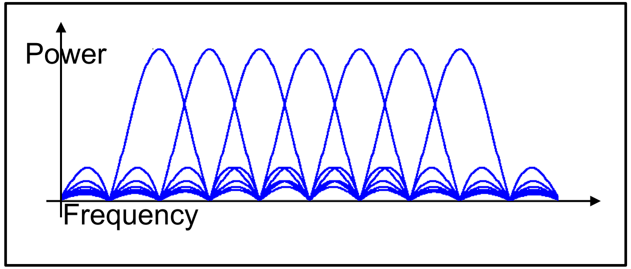
	D	e	m	o
ASCII	68	101	109	111
128	0	0	0	0
64	1	1	1	1
32	0	1	1	1
16	0	0	0	0
8	0	0	1	1
4	1	1	1	1
2	0	0	0	1
1	0	1	1	1


Direct Sequence Transmission


OFDM Transmission

Orthogonal Frequency Division Multiplex (802.11a)

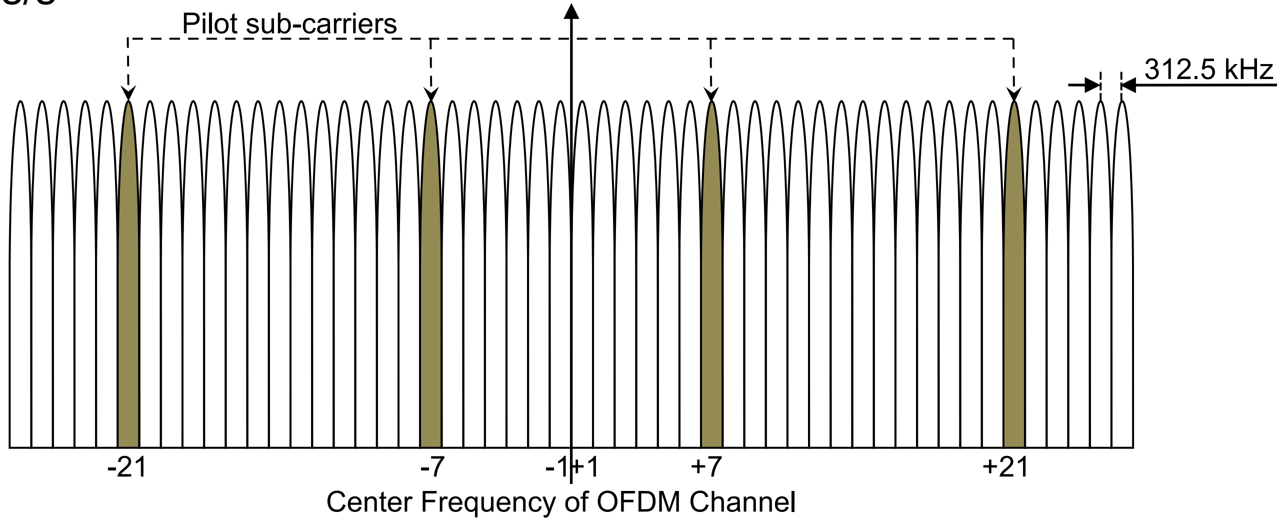
- Abbreviation: OFDM
- Introduced by 802.11a-1999
  - Cooperation with ETSI
  - Initially 5 GHz only
    - No need for backward compatibility



- Robust against reflections and multipath propagation
- Transforms data into a set of orthogonal signals
  - Each signal is build by a combination of ‘tones’
- Generation/separation by FFT-64
  - FFT/IFFT required for coding/decoding
  - 52 sub-carriers out of the 64 samples used
- Guard periods between symbols enable orthogonality of subsequent symbols despite delay spread

OFDM – Time and frequency

- OFDM channel comprises 52 sub-carriers
  - 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

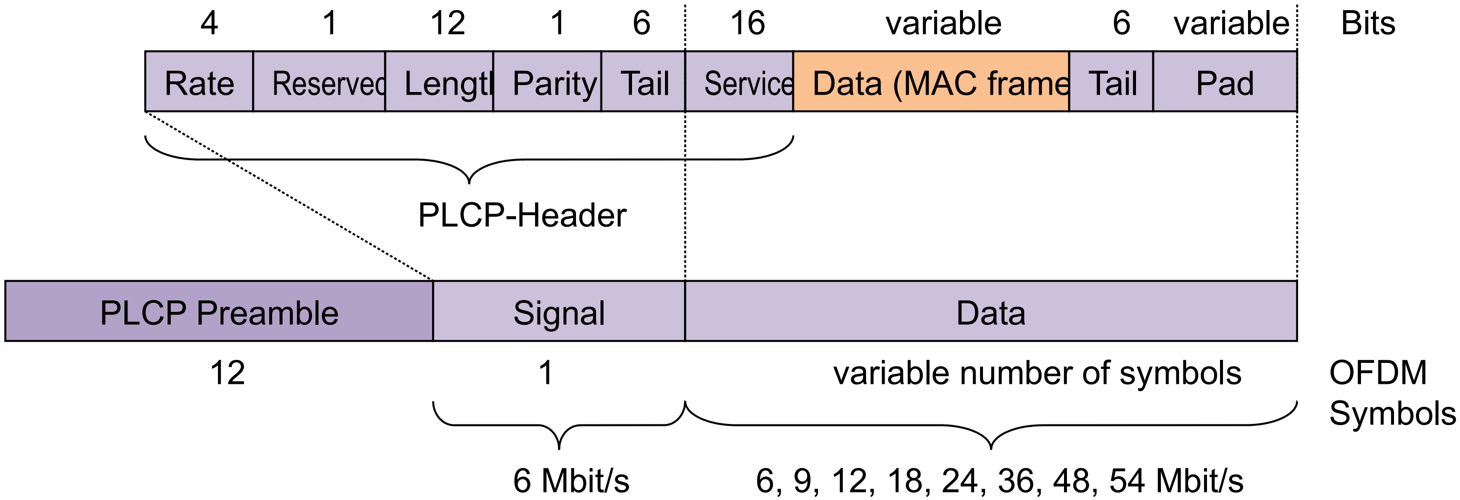


OFDM - Coding and Modulation

- 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
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

OFDM - PHY Frame Format



- OFDM PHY Preamble with 12 symbols takes 16 µs
  - 10 short training symbols without guard periods
    - Timing synchonization, 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

WLAN IEEE 802.11

EXTENDED RATE

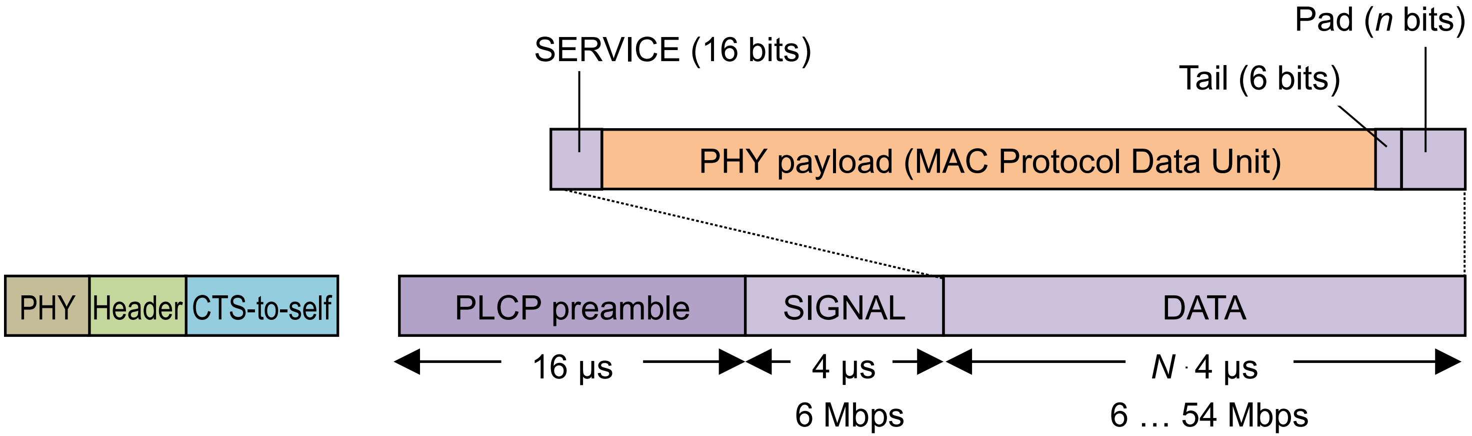
Extended Rate PHY (802.11g)

- Introduced by 802.11g
  - Uses 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-free frequency band
  - lower attenuation than in the 5GHz band
    - less transmission power required
- MAC layer extensions with backward compatibility to HR/DSSS
- Can use same transmission channels as HR/DSSS
  - 18 MHz OFDM fits easily in 22 MHz HR/DSSS channel

ERP PHY frame (OFDM native)

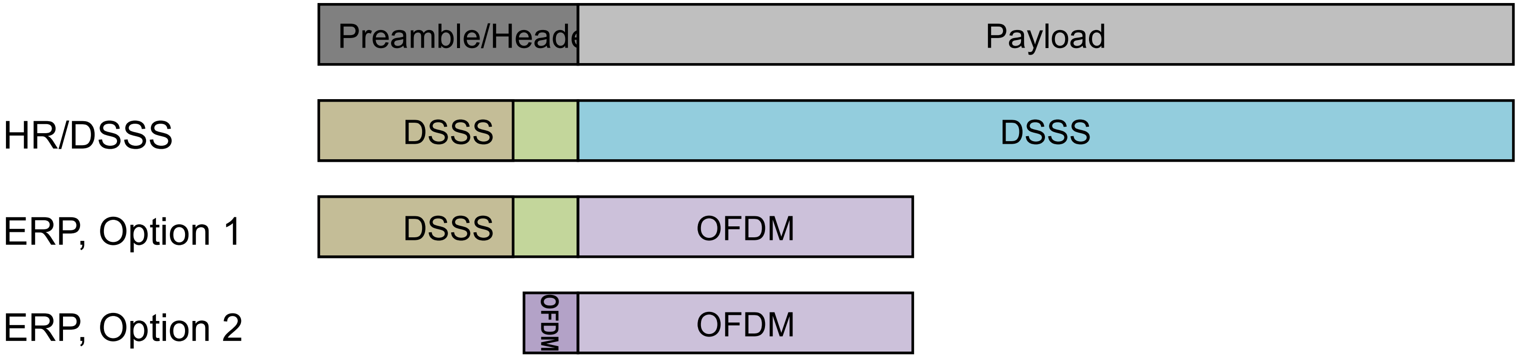
- Without backward compatibility, ERP deploys the same PHY frame as OFDM (802.11a)



- 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

ERP – HR/DSSS Interworksing

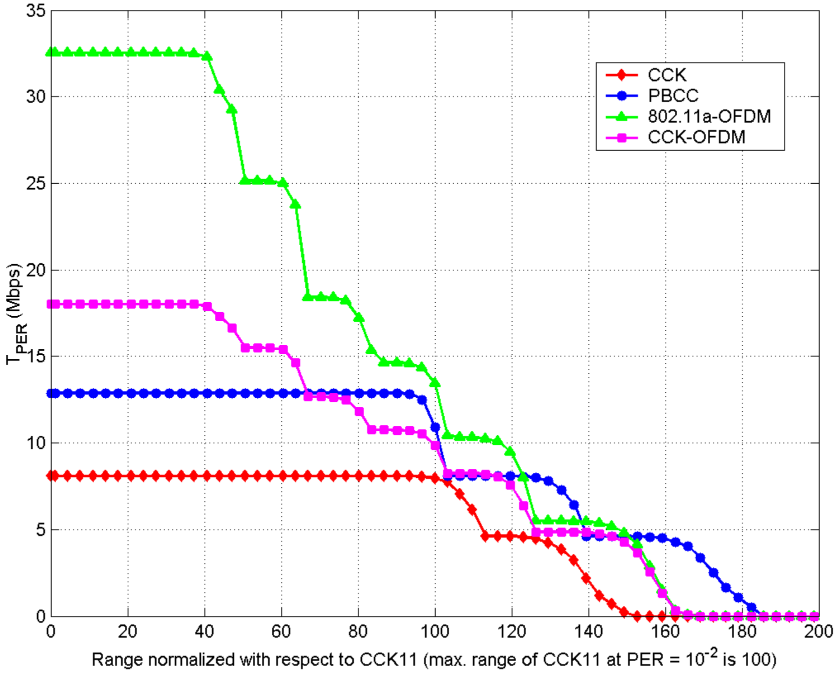
- ERP (802.11g) and HR/DSSS (802.11b) interworking is based on two alternatives regarding the ERP PHY frame structure:



- 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.

IEEE802.11 a/b/g – performance and efficiency

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)

WLAN IEEE 802.11

HIGH THROUGHPUT (HT)

High Throughput (802.11n)

- Enhancement to OFDM (5GHz) and ERP (2.4GHz)
  - Up to 600 Mbps in either band
- Main techniques deployed for increase of bitrate:
  - Enhancements to OFDM modulation scheme and timing
  - Channel bonding of two adjacent channels to 40 MHz
  - Up to 4 parallel streams using MIMO (Multiple Input Multiple Output) technique
  - MAC frame aggregation
    - A-MPDU as well as A-MSDU
  - Block acknowledgements

HT PHY layer improvements

- OFDM (54 -> 58.5 Mbps)
  - 52 data sub-carriers instead of 48
- 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-carrier)
- MIMO (150 -> 600 Mbps)
  - Up to 4 parallel streams

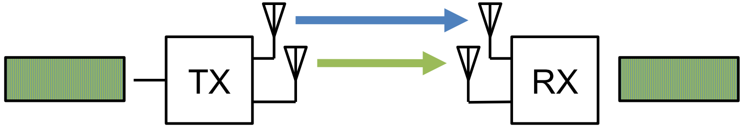
HT MCS Options for single stream

MCS Index	Spatial Streams	Modulation type	Coding rate	Data Rate [Mbps]			
				20MHz		40 MHz	
				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 multiply numbers in table by number of streams.

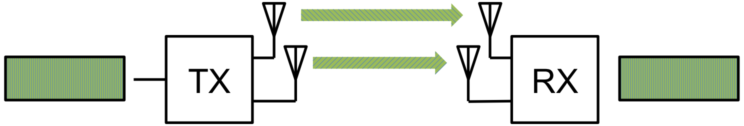
HT MIMO (Multiple Input Multiple Output)

- 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.

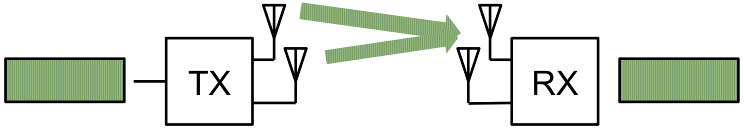
- Space-Time Block Coding (STBC)



  - 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

- Transmit Beamforming (TxBF)

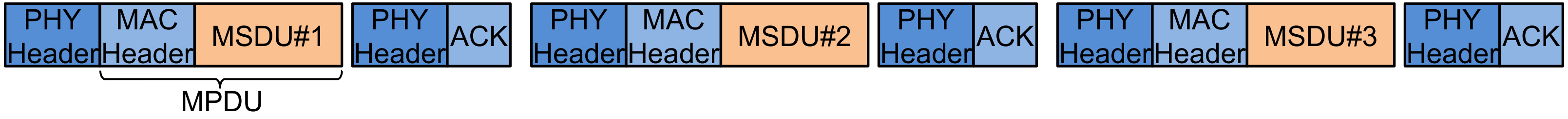


  - Steers signal stream towards the intended receiver by concentrating transmitted RF energy in a given direction.
  - Leverages signal reflection and multipath to improve received signal strength and sustain higher data rates.
  - Required channel knowledge can be obtained implicitly or explicitly by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

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

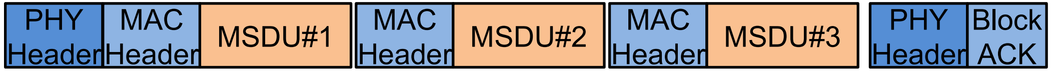
HT MAC Protocol Data Unit Aggregation

- 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

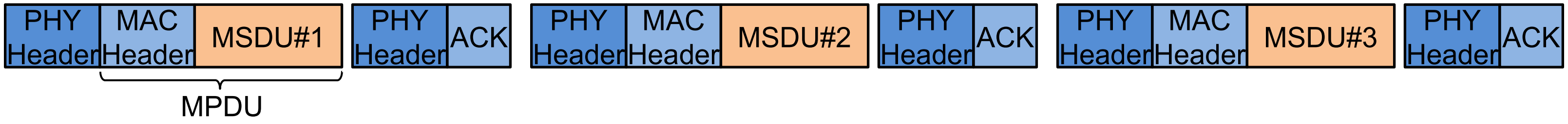
- MAC Protocol Data Unit Aggregation (A-MPDU) groups multiple MPDU sub-frames each with its own MAC header into one PSDU with up to 65535 bytes.



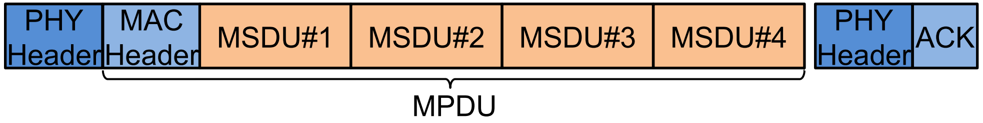
  - Reduced Interframe Space (RIFS) of 2µs used as delimiter between MPDUs
  - Block Acknowledgement for reduction of ACKs to one per multiple MPDU transmission
  - Selective retransmission of a single MPDU possible in the case that one of the aggregated MPDUs gets impacted.

HT MAC Service Data Unit Aggregation

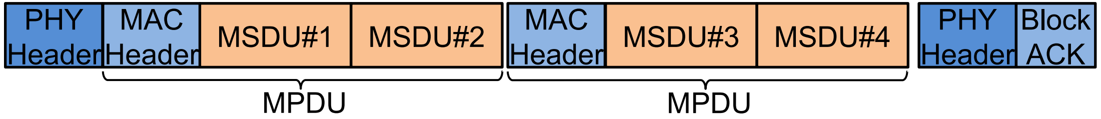
- MAC efficiency suffers when transferring sequence of smaller frames



- 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.

WLAN IEEE 802.11

VERY HIGH THROUGHPUT (VHT)

Very High Throughput (802.11ac)

Extension to High Throughput in 5GHz with:

- 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)

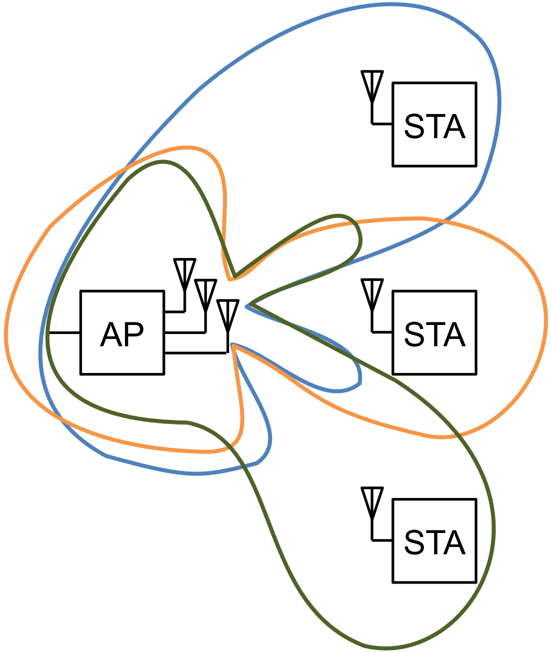
VHT MCS Options for single stream

MCS index	Spatial Streams	Modulation type	Coding rate	Data rate [Mbps]							
				20 MHz		40 MHz		80 MHz		160 MHz	
				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.

Multi-User 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 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

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

- *‘ac Wave 2’* certification supports MU-MIMO, up to 4x4 MIMO and 160 MHz channel

WLAN IEEE 802.11

P802.11AX (HE): NEXT GENERATION WI-FI

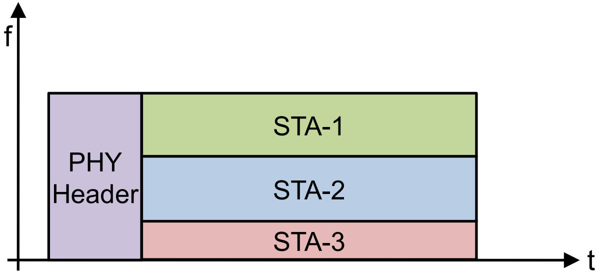
IEEE P802.11ax High Efficiency Wireless LAN

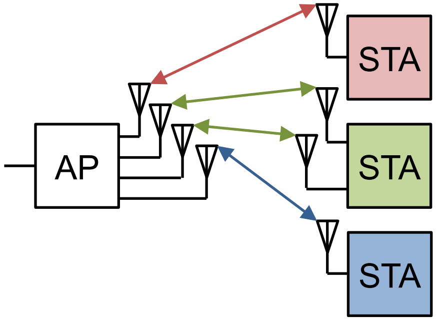
- The amendment defines standardized modifications to both the IEEE 802.11 physical layers (PHY) and the IEEE 802.11 Medium Access Control layer (MAC) that enable at least one mode of operation capable of supporting at least four times improvement in the average throughput per station (measured at the MAC data service access point) in a dense deployment scenario, while maintaining or improving the power efficiency per station.
  This amendment defines operations in frequency bands between 1 GHz and 6 GHz. The new amendment shall enable backward compatibility and coexistence with legacy IEEE 802.11 devices operating in the same band.

- No drive to increase peak data rates beyond what is already available by VHT
- Focus is on increasing usage 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)

High Efficiency technical highlights

- Increase network efficiency through multiplexing users in both frequency and space
  - Uplink and downlink OFDMA and MU-MIMO

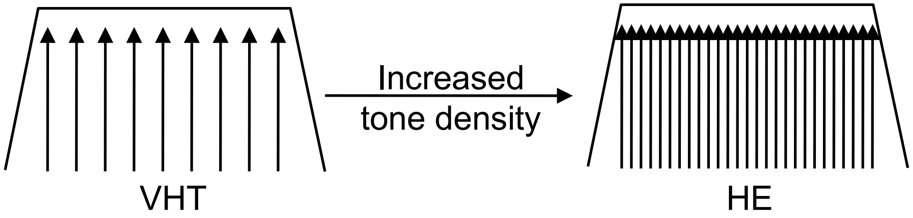




- Increase link efficiency with longer OFDM symbol (256-FFT) and high order modulation (1024-QAM)
- Increase spatial reuse through dynamic clear channel assessment (CCA)
- Improved support for outdoor operation (optional longer guard interval)

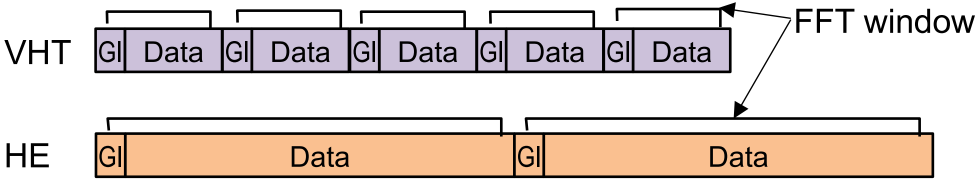
High Efficiency increased link efficiency

Frequency domain
(~ 5% gain)



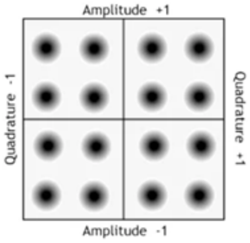
Squeeze more
tones in around
DC and edge

Time domain
(~ 15% gain)

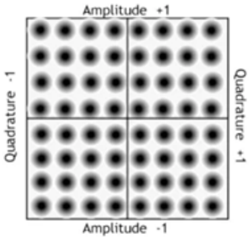


Guard Interval (GI)
overhead reduced

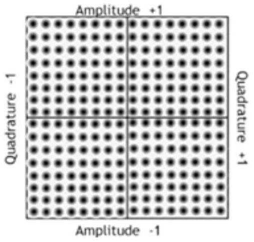
Modulation
(~ 25% gain)



16-QAM



64-QAM



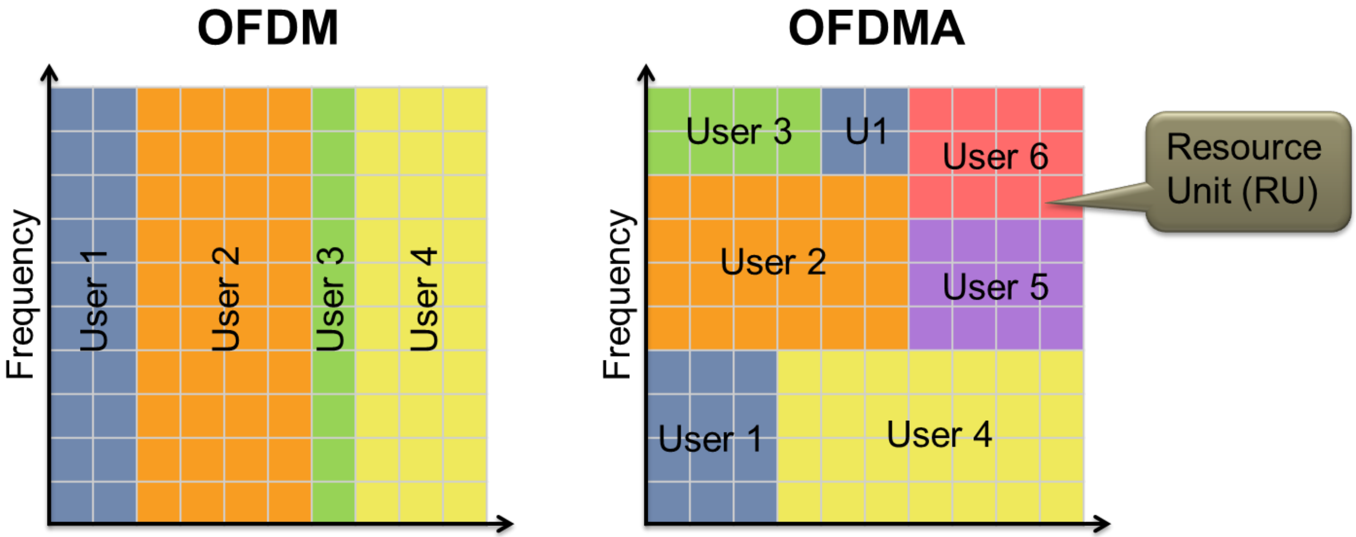
256-QAM

+ 1024-QAM

P802.11ax Modulation and coding schemes 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

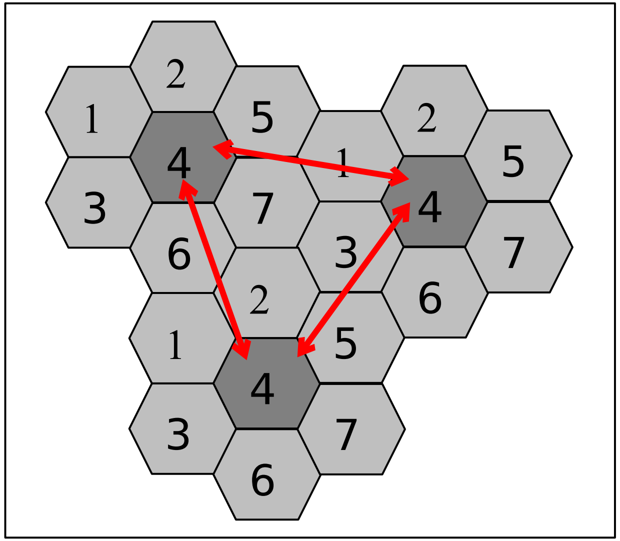
OFDMA in comparison to OFDM



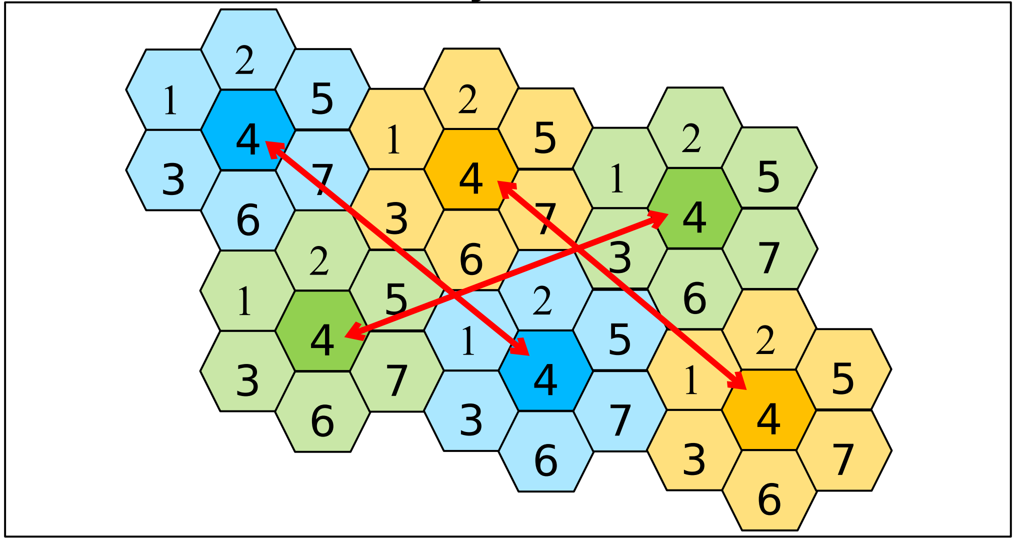
- OFDMA enables access points to further customize channel usage to match client and traffic demand
- Leads to increased efficiency for frequent short data frames

BSS Color Coding

All same-channel BSS block



Same-channel BSS only block on Color Match



- Adjust CCA threshold based on transmit power of device
  - A device with low transmit power causes less interference than a device with high transmit power
  - CCA threshold adjustment mitigates overlapping BSS traffic
- BSS Color in the PHY header allows the identification of intra-BSS and inter-BSS PPDUs

Further improvements

- Improved outdoor operation
  - Operates in higher delay spread channels than 11ac:
    - 11ac GI options: 0.4 μs and 0.8 μs
    - 11ax GI options: 0.8 μs, 1.6 μs and 3.2 μs
    - GI overhead mitigated with longer OFDM symbol
  - Some preamble fields repeated for higher reliability
  - Dual carrier modulation improves robustness in Data field
- Better support of IoT devices
  - 20 MHz-only clients: Low-power devices
  - Dual carrier modulation: Repeat information in different subcarriers
  - Intra-PPDU power saving: Doze state until the end of selected PPDUs
  - Target wake time (TWT): Power-saving service reservation mechanism

P802.11ax (HE) enhancements compared to IEEE 802.11ac (VHT)

Feature	IEEE 802.11ac	802.11ax
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 Random Access	Not available	Allows performing UL OFDMA transmissions by stations which are not allocated RUs directly.
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.
NAV	Single NAV	Two NAVs
Target Wait Time (TWT)	Not available	TWT reduces power consumption and medium access contention.
Fragmentation	Static fragmentation	Dynamic fragmentation
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

IEEE 802.11ax / Wi-Fi 6 timeline

- Numerous chipsets and products already available.
- Wi-Fi Alliance certification of Wi-Fi 6 started based on profile based on P802.11ax-D2.0
  - Happened September 2019
- Ratification of standard expected for end of 2020
  - Well after first WFA certified products!
- More features and full compliance with ratified standard will be subject of Wi-Fi 6 Wave 2 certification
  - Could be about 2021

Looking ahead: P802.11be, the successor of 802.11ax

- Extreme high throughput
  - New MAC and PHY modes of operation.
  - Maximum MAC throughput of 30 Gbps/AP (4x compared to 802.11ax).
  - Carrier frequencies between 1 and 7.125 GHz.
- Low latency
  - At least one mode of operation capable of improved worst case latency and jitter -- no specific requirements set.
- Compatibility
  - Backward compatibility and coexistence with legacy 802.11 devices in the 2.4, 5 and 6 GHz unlicensed bands.
- Timeline
  - Ratification expected for May 2024
- Potential technical features
  - Wider bandwidth, more antennas and spatial streams, better efficiency

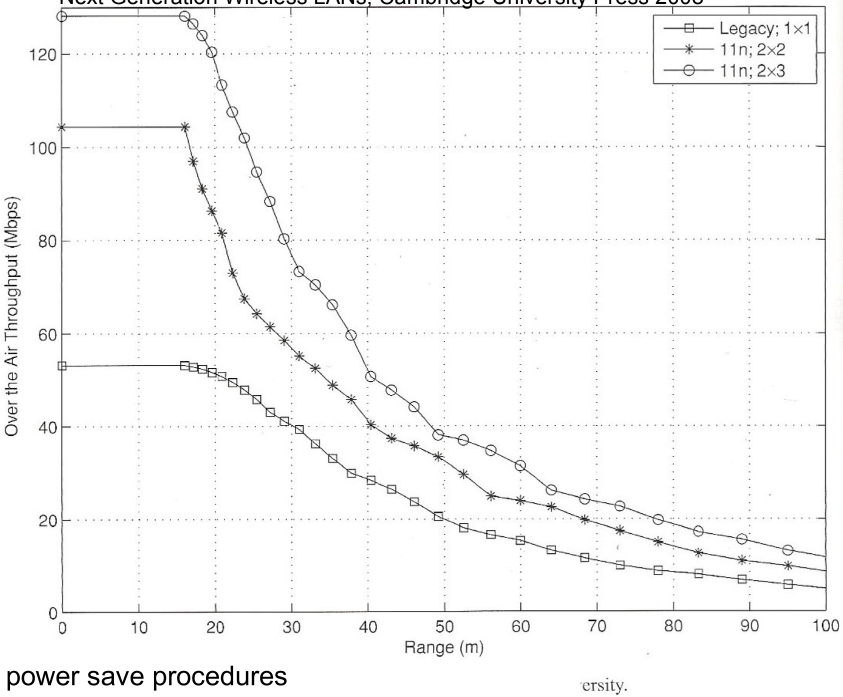
WLAN IEEE 802.11

WI-FI RADIO DEPLOYMENT HINTS

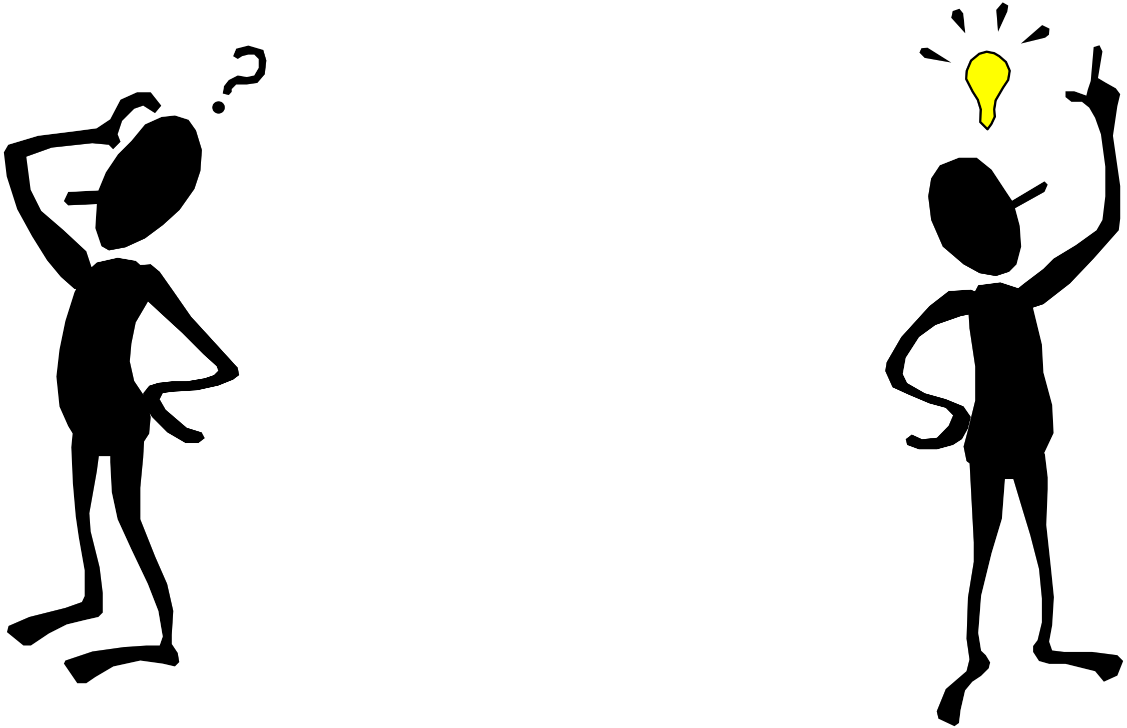
Wi-Fi Radio coverage and data throughput

- Wi-Fi basic parameters:
  - TX power usual 30..50 mW
  - Coverage range:
    - indoor: 30m, outdoor: 300m
    - strongly depending on environment
  - Max. stations per AP: ~ 35;
    - caused by particularities of CSMA/CD
    - newer deployments: ~ 10
  - Actual throughput:
    - up to ~ 500 Mbps (VHT (11ac) 2x2 MIMO, 80 MHz)
    - up to ~ 120 Mbps (HT (802.11n), 2x2MIMO)
    - ~ 27 Mbps (ERP (802.11g))
    - ~ 5 Mbps (HR/DSSS(802.11b))
- Extending the coverage range:
  - APs more exposed, better antennas, more antennas, more MIMO, Wi-Fi mesh
- Extending the capacity limits:
  - smaller cells, more APs, sector antennas, better scheduling
    - decrease TX power to limit neighbor cell interference, deploy advanced power save procedures
- Unwanted interference
  - risky usage of unlicensed spectrum, heavily loaded, many potential interferer
  - denial of service attacks (intentionally or unintentionally

Reference: E. Perahia, R. Stacey,
Next Generation Wireless LANs, Cambridge University Press 2008



Questions and answers



Wi-Fi radio questions

1) What are the IEEE 802.11 radio standards for operation in 2.4 GHz?
2) What are the IEEE 802.11 radio standards for operation in 5 GHz?
3) What are the bit-rates provided by Complementary Code Keying in 2.4 GHz?
4) What modulation schemes are used for direct sequence spread spectrum?
5) What are the bit-rates supported by a high-rate direct sequence spread spectrum system?
6) What is the difference between a PPDU and MPDU data frame?
7) What is the purpose of the preample of the physical layer protocol data unit?
8) What is the difference between the long preample and short preample?

More Wi-Fi radio questions…

9) What does OFDM stand for?
10) How many sub-carriers are used by the OFDM introduced by 802.11a?
11) What is the purpose of guard intervals in OFDM?
12) Which data rates are supported by OFDM as introduced by 802.11a?
13) How long does a OFDM PHY preample in 802.11a take?
14) What is the benefit when operating the Extended Rate PHY without backward compatibility to HR/DSSS?
15) What additional methods are needed for coexistence of Extended Rate PHY without backward compatibility with HR/DSS?
16) What bitrates are supported by the Extended Rate PHY?

More Wi-Fi radio questions…

17) What are the main techniques deployed by the High Throughput PHY for increased bitrates?
18) What additional modulation types are available in High Throughput PHY (802.11n) compared to OFDM (802.11a)?
19) Which MIMO methods are specified in 802.11n, and which of them is mandatory for certification?
20) What is the benefit of MAC Protocol Data Unit aggregation compared to MAC Service Data Unit aggregation?
21) What is the drawback of MAC Protocol Data Unit aggregation compared to MAC Service Data Unit aggregation?
22) By which means does Very High Throughput PHY (802.11ac) provide higher bitrates compared to High Throughput PHY (802.11n)?
23) What is the difference between explicit beam-forming and implicit beam-forming?
24) What is the maximum bitrate of Very High Throughput PHY, and what is the maximum bitrate for serving a single STA with MU-MIMO?

WLAN IEEE 802.11

WLAN EXTENSION FOR BELOW 1GHZ

IEEE802.11 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 8 085 // 6 756	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	~ 2020*	1...6	2.5/5/10/20/ 40/80/160	up to 15/30/63/143/287/600/1201	8	OFDMA	80	300
ay	~ 2020*	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

* 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

WLAN IEEE 802.11

SUB 1GHZ UNLICENSED SPECTRUM

Unlicensed spectrum below 1 GHz

- Frequencies below 1 GHz provide link budget benefits of at least 10dB
  - Well suited for applications requiring longer reach and low power consumption
- Band allocation for some countries:

Country	Frequency [MHz]	max. allowed channel BW [MHz]	max. transmission power EIRP [mW]
China	775 - 779	1	5
	779 - 787	not defined	10
Europe	863 – 868.6	not defined	25
Japan	915.9 – 929.7	1	2 / 40
	920.5 – 923.5		500
South Korea	917 – 923.5	not defined	3 / 10
United States	902 - 928	not defined	1000

- Availability of spectrum and allowed operational parameters for WLAN below 1 GHz strongly depends on the geographic area.

WLAN IEEE 802.11

SUB 1 GHZ WLAN (HALOW)

HaLow (IEEE 802.11ah)

WLAN operating in frequency bands below 1 GHz for IoT and extended range

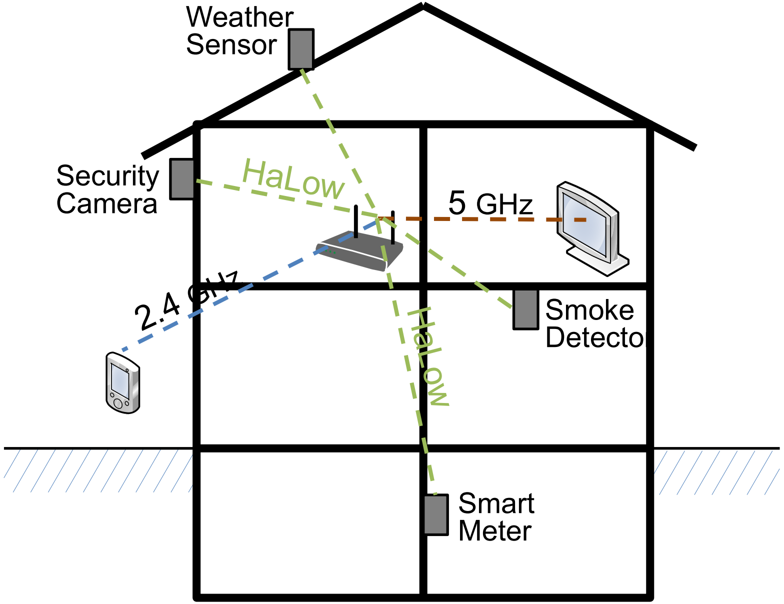
- Increased range compared to traditional Wi-Fi
  - For frequency bands below 1GHz with at least 10 dB link budget advantage
  - Reluctant to larger delay spread and Doppler spread supporting outdoor operation
  - An extra robust 1 MHz mode (MCS10) for up to 1 km range
- No need for interoperability with legacy IEEE 802.11 devices
- Two types of device configurations:
  - IEEE 802.11ah-only for IoT-type connectivity
  - Multi-band devices
- Low Power Consumption
  - Multi-year battery life operation for sensors
- Rich Data Sets
  - 150Kbps ~ 87 Mbps per spatial stream
- Scalable bandwidth and MIMO support
  - 1, 2, 4, 8, 16 MHz channel; up to 4 parallel streams
- Scalable
  - Supports up to 8191 devices per AP
- IP Connectivity
  - Same as Wi-Fi

	Edge Rate (Range)	TxR
11ac/n 5 GHz 20 MHz BW 40 MHz BW	6.5 Mbps (27m)	3x2
11n/g 2.4 GHz 20 MHz BW	6.5 Mbps (54m)	3x2
11ah 900 MHz 8 MHz BW (US Only)	5.8 Mbps (88m)	2x2

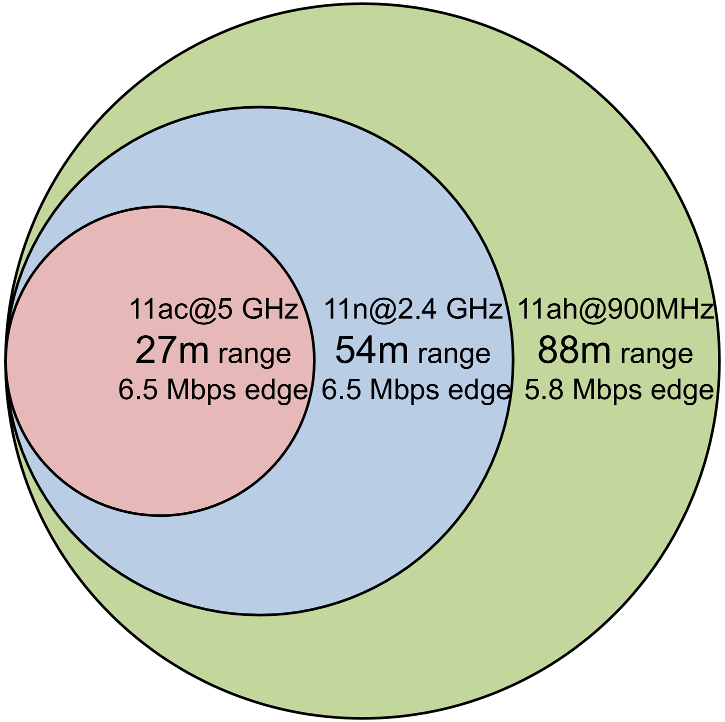
Simulation Assumptions: Minimum QoS 5Mbps,
Retail AP, 21 dBm/Tx chain Tx power,
Indoor to outdoor (d^4) channel model

HaLow (802.11ah) use cases

Sensors and meters



Extended range



HaLow (802.11ah) MAC Features

- Short frames to reduce active Tx/Rx time
  - 11ah Short Control frames: use an NDP (Non-Data-Packet) with MAC info in S1G field
  - Short MAC header
  - Short beacon frame (and compressed TIM) to reduce beacon decode times
  - Short probe request/response
- Support for larger number of associations
  - New TIM structure and encoding
  - Multiple TIM segments. First segment aligns with DTIM.
- Pseudo-scheduling and grouping sensor traffic
  - To support large number of devices in network and reduce contention time
  - Target wakeup times (TWT) for STAs agreed with AP
  - Periods of time where contention is restricted to group of STAs
  - Speed frame exchange, for quick UL/DL transaction
  - Improved PS-poll operation to allow sensors to sleep while AP fetches data
- Increase standby time
  - Operation without beacon; use of PS-Poll to check for data and/or re-synch
  - Expand listen and MAX BSS idle periods to allow STAs sleep for hours/days
- Coexistence and prioritization of sensor traffic
  - Ad hoc EDCA parameters to favor battery operated STAs
  - Reservation of periods of time for sensors

HaLow (802.11ah) basic PHY features

- 150 kbps – 346 Mbps data rates

Channel Bandwidth	Data rates for 1SS	Data rates for 2SS
1 MHz	150 kbps – 4.44 Mbps	600 kbps – 8.88 Mbps
2 MHz	650 kbps – 8.67 Mbps	1.3 Mbps – 17.3 Mbps
4 MHz	1.35 Mbps – 20 Mbps	2.7 Mbps – 40 Mbps
8 MHz	2.9 Mbps – 43.3 Mbps	5.8 Mbps – 87 Mbps
16 MHz	5.8 Mbps – 87 Mbps	11.7 Mbps – 173 Mbps

- 2, 4, 8, or 16 MHz channel bandwidth
  - 802.11ac OFDM design on a tenth clocking rate, i.e. 31.25 kHz spacing
  - Symbol length ten times of that in 802.11ac.
  - Up to 4x4 MIMO
- 1 MHz channel bandwidth:
  - 24 data subcarriers per OFDM symbol maintaining 31.25 KHz spacing
  - MCS 10 added for single stream long range transmission w/ 150 kbps
    - For sensing-type applications requiring extended range

S1G Data Rates

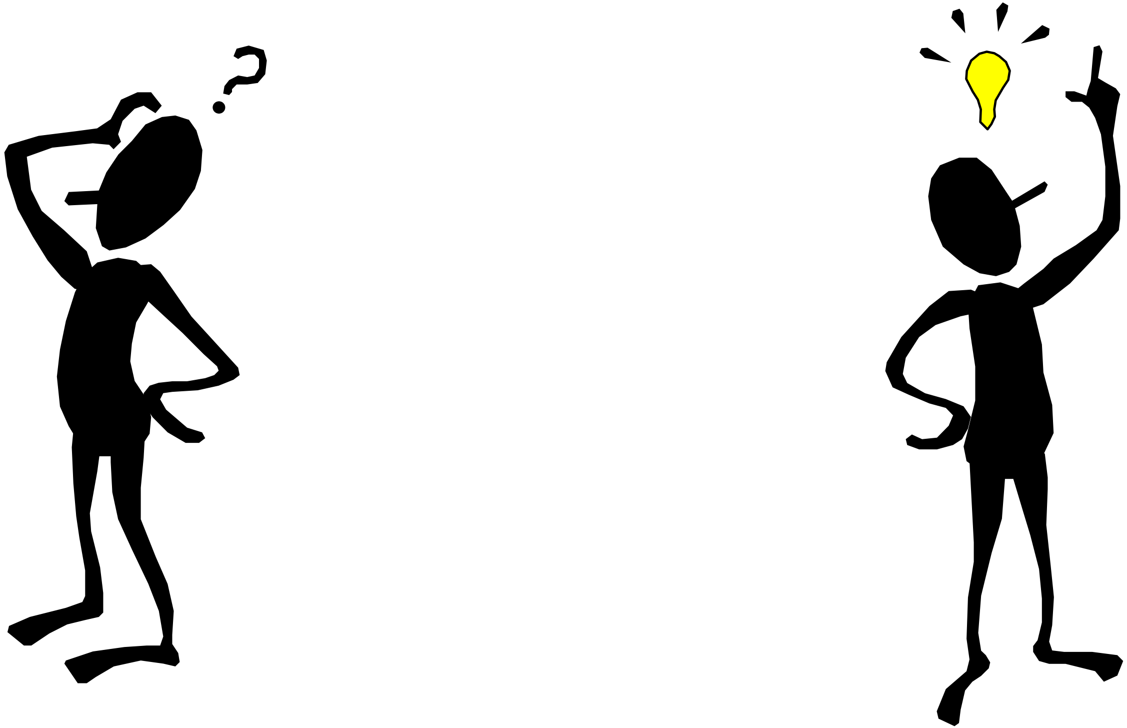
- Baseline design according 11ac/11n
  - Optimized for robust link and extended coverage in sub-GHz band
- IEEE 802.11ah MCS for 2MHz Bandwidth Channels:
  - MCS 9 is not valid for 802.11ah with a single spatial stream for a 2 MHz channel.

MCS Index	Modulation	Code Rate	Data Rate (Mbps) Normal GI (8µs)	Data Rate (Mbps) Short GI (4µs)
0	BPSK	1/2	0.65	0.72
1	QPSK	1/2	1.3	1.44
2	QPSK	3/4	1.95	2.17
3	16-QAM	1/2	2.6	2.89
4	16-QAM	3/4	3.9	4.33
5	64-QAM	2/3	5.2	5.78
6	64-QAM	3/4	5.85	6.5
7	64-QAM	5/6	6.5	7.22
8	256-QAM	3/4	7.8	8.67
9	256-QAM	5/6	8.67	9.63

WLAN IEEE 802.11

END OF SON WLAN LECTURE

Questions and answers



HaLow (802.11ah) questions…

1) What are the two main use cases of 802.11ah?
2) For what frequency range is 802.11ah designed for?
3) Which channel bandwidths are supported by 802.11ah?
4) What is the maximum bitrate of MCS10 at 1 MHz bandwidth of 802.11ah?
5) What is the maximum bitrate of HaLow for a single stream?
6) How many terminals can concurrently connect to an 802.11ah AP?
7) How relates the OFDM used by 802.11ah to the OFDM used by 802.11ac?
8) What is the length of the guard interval of HaLow?

Anything left?

Thank you for your attendance!