Wi-Fi 6 (802.11 ax)
Part 1-The underlying physics

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Wi-Fi 6

11ax

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Agenda

1 Evolution of Wi-Fi towards 802.11 ax (The Physics and Math's behind it)

2 Why MCS chart plays an important role in Wi-Fi discussions ?

3 What does 802.11 ax or Wi-Fi 6 offers over the previous generations of Wi-Fi technology, that gives it a alternate name «HIGH EFFICIENCY» or HE ??

4 Discussing all the features of 802.11ax

How 802.11 ax differs from it’s predecessor technologies

	802.11n (Wi-Fi 4)	802.11ac Wave 2 (Wi-Fi 5)	802.11ax (Wi-Fi 6)
Released	2009	2013	**2019**
Bands	2.4GHz & 5GHz	5GHz	**2.4GHz & 5GHz, spanning to 1GHz - 6GHz eventually**
Channel Bandwidth	20MHz, 40MHz (40MHz optional)	20MHz, 40MHz, 80MHz, 80+80MHz & 160MHz (40MHz support made mandatory)	**20MHz/40MHz @ 2.4GHz, 80MHz, 80+80MHz & 160MHz @ 5GHz**
Subcarrier Spacing	312.5kHz	312.5kHz	**78.125 kHz**
OFDM Symbol Duration	3.6us (short guard interval) 4us (long guard interval)	3.2us (0.4/0.8us cyclic prefix)	**12.8us (0.8/1.6/3.2us cyclic prefix)**
Highest Modulation	64-QAM	256-QAM	**1024-QAM**
Data Rates	Ranging from 54Mb/s to 600Mb/s (max of 4 spatial streams)	433Mb/s (80MHz, 1 spatial stream) 6933Mb/s (160MHz, 8 spatial stream)	**600Mb/s (80MHz, 1 spatial stream) 9607.8Mb/s (160MHz, 8 spatial stream)**
Channel Configuration	Single User MIMO & OFDM	Single User MIMO & OFDM Wave 1, Multi User MIMO (Only DL) & OFDM Wave 2	**Multi User MIMO (UL and DL & OFDMA (UL and DL)**

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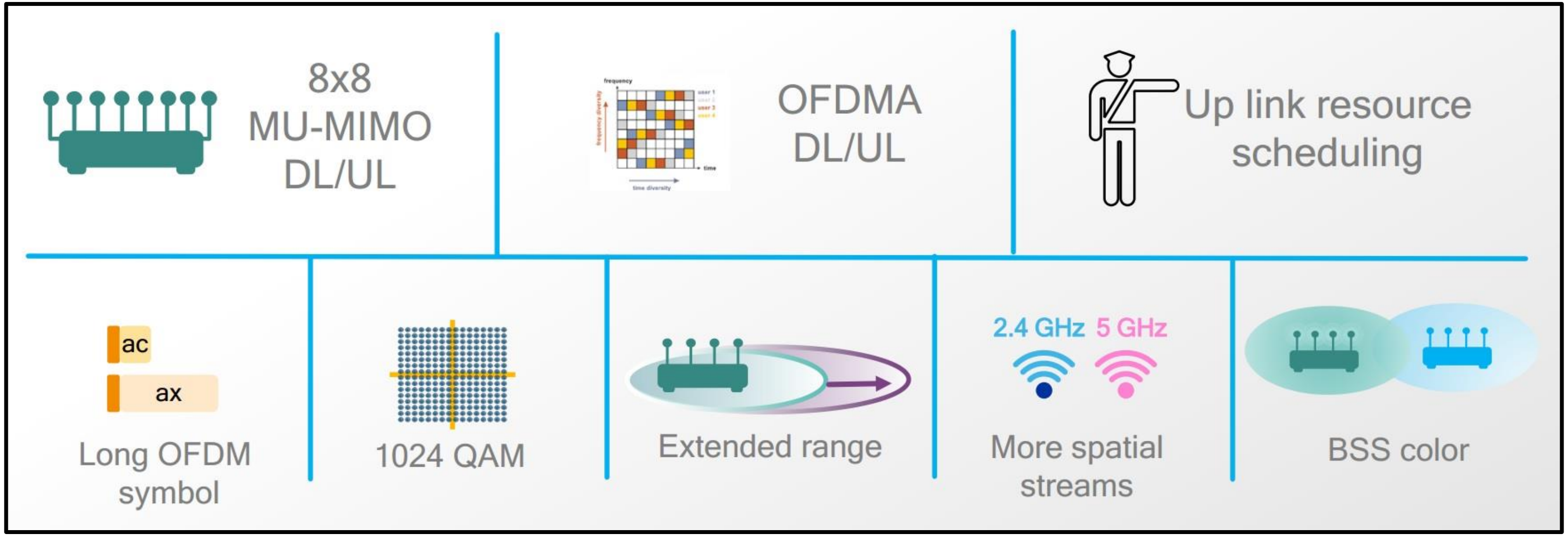
Wi-Fi 802.11ax Features



A Side note:

After 802.11 n, 11ax is the technology that is adopted on both 2.4 GHz and 5 GHz Radio Spectrum.

Wi-Fi 802.11ax Feature Set Summary

OFDMA	MU-MIMO	1024 QAM	Long Symbol Duration in 11ax.	Preamble updates or PPDU formats	Spatial Re-use (BSS coloring)	Target Wake Time
Orthogonal Frequency Division Multiple Access (OFDMA): **multi-user version of OFDM enabling concurrent AP communication** (Uplink/Downlink) with multiple clients by assigning subsets of subcarriers, called Resource Units (RUs) to the individual clients. **Based on client traffic needs, the AP can allocate the whole channel to only one user or may partition it to serve multiple users simultaneously.**	Multi-User Multiple Input Multiple Output (MU-MIMO): Introduced in very high throughput Wi-Fi (802.11ac), MUMIMO technology allows the simultaneous transmitting of multiple frames to different receivers at the same time on the same channel using multiple RF streams to provide greater efficiency. **11ax adds 8×8 and uplink MU-MIMO services to provide significantly higher data throughput.**	QAM - 1024: Modulation techniques are used to optimize throughput and range. The number of points in the modulation constellation determines the number of bits conveyed with each symbol. 802.11ac uses 256 QAM which transfers 8 bits/symbol. **802.11ax supports 1024 QAM, using 10 bits/symbol for A 25% increase in throughput.**	Long Symbol Duration: 4× larger OFDM symbol times **increase efficiency and improves robustness, especially for transmission in outdoor scenarios.**	Preamble Updates or PPDU formats: Modified frame formats provide High Efficiency (HE) and legacy information to support new advanced capabilities as well as information required to **support legacy stations and backward compatibility.**	(OBSS): To improve spatial reuse efficiency and performance, 11ax adjusts the carrier sense operation based on the color of the BSS. **Depending on the BSS the traffic is generated from, the station can use different sensitivity thresholds to transmit or defer. This results in higher overall performance.**	Target Wake Time (TWT): TWT allows the AP to schedule a series of times for a station to wake up at scheduled intervals to exchange data frames. **This allows the station to sleep longer and reduces energy consumption. Key capability for IOT devices**

Pre-requisites before venturing into 11ax, as 11ax is not just another 802.11 standard that promises significant increase in throughout, but also promises High Spectral usage Efficiency (Thus, the name HE or High Efficiency for 802.11ax)

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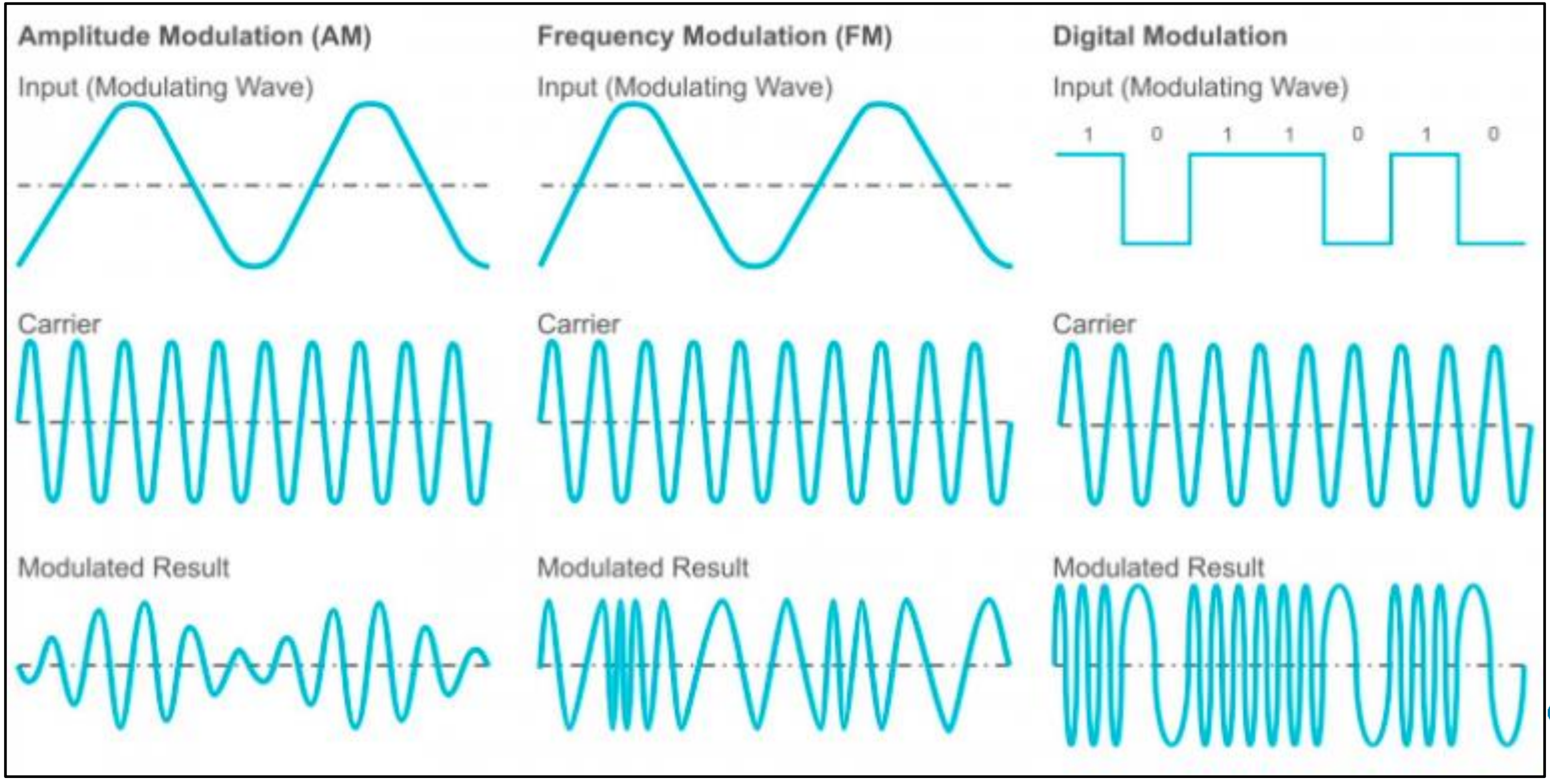
In Signal processing world, in the simplest sense, a wave can be modulated by its amplitude, frequency and phase. Wi-Fi uses these fundamentals to achieve complex modulation that play a huge role in throughput.



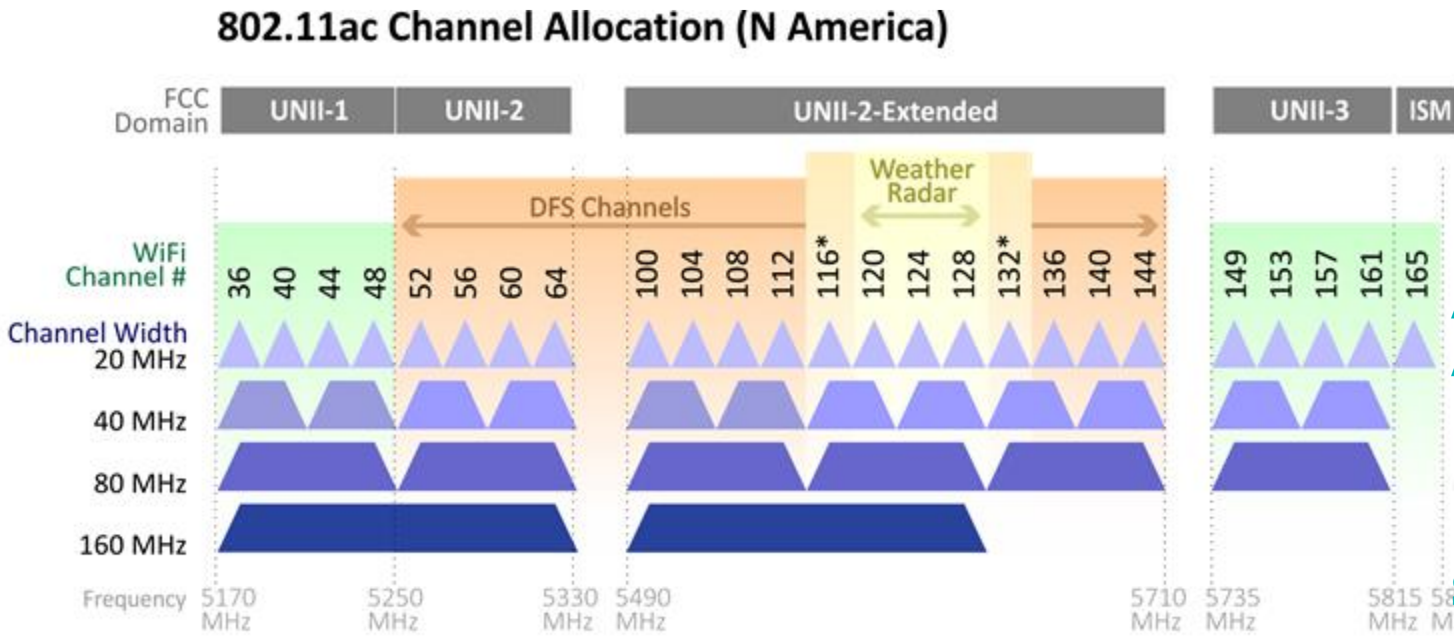
To include speech information or data information, another wave needs to be imposed, **called an input signal, on top of the carrier wave.** This process of imposing an input signal onto a carrier wave is called **modulation.** In other words, **modulation changes the shape of a carrier wave to somehow encode the speech or data information that we were interested in carrying. Modulation is like hiding a code inside the carrier wave.**

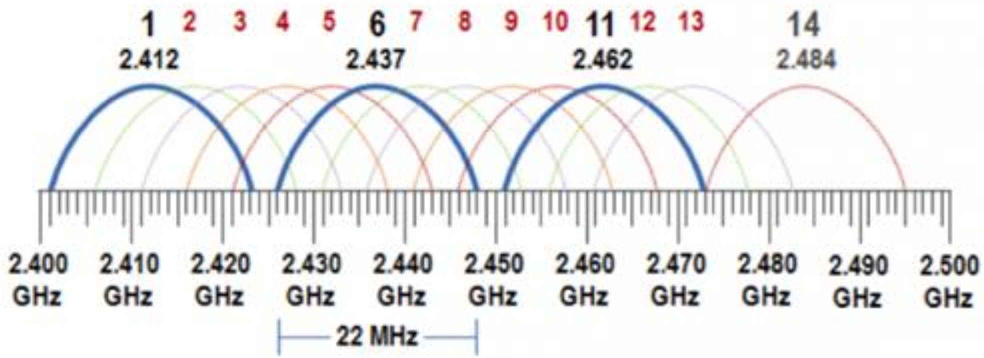
Any wave has three basic properties:

1) Amplitude – the height of the wave
2) Frequency – number of waves passing through in each second
3) Phase – where the phase is at any given moment.

Why are carriers and modulation needed at all?

Interestingly, the input signals could be carried (without a carrier wave) by very low frequency electromagnetic waves. The problem, however, is that this will need quite a bit of amplification in order to transmit those very low frequencies. The input signals themselves do not have much power and need a large antenna in order to transmit the information.





A quick look At 5 GHz And 2.4 GHz Radio Spectrum Before jumping To the various Modulation techniques

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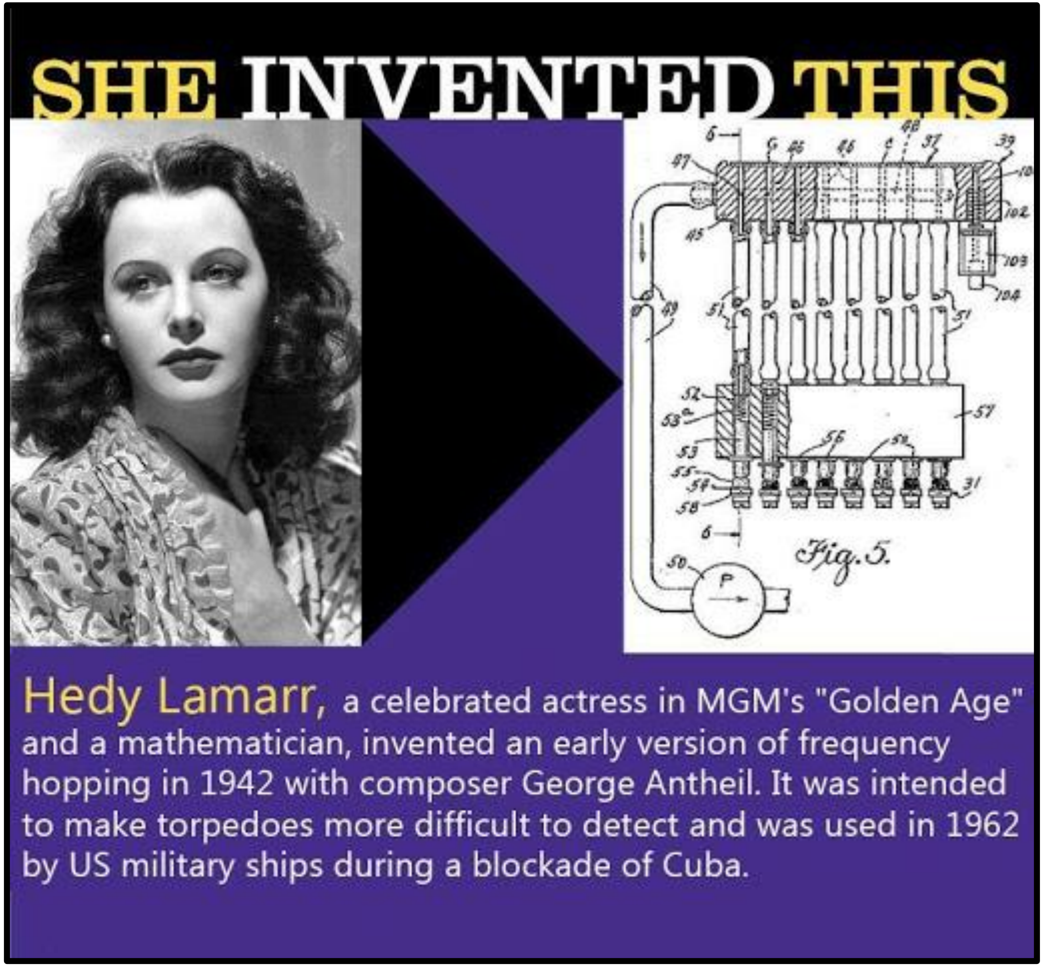
Frequency Hopping Spread Spectrum (FHSS)

Must Read Inspiring story about .....



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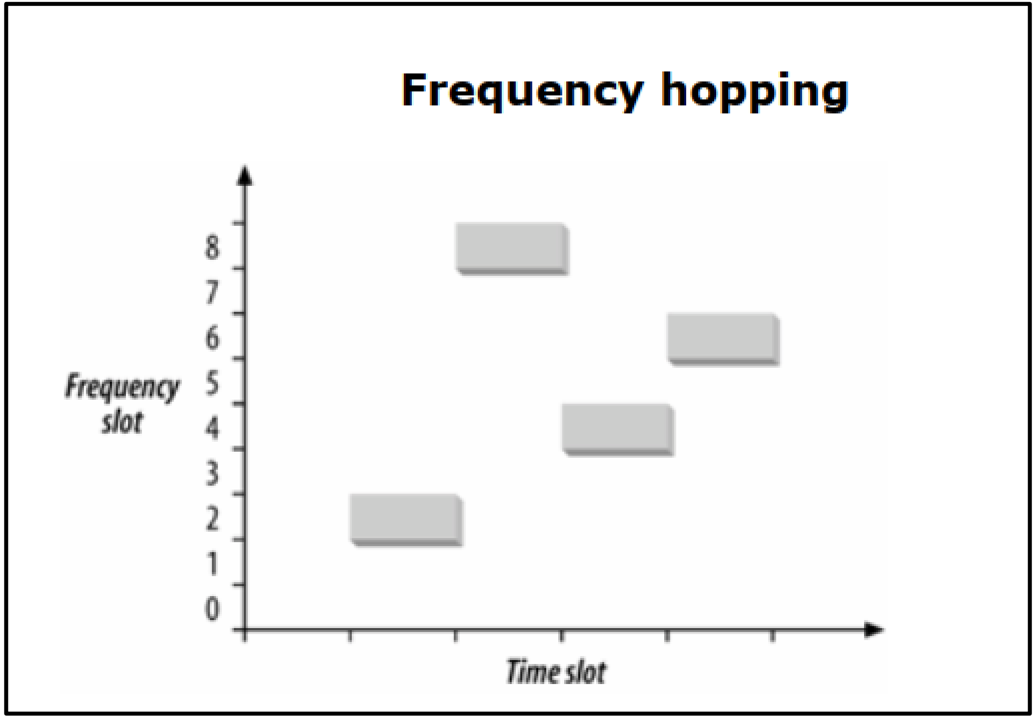
Frequency Hopping

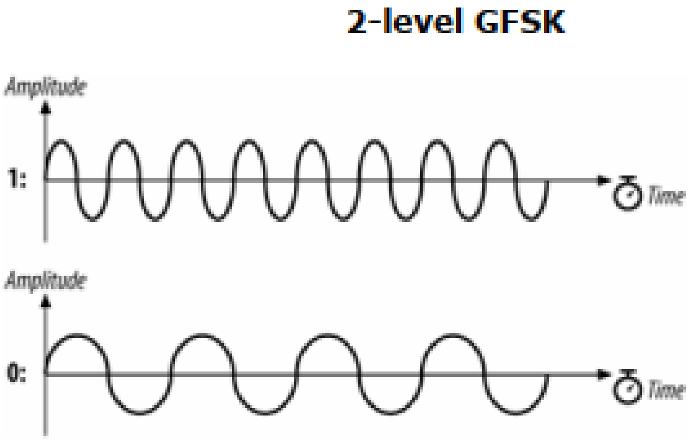


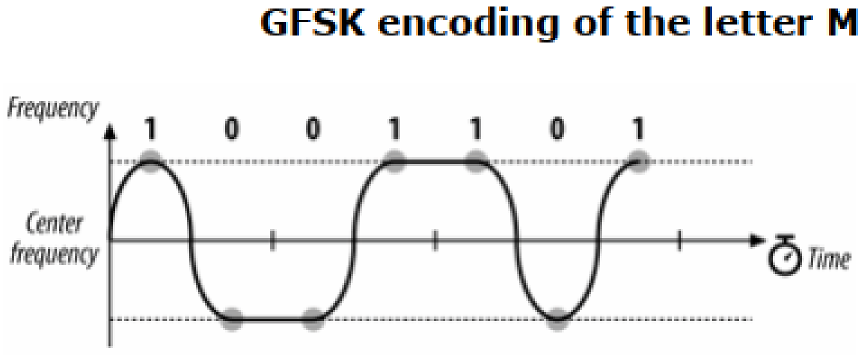
The Frequency Hopping Uses Gaussian Frequency Shift Keying

2 Level GFSK

0 and 1 bit are represented with 2 different Frequencies and in 2 level GFSK, only 1 bit can be Transmitted in a symbol time.

M (ASCII val): 01001101

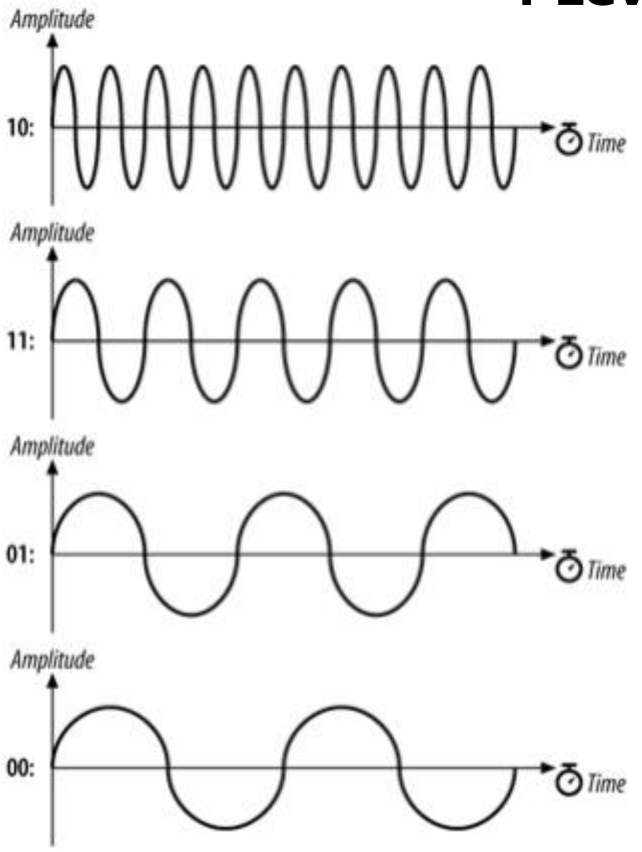




Y-Axis : Frequency
X-Axis : Symbol Time

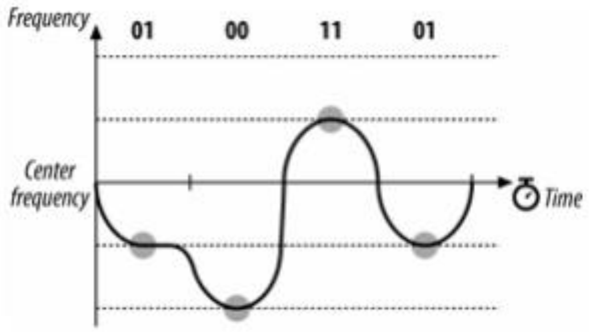
The Frequency Hopping Uses Gaussian Frequency Shift Keying (cont..)

4 Level GFSK



M (ASCII val): 01001101

4GFSK encoding of the letter M



00, 01, 10 and 11 are represented with 4 different Frequencies and in 4 level GFSK, 2 bits can be Transmitted in a symbol time.

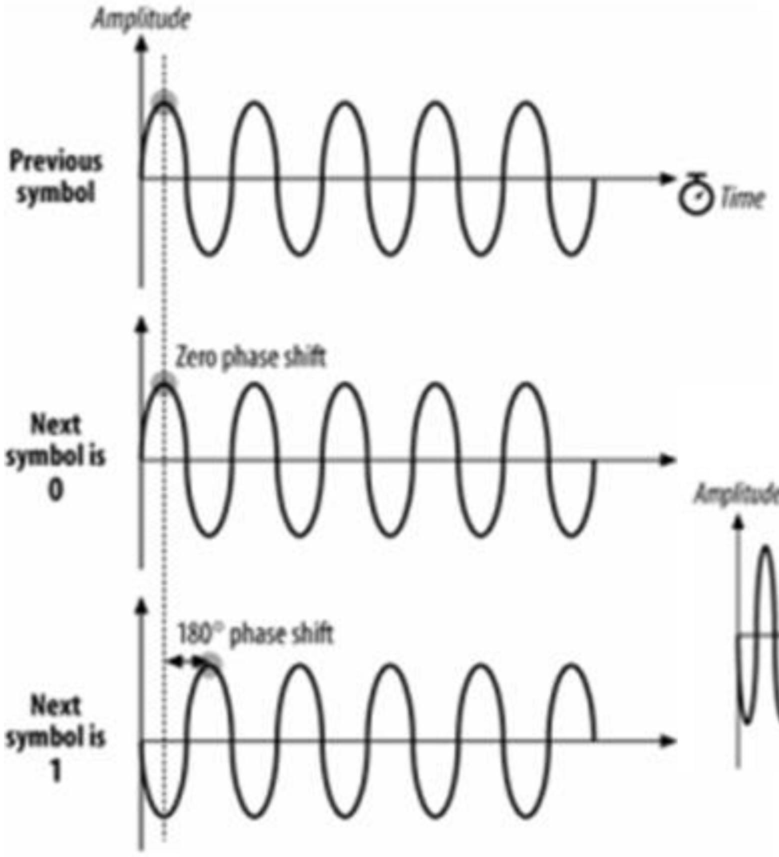
Y-Axis : Frequency
X-Axis : Symbol Time

Though Frequency hopping is no longer used in Wi-Fi technologies now, But this modulation technique was point, where it all began.

The Direct Sequence Spread Spectrum
DSSS and HR/DSSS (802.11b)

[Up to 11 Mbps]

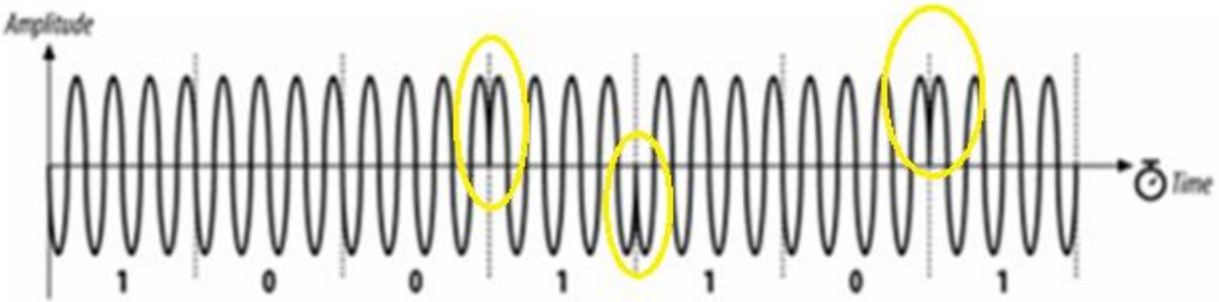
Differential Phase Shift Keying (DPSK) encoding



Differential phase shift keying (DPSK) is the basis for 802.11 direct-sequence systems. As the name implies, phase shift keying (PSK) encodes data in phase changes of the transmitted signal.

M (ASCII val): 01001101

The letter M encoded in DBPSK



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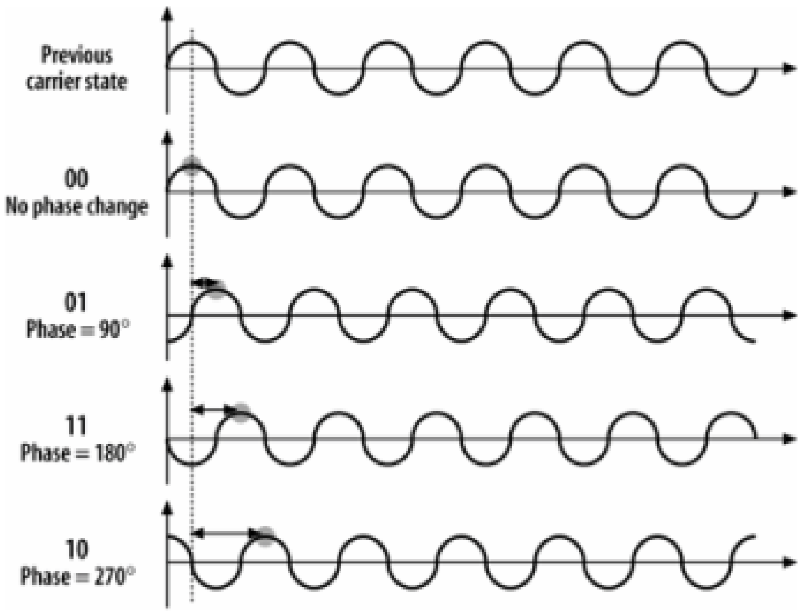
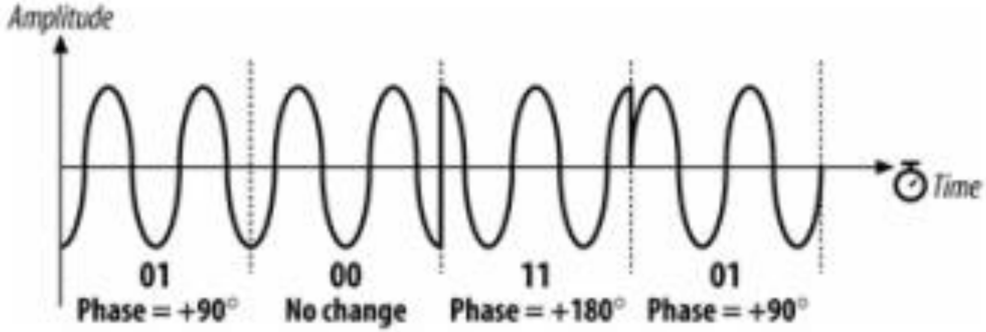
Differential Quadrature Phase Shift Keying (DQPSK) encoding

DQPSK encoding



M (ASCII val): 01001101



DQPSK phase shifts

Symbol	Phase shift
00	0
01	90° (π/2 radians)
11	180° (π radians)
10	270° (3π/2 or -π/2 radians)

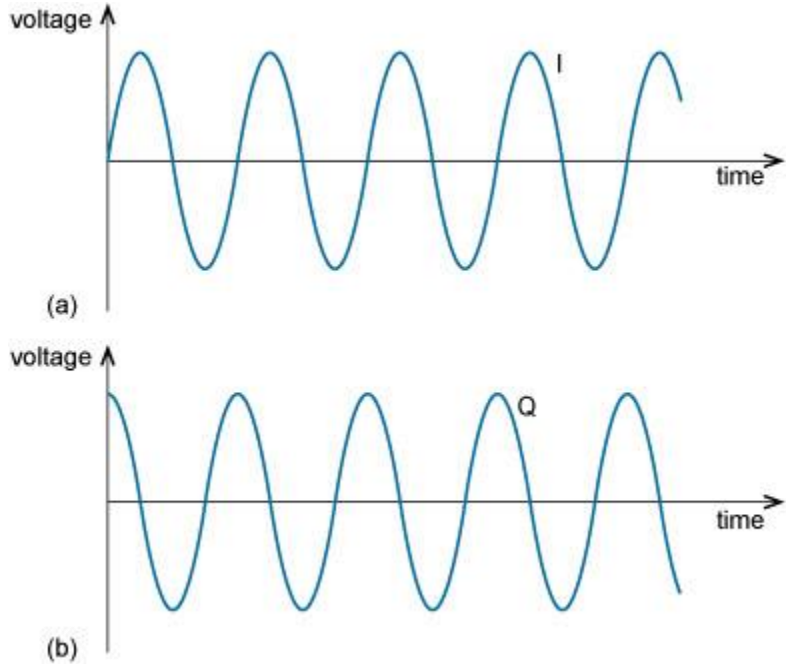
Constellation Diagrams for Various Modulation Techniques

The rate at which data is sent through the system is called the ***symbol rate.***

Hence, the no. of bits transmitted by a modulation technique in a symbol, Dictates the throughput of the Wi-Fi Standard using that modulation Technique.

QAM Constellation Diagrams

QAM is based on the application of ASK and PSK to two sinusoidal waves of the same frequency but with a phase difference of 90°. Sinusoidal waves 90° apart are said to be in a quadrature phase relationship. It is customary to refer to one of these waves as the **I wave**, or in-phase wave or component, and the other as the **Q wave**, or quadrature wave or component

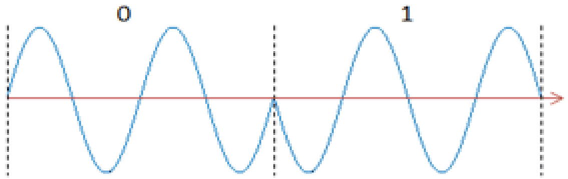


I (in-phase or sine) wave and (b) Q (quadrature or cosine) wave

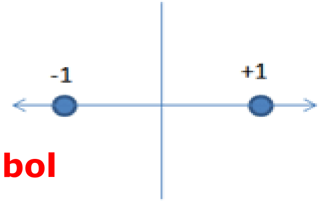
You may recognise the **I wave in as a sine function** and **the Q wave as a cosine function**. These functions are said to be **orthogonal** to each other. **If two signals are orthogonal, when they are transmitted simultaneously one can be completely recovered at the receiver without any interference from the other.**

The I and Q waves remain orthogonal. Even if either or both of them are inverted (multiplied by –1, or flipped vertically). Negative amplitudes just mean that the wave is inverted.

BPSK, QPSK and 16 QAM

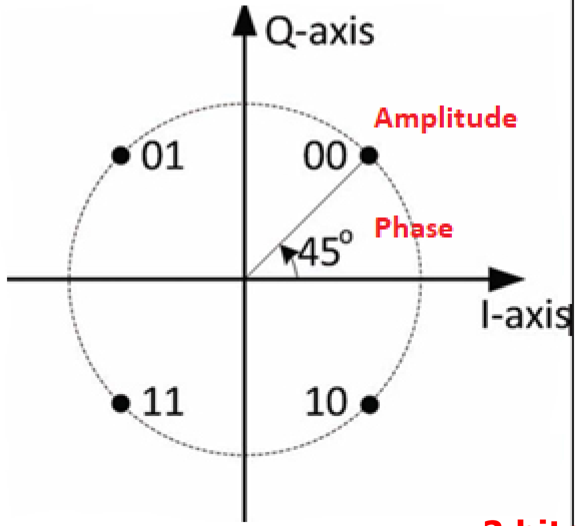


BPSK Modulation



BPSK Constellation Diagram

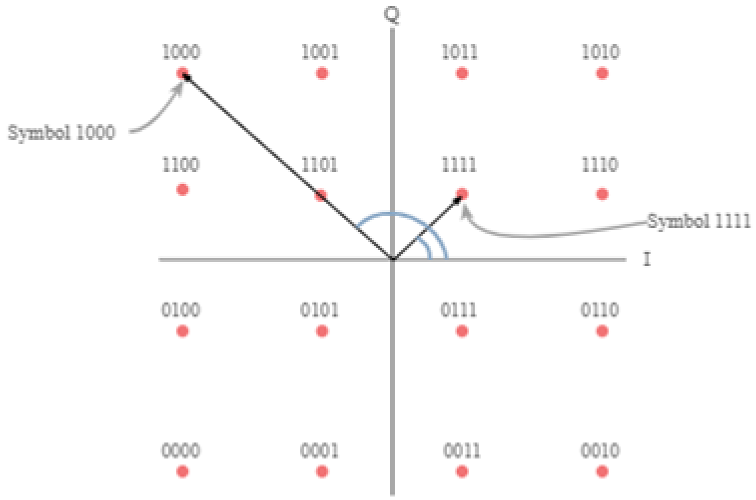
1 bit per symbol



QPSK Constellation Diagram

2 bits per symbol

4 bits per symbol



16 QAM Constellation Diagram

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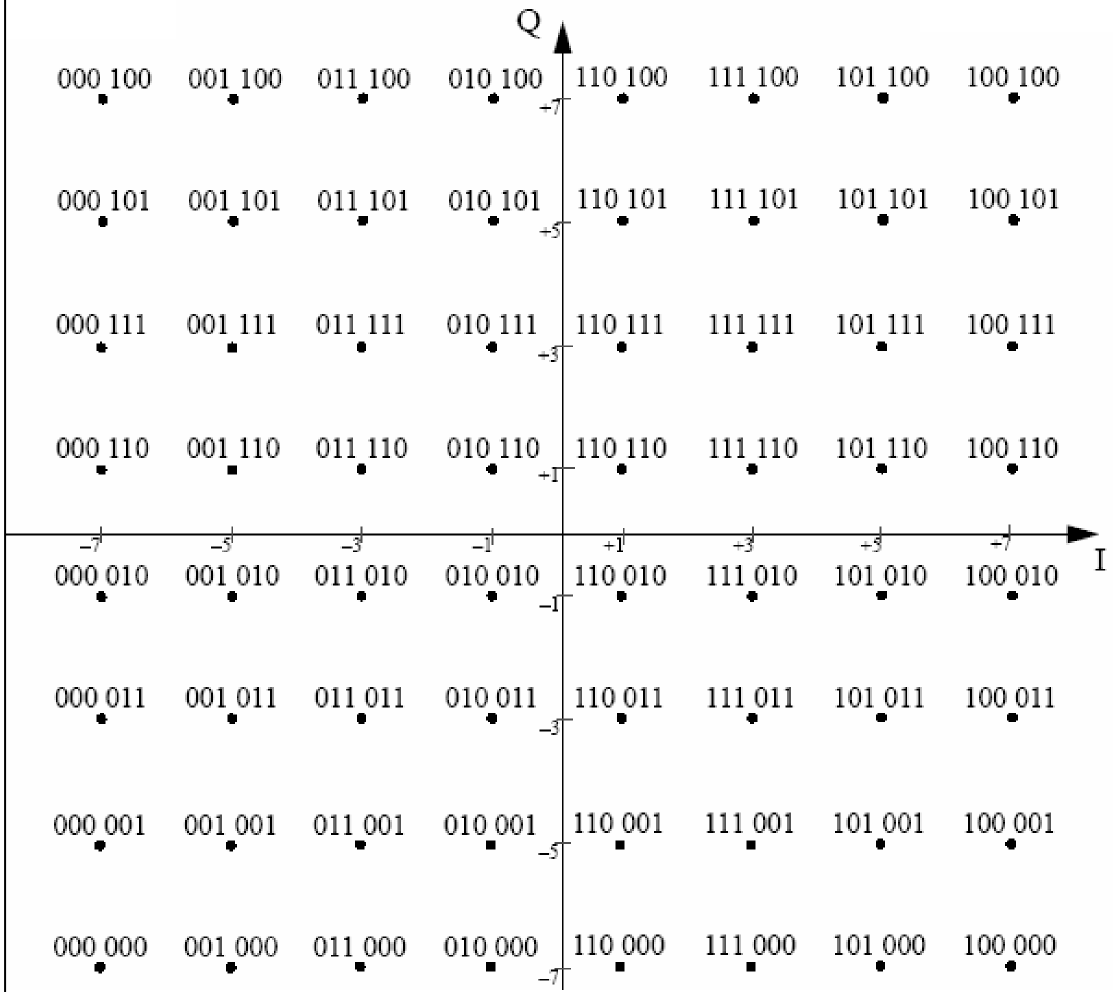
64 QAM

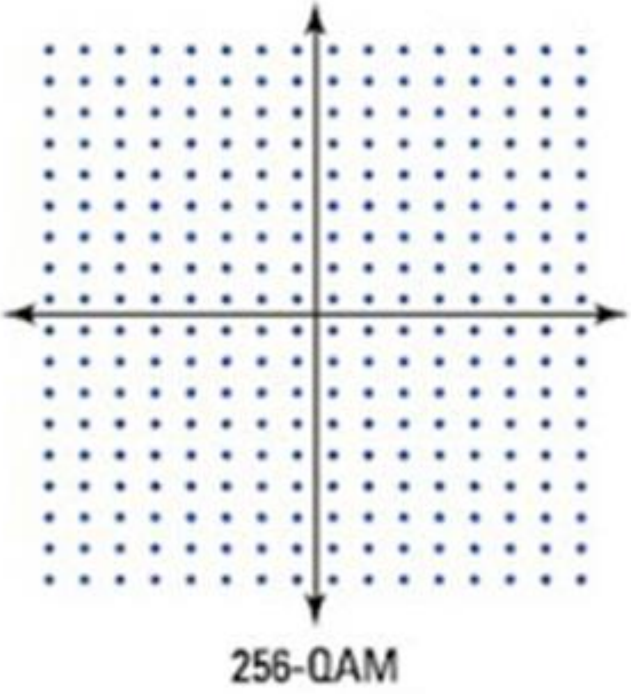
6 bits per symbol



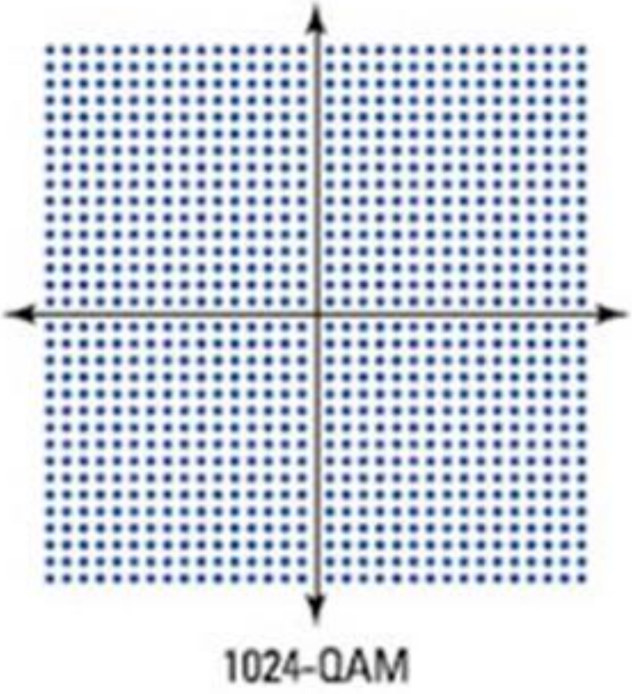
64 QAM Constellation Diagram

1024 QAM (one of the highlight of 802.11 ax)

8 Bits per symbol



10 Bits per symbol



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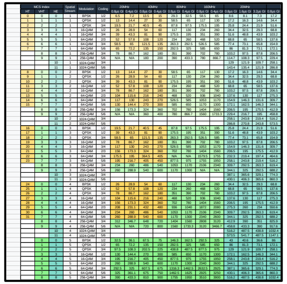
MCS chart for 11n, 11ac and 11ax

**Click on the picture to view MCS chart in excel sheet.
At any given point of time, the MCS chart determines the throughput rate
of the selected Wi-Fi Standard.**



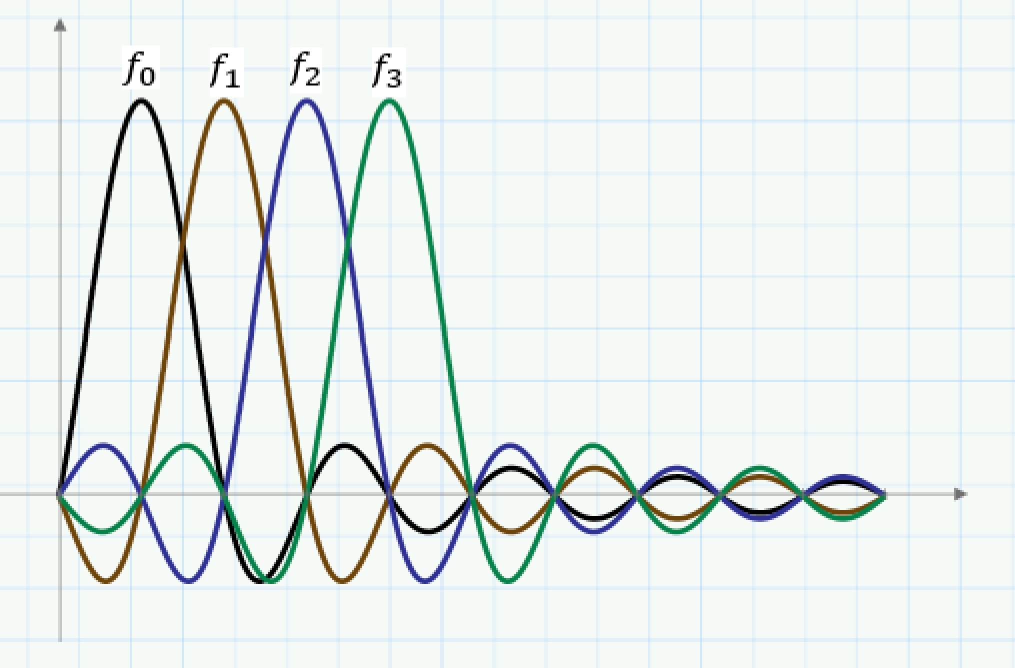
Each MCS value starting from HT-OFDM is based on a combination of these parameters:

1. Channel size
2. Number of spatial streams
3. Coding method
4. Modulation technique
5. Guard interval.

OFDM (Orthogonal Frequency Division Multiplexing) and QAM (Quadrature Amplitude Modulation)

OFDM is a frequency-division multiplexing (FDM) scheme that was introduced by Robert W. Chang of Bell Labs in 1966.[2][3][4] In OFDM, multiple closely spaced orthogonal subcarrier signals with overlapping spectra are transmitted to carry data in parallel.

Each subcarrier (signal) is modulated with a conventional modulation scheme (such as **quadrature amplitude modulation or phase shift keying**) at a low symbol rate. This maintains total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.



These same subcarriers in the frequency domain, shown with some modulation bandwidth to indicate the overlap between subcarriers. The subcarriers are orthogonal to each other and will exhibit minimal interference to the other subcarriers, resulting in efficient use of bandwidth. Note that the amplitude of each subcarrier crosses zero at the center of other subcarriers, minimizing adjacent subcarrier impact.

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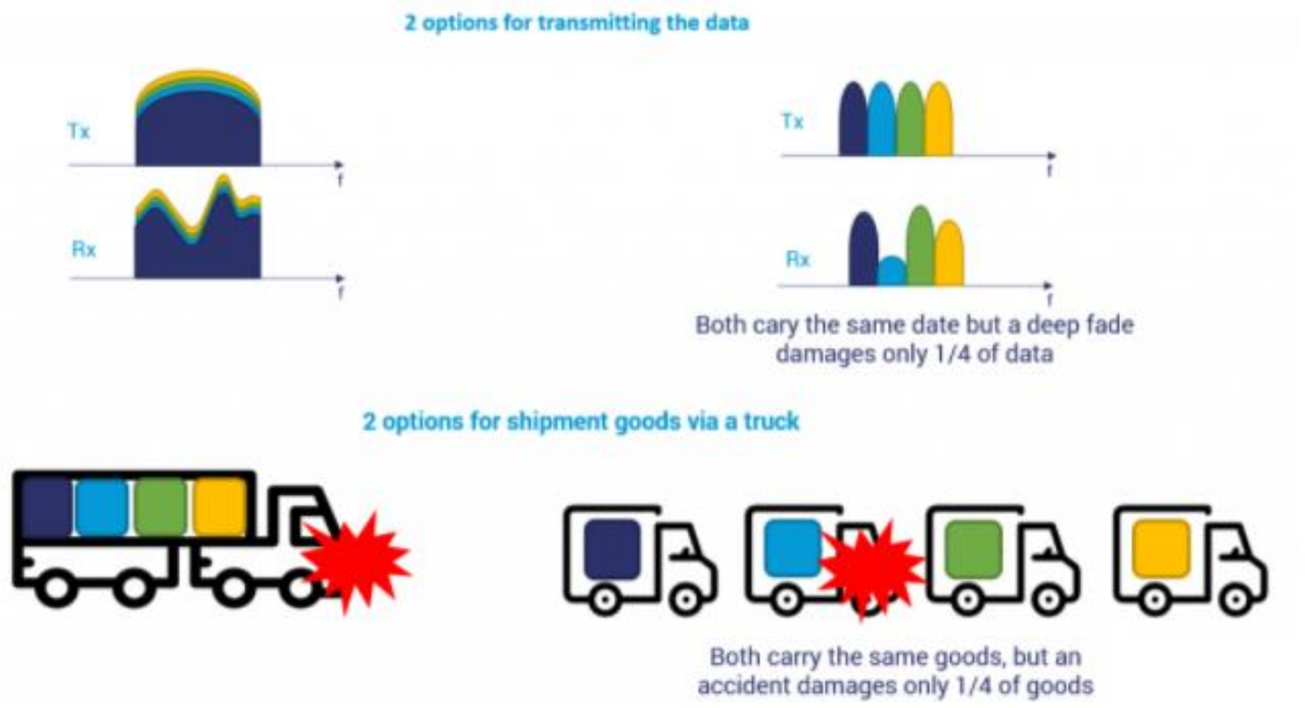
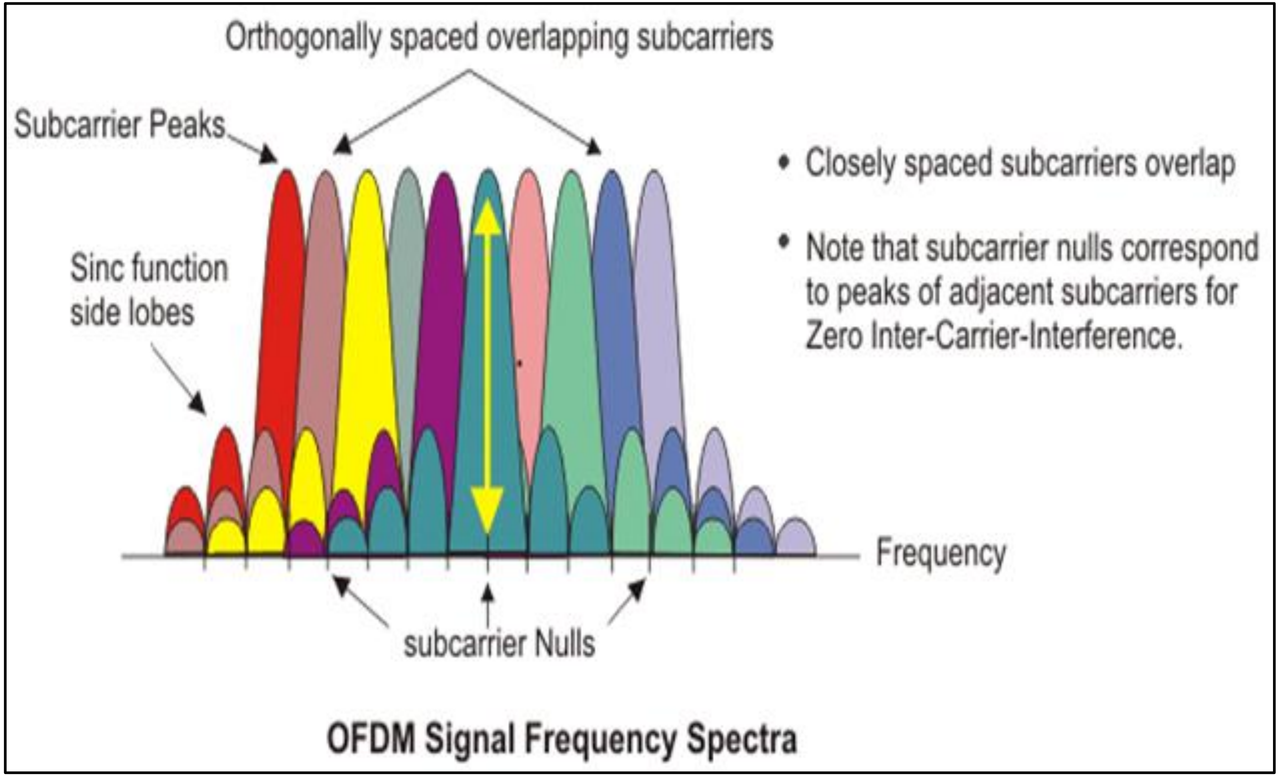
OFDM,

***Orthogonal Frequency Division Multiplexing** is a form of signal modulation that divides a high date rate modulating stream placing onto multiple close spaced carriers each with low-rate data for resilient communications (*selective fading, interference, and multipath effects, as well providing a high degree of spectral efficiency.*).*



Orthogonal Frequency Division Multiplexing



The use of orthogonal subcarriers allows more subcarriers per bandwidth resulting in an increase in spectral efficiency. In a perfect OFDM signal, Orthogonality prevents interference between overlapping carriers. In FDM systems, any overlap in the spectrums of adjacent signals will result in interference.

In OFDM systems, the subcarriers will interfere with each other only if there is a loss of orthogonality. For example, frequency error will cause the subcarrier frequencies to shift so that the spectral nulls will no longer be aligned resulting in inter-subcarrier-interference.

For 20 MHz bandwidth signals, Legacy Mode uses 48 data subcarriers and 4 pilot subcarriers, while HT modes use 52 data subcarriers and 4 pilot subcarriers. This gives 20 MHz HT mode slightly more throughput than Legacy Mode. For 40 MHz bandwidth signals, there are 108 data subcarriers and 6 pilot subcarriers

Encoding details for different OFDM data rates

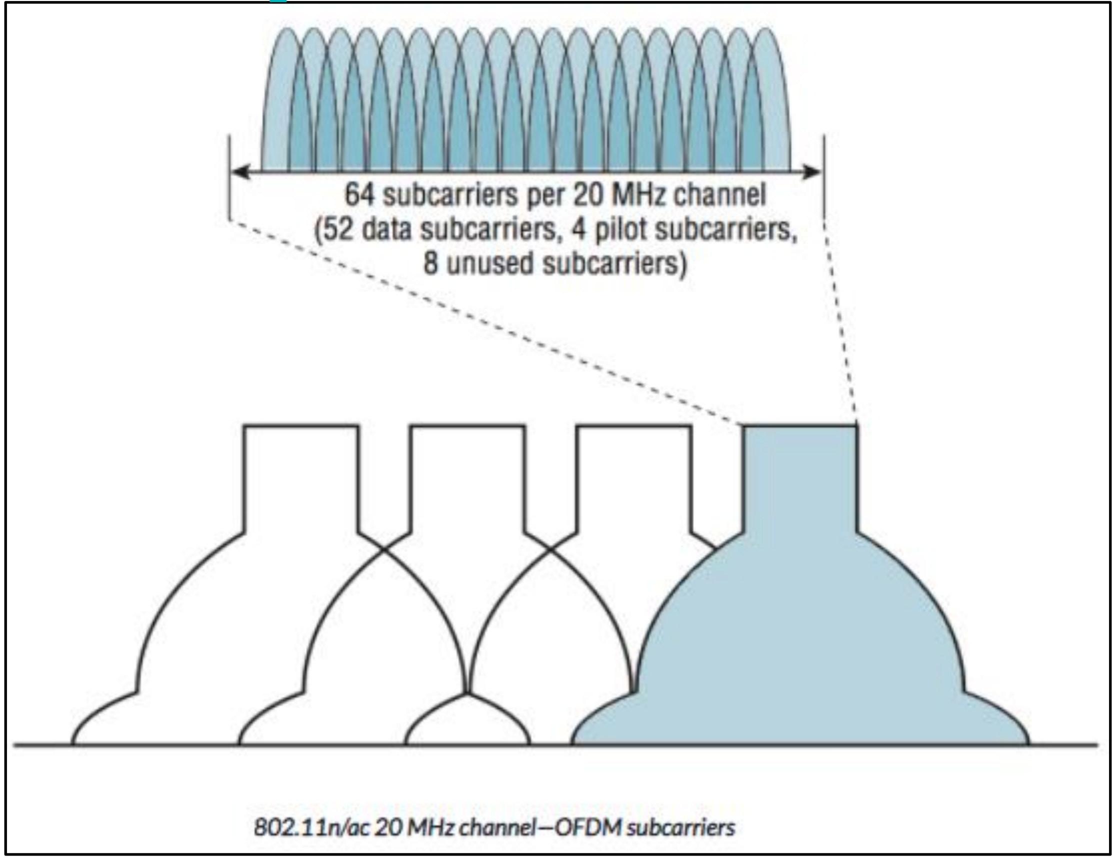
Speed (Mbps)	Modulation and coding rate (R)	Coded bits per carrier	Coded bits per symbol	Data bits per symbol
6	BPSK, R=1/2	1	48	24
9	BPSK, R=3/4	1	48	36
12	QPSK, R=1/2	2	96	48
18	QPSK, R=3/4	2	96	72
24	16-QAM, R=1/2	4	192	96
36	16-QAM, R=3/4	4	192	144
48	64-QAM, R=2/3	6	288	192
54	64-QAM, R=3/4	6	288	216
72	64-QAM	6	288	288

Coded bits per subchannel is a function of the modulation (BPSK, QPSK, 16-QAM, or 64-QAM).

The data bits per symbol is a function of the rate of the convolutional code.

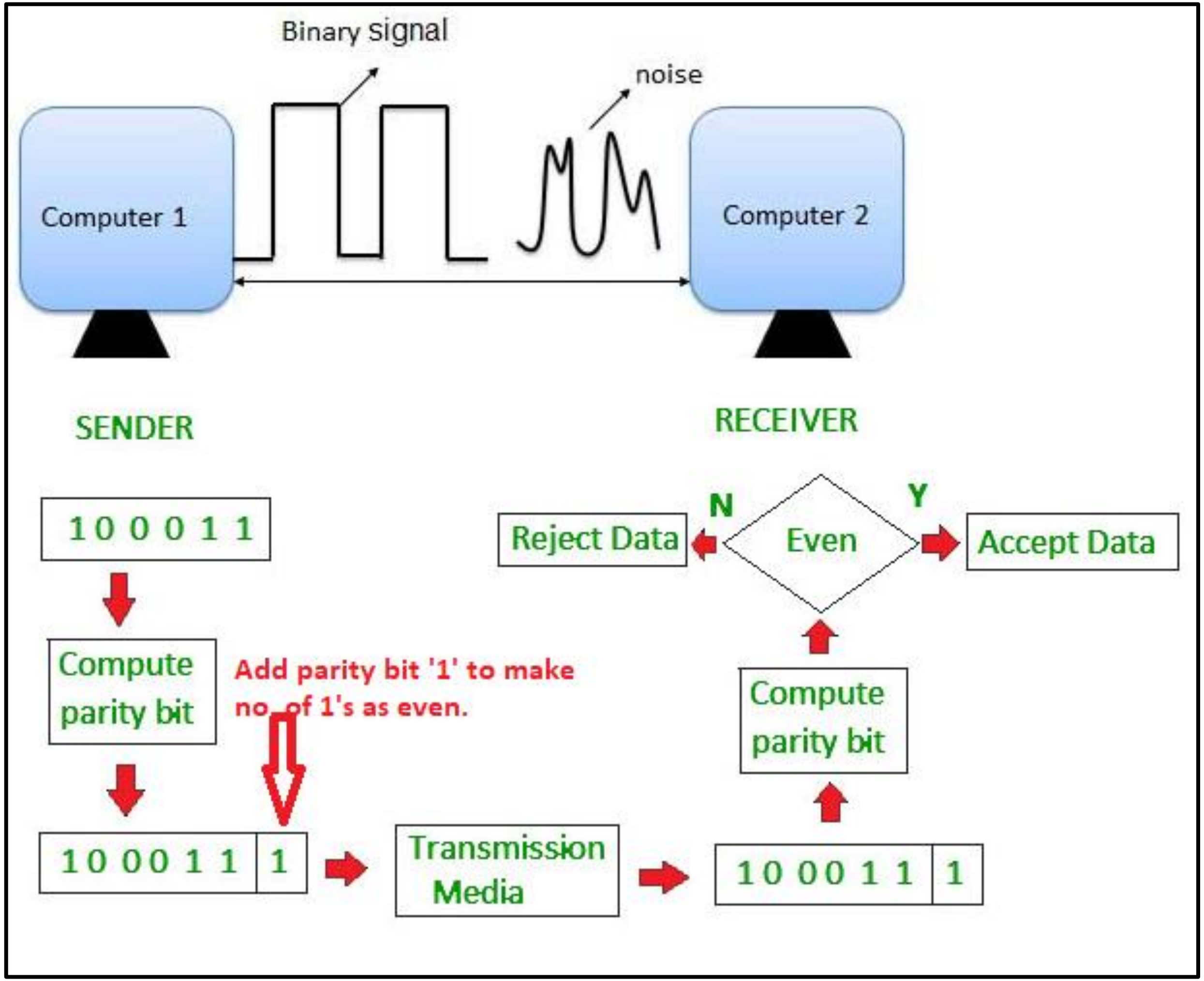
Note that the actual
Data bits per symbol
Are lesser than
Code bits per
Symbol, as the
Diff bits are “redundant
Bit” that are added
To increase the reliability
Of the communication,
Which gets affected
By noice, interference,
Multi path fading etc..

OFDM Sub-Carriers Representation



What is “coding” in MCS ?

A Simplest example to explain why “coding” is necessary while transmitting data bits over modulated Radio signal.



Math behind calculating Data Rate corresponding to MCS value for an OFDM PHY

PHY	Modulation		R	N_{SS}	N_{SD}				T_{DFT}	T_{GI}	
	Name	N_{BPSCS}			20MHz	40MHz	80MHz	160MHz		Long	Short
802.11n (HT)	BPSK	1	1/2	1 to 4	52	108	234	468	3.2 µs	0.8 µs	0.4 µs
	QPSK	2	1/2 & 3/4								
	16-QAM	4	1/2 & 3/4								
	64-QAM	6	1/2 & 2/3 & 3/4								
802.11ac (VHT)	BPSK	1	1/2	1 to 8							
	QPSK	2	1/2 & 3/4								
	16-QAM	4	1/2 & 3/4								
	64-QAM	6	1/2 & 2/3 & 3/4								
	256-QAM	8	2/3 & 5/6								

HT and VHT OFDM Parameters

Number of Data Subcarriers · *Number of Coded Bits per Subcarrier per Stream* · *Coding* · *Number of Spatial Streams*

$$\text{Data Rate} = \frac{N_{SD} * N_{BPSCS} * R * N_{SS}}{T_{DFT} + T_{GI}}$$

OFDM Symbol Duration · *Guard Interval Duration*

Data Rate for 802.11n (64 QAM and 20 MHz BW And coding ½ and SS=1)

=

$$\frac{52 * 6 * (2/3) * 1}{(3.2 + 0.8) * 10^{-6}} = 52 \text{ Mbps}$$

This will align with the value from the MCS chart.

OFDM
Symbol
Duration:
3.2 µs + 0.4µs/0.8µs
As GI. = a subcarrier
spacing of 0.3125 MHz (1/3.2 µs)

Number of Data Subcarriers
Number of Coded Bits per Subcarrier per Stream
Coding
Number of Spatial Streams

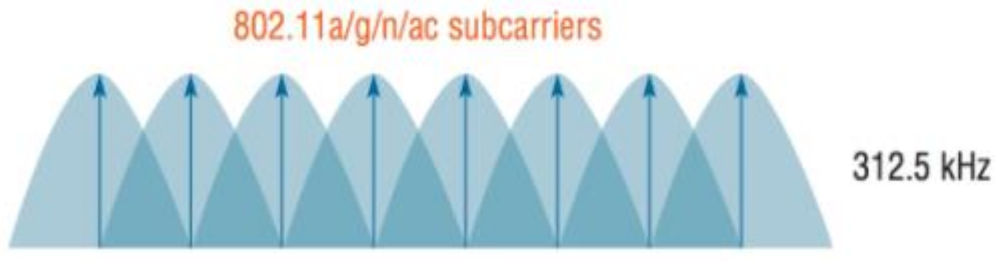
$$\text{Data Rate} = \frac{N_{SD} * N_{BPSCS} * R * N_{SS}}{T_{DFT} + T_{GI}}$$

OFDM Symbol Duration
Guard Interval Duration

The Math for no. of Sub-carriera for OFDM for 20 MHz Bandwidth is:

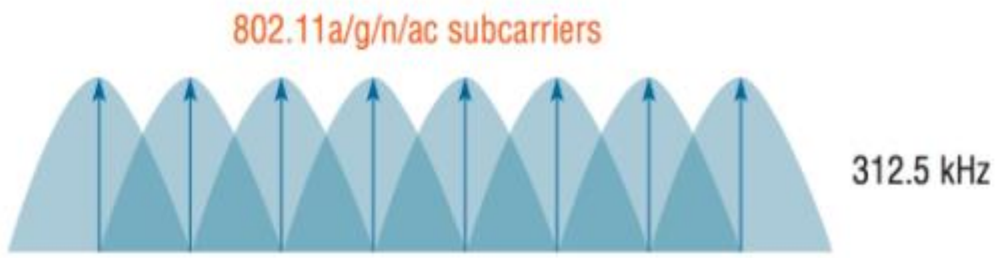
20 MHz/312.5 KHz = 64 sub-carriers.

= 52 data sub-carrier + 4 pilot carrier + 8 unused sub-carrier



802.11a matches the 800-ns guard time with a 4-µs symbol time. Subcarrier spacing is inversely related to the FFT integration time. 802.11a has a 3.2-µs integration time and a subcarrier spacing of 0.3125 MHz (1/3.2 µs)

For **20 MHz bandwidth signals**, Legacy Mode uses 48 data subcarriers and 4 pilot subcarriers, while HT modes use 52 data subcarriers and 4 pilot subcarriers. This gives 20 MHz HT mode slightly more throughput than Legacy Mode. For **40 MHz bandwidth** signals, there are 108 data subcarriers and 6 pilot subcarriers



The Math for no. of Sub-carriera for OFDM for 20 MHz Bandwidth is:

20 MHz/312.5 KHz = 64 sub-carriers.

Data Subcarriers: These subcarriers carry the modulated data in bits

Pilot Subcarriers: The pilot subcarriers do not carry modulated data; however, they are used for synchronization purposes between the receiver and transmitter.

Unused Subcarriers: The remaining unused subcarriers are mainly used as guard carriers or null subcarriers against interference from adjacent channels or sub-channels.

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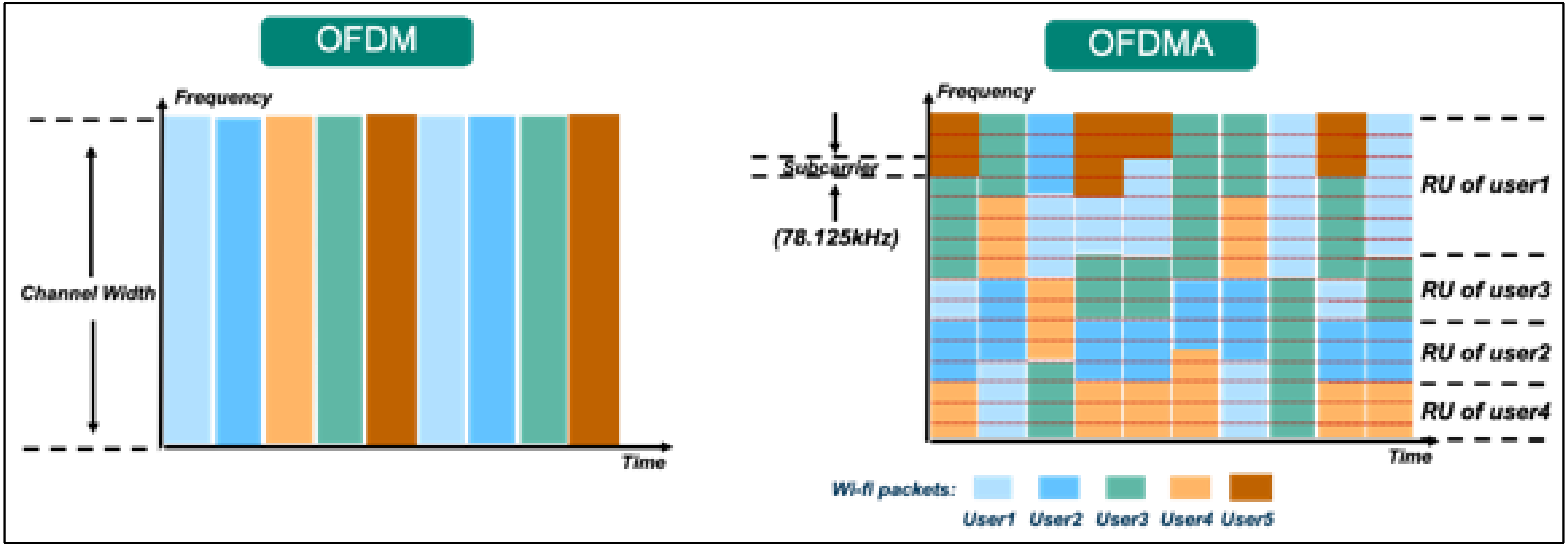
OFDMA
(Orthogonal Frequency-Division Multiple Access)

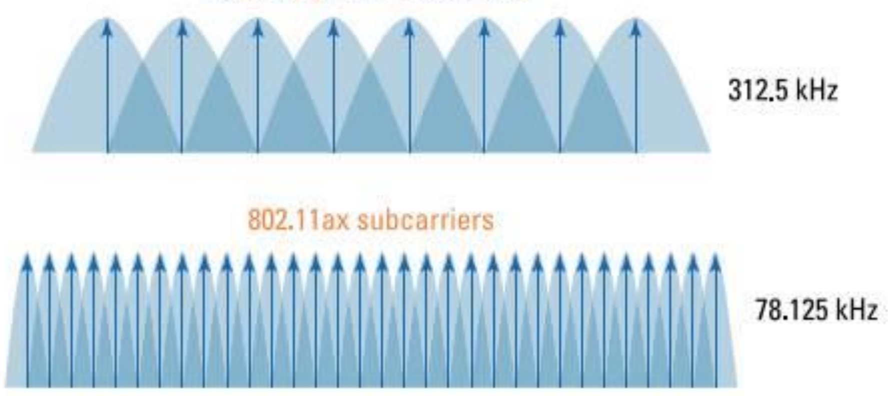
OFDMA (Orthogonal Frequency-Division Multiple Access)



Orthogonal frequency-division multiple access (OFDMA) is a **multi-user version** of the popular **orthogonal frequency-division multiplexing (OFDM)** digital modulation scheme. **Multiple access** is achieved in OFDMA by assigning **subsets of subcarriers to individual users.**

OFDMA (Orthogonal Frequency-Division Multiple Access)

- An OFDM 20 MHz 802.11n/ac channel consists of 64 [312.5 kHz] subcarriers.
- 802.11ax introduces a longer OFDM symbol time of 12.8 microseconds, which is four times the legacy symbol time of 3.2 microseconds. As a result of the longer symbol time, the subcarrier size and spacing decreases from 312.5 kHz to 78.125 kHz
- The narrower subcarrier spacing allows better equalization and enhanced channel robustness.
- Because of the 78.125 kHz spacing, an OFDMA 20 MHz channel consists of a total of 256 subcarriers.



OFDM and OFDMA subcarriers.

General Misconception:
OFDMA doesn't offer any greater Throughput compared to OFDM For the same bandwidth. However, it provisions serving Multiple 11ax clients within a Single contention Window.

OFDMA (Orthogonal Frequency-Division Multiple Access)

an OFDMA channel consists of a total of 256 subcarriers. These subcarriers can be grouped into smaller subchannels know as resource units (RUs). When subdividing a 20 MHz channel, an 802.11ax AP can designate 26, 52, 106, and 242 subcarrier RUs, which roughly equates to 2 MHz, 4 MHz, 8 MHz, and 20 MHz channels, respectively.

OFDMA Resource Units – 20 MHz channel.

Resource Units and Wide Channels

Resource Units (RUs)	20 MHz channel	40 MHz channel	80 MHz channel	160 MHz channel	80 + 80 MHz channel
996 (2x) subcarriers	n/a	n/a	n/a	1 client	1 client
996 subcarriers	n/a	n/a	1 client	2 clients	2 clients
484 subcarriers	n/a	1 client	2 clients	4 clients	4 clients
242 subcarriers	1 client	2 clients	4 clients	8 clients	8 clients
106 subcarriers	2 clients	4 clients	8 clients	16 clients	16 clients
52 subcarriers	4 clients	8 clients	16 clients	32 clients	32 clients
26 subcarriers	9 clients	18 clients	37 clients	74 clients	74 clients

OFDM sub-carriers can dynamically be allocated to multiple users according to their instantaneous channel conditions. Therefore, the multiuser version of OFDM, called orthogonal frequency division multiple access (OFDMA),

Formula for calculating OFDMA Data Rate per user, for given MCS parameter values.

Number of Data Subcarriers per Resource Unit

Number of Coded Bits per Subcarrier per Stream for the Resource Unit

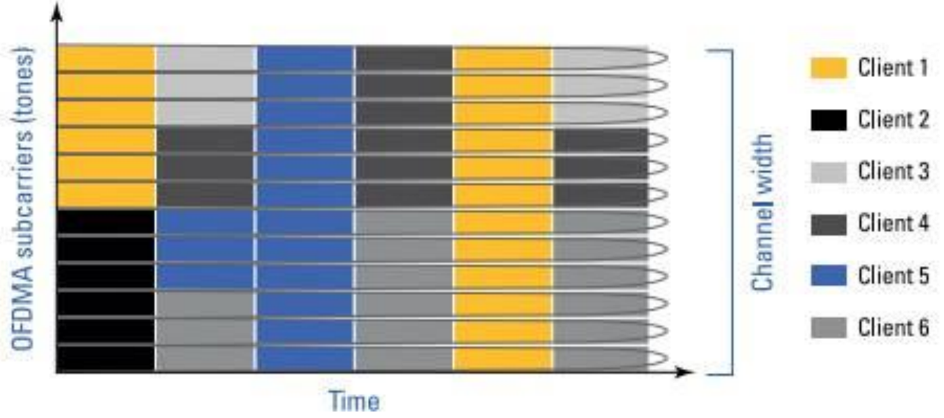
Coding

Number of Spatial Streams

$$\text{Data Rate} = \frac{N_{SD,U} * N_{BPSCS,U} * R * N_{SS}}{T_{DFT} + T_{GI}}$$

OFDM Symbol Duration

Guard Interval Duration



Notice that N_{SD} in OFDM changes to $N_{SD,U}$ in OFDMA, as 1 RU is allocated to one 11ax client.

A real Time output from Wi-Fi Chipset for 11ac vs 11ax (OFDM vs OFDMA)

11ac, where in the cumulative AirTime of all the 11ac clients is "less than" or "equal to" 100 %.

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
04:F0:21:12:60:34	925.0	159.8	24.3%	24.9%	29.0%	80	7.1	2.9	0.0%	0.0%
04:F0:21:F8:03:34	747.5	141.8	22.5%	22.1%	10.6%	80	5	3	0.0%	0.0%
04:F0:21:CF:88:34	943.3	164.4	26.2%	25.6%	38.3%	80	7	3	0.0%	0.0%
04:F0:21:07:61:34	974.8	176.1	26.1%	27.4%	32.9%	80	7	3.0	0.0%	0.0%
(overall)	-	642.0	**99.1%**	-	-					

11ax, where in the cumulative AirTime of all the 11ax clients is greater than 100 %. Also, there is a depiction of parallel Airtime, Which is what OFDMA RU is all about. i.e., when the 11ax clients connected to an AP get the contention window, the traffic is served equally to all the clients at the same time. This is very useful in congested environment, where clients connected to multiple AP's are fighting for contention window.

94:E6:F7:2F:46:92	1976.0	243.2	70.6%	29.0%	5.1%	156.4	9.4	2.0	96.1%	0.0%
94:E6:F7:71:39:CB	1630.4	206.6	72.5%	24.7%	2.0%	153.0	7.8	1.9	95.6%	0.0%
4C:1D:96:2B:E7:D7	1282.0	156.3	74.0%	18.7%	2.3%	159.3	6.2	2.0	99.5%	0.0%
4C:1D:96:8D:6A:83	1886.2	231.8	68.5%	27.7%	7.8%	157.5	9.0	2.0	96.6%	0.0%
(overall)	-	837.9	**285.6%**	-	-					

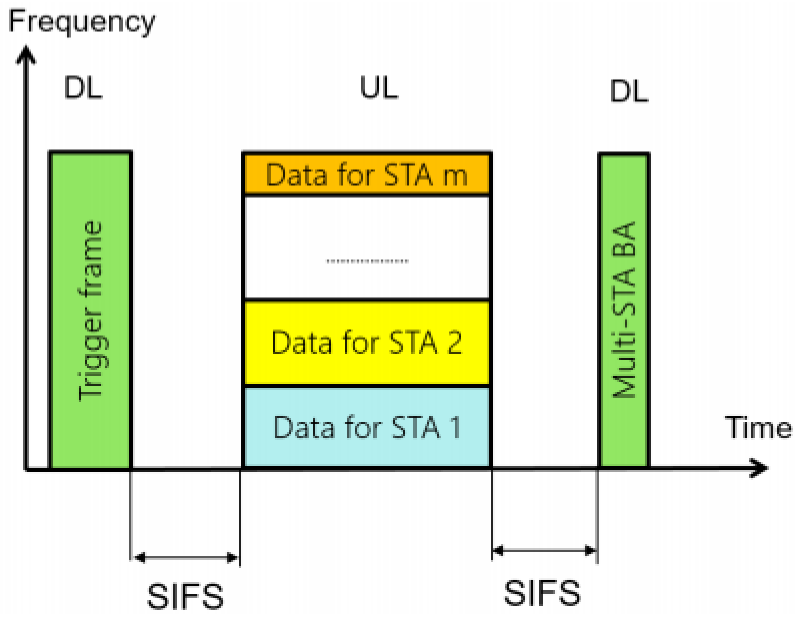
The advantages of the OFDMA can be felt in congested environment (with multiple clients and multiple Access points). However, in a non-congested environment, OFDMA doesn't offer any advantage and has negative impact on the throughput due to OFDMA header processing overhead .

Note:
If there is only one 11ax client connected to the AP, then OFDMA And MU-MIMO technologies become over head. In that case, RG would Scale down the transmission technology to OFDM or SU-MIMO.

This information is based on the real time testing performed on BCM's 43684 11ax Wi-Fi chipset.

OFDMA UL

OFDMA UL Transmission



An example of UL OFDMA transmission.

Organizing the UL MU transmission is a more challenging task. MU transmissions in Wi-Fi shall be synchronized in the time domain. Since it is difficult to maintain strict time synchronization because of clock drifting, an AP coordinates the UL MU transmission as follows.

The AP transmits a new type of a control frame — Trigger frame — in which it specifies the common parameters of the upcoming UL MU transmission (duration, GI which shall be the same for all the STAs participating in the UL MU transmission), allocates Rus for the STAs, and defines transmission parameters for each particular STA (MCS, coding, etc.).
To achieve synchronization, the MU transmission is performed immediately, i.e., a SIFS after the Trigger frame. **Since it may take more than SIFS to prepare a UL transmission, the AP can pad the Trigger frame.**

OFDMA UL Transmission

1. **If the AP wins contention before the Stations:**

Explicit BSR/Solicited BSR: AP sending Trigger Frame to all stations

In 802.11ax networks, OFDMA works on top of the legacy CSMA/CA (Carrier Sense Multiple Access With Collision Avoidance) mechanism called EDCA or DCF.5 It means that to transmit a Trigger frame, the AP shall contend for the channel with other STAs. Consider a network with an AP and several STAs having UL traffic. Since the number of STAs is usually much higher than one, the AP rarely wins the contention if the AP uses the same channel access parameters. **However, when the AP succeeds, it sends a Trigger frame to allocate resources for the associated STAs.**

OFDMA is much more efficient than EDCA. So, to achieve higher throughput, the STAs should rarely access the channel with EDCA but they should almost always use OFDMA. In other words, the AP shall almost always win the contention.

2. **If the 11ax station wins contention before AP :**

Implicit BSR/Unsolicited BSR: Stations sending BSR to AP.

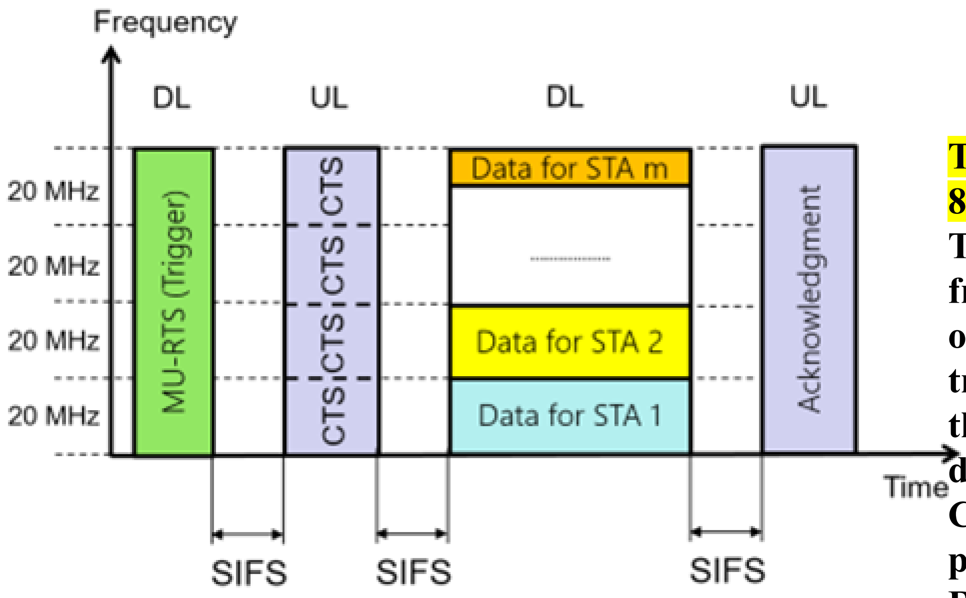
BSR Trigger Frame (Buffer Status Report)

One more variant of the Trigger frame is used to collect BSRs. In each BSR, each STA informs the AP about the amount of buffered traffic in a queue of the requested AC (AC_BE, AC_BK, AC_VI, or AC_VO) or of a subset of ACs.

A STA having data for transmission can generate a BSR and send it with random access to ask the AP for channel resources. Note that in the case of arrival of packets for uplink transmission, the STA can use the legacy EDCA to transmit either these packets or BSR.

OFDMA DL

OFDMA DL Transmission



MU-RTS/CTS exchange.

To protect a DL MU transmission from hidden nodes, 802.11 ax introduces the MU-RTS/CTS handshake. **Thanks to the UL MU transmissions in 802.11ax, the CTS frames can be sent simultaneously. The main peculiarity of the MU-RTS/CTS frames is that a CTS frame is transmitted on the primary 20 MHz, 40 MHz, 80 MHz or the entire 160 MHz or 80+80 MHz channel being duplicated on each 20 MHz subchannel using the legacy CTS frame format. The channel which shall be used by a particular STA to transmit the CTS is determined in MU-RTS and shall contain all the subcarriers which will be used for the following transmission to the STA.**

```
# wl -i wl1 msched
MU scheduler:
DL policy: AUTO (-1)  ofdma_en: 1 schidx: 1 flag: 0x0001 ack policy: trig_in_amp
(1)
        RU alloc mode: UCRU (-1), mu-rts: 2, mixackp: 1, mixbw (80+160): 1
        dlofdma_users min 2 max 96 num 0
        maxn bw20: 4 bw40: 4 bw80: 4 bw160: 4
```

The efficiency of the OFDMA transmissions, though, mainly hinges on how the AP selects the stations and allocates the available resources. Therefore, intelligent multi-user scheduling is crucial for attaining the best possible system performance.

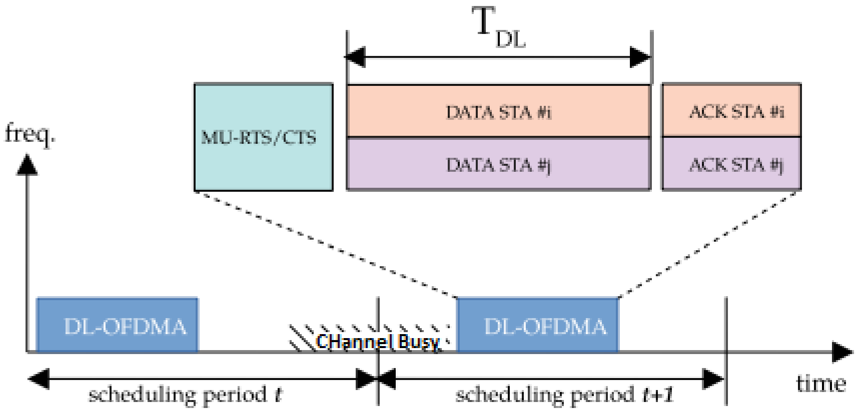


Illustration of a DL OFDMA transmission

Symbol Time and Guard Intervals

11ax has long symbol time and longer guard interval thus making it more robust in indoor/outdoor communication and aiding Multi-User transmission(OFDMA) and the frequency of the sub-carriers are reduced by 4 times.

Comparison of 802.11ac and 802.11ax

	802.11ac	802.11ax
Bands	5 GHz	2.4 GHz & 5 GHz
Channel Bandwidth	20 MHz, 40 MHz, 80 MHz, 80+80 MHz & 160 MHz	20 MHz, 40 MHz, 80 MHz, 80+80 MHz & 160 MHz
FFT Sizes	64, 128, 256, 512	256, 512, 1024, 2048
Subcarrier Spacing	312.5 kHz	78.125 kHz
OFDM Symbol Duration	3.2 us + 0.8/0.4 us CP	12.8 us + 0.8/1.6/3.2 us CP
Highest Modulation	256 QAM	1024 QAM
Data Rates	433 Mbps (80 MHz, 1 SS) 6933 Mbps (160 MHz, 8 SS)	600.4 Mbps (80 MHz, 1 SS) 9607.8 (160 MHz, 8 SS)

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MIMO or SU-MIMO

[Multiple Input/Multiple-Output
or
Single User MIMO]

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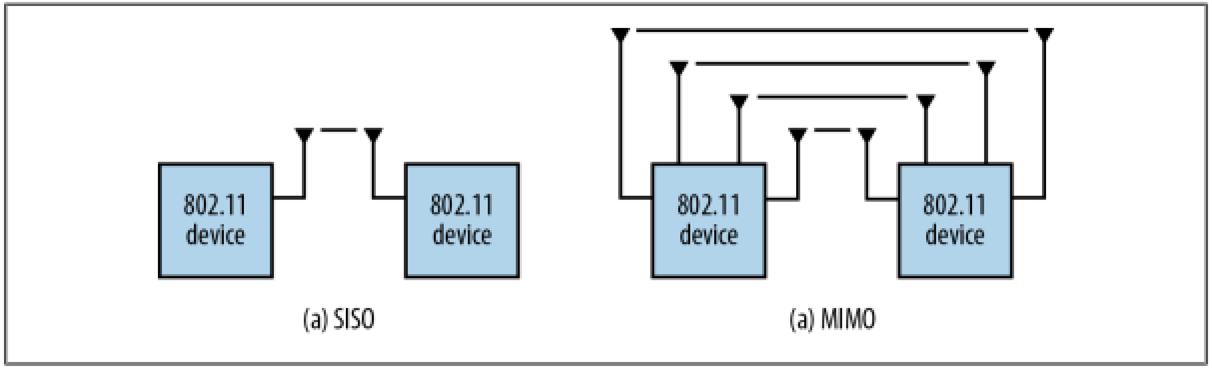
Light weight MIMO Basics

- Before MIMO, 802.11 interfaces had a single antenna.
- SISO system, a single active antenna transmits to a single active antenna.
  Although SISO systems may have multiple antennas, only one is active for any given data frame
- Attach an RF chain to each antenna in the system. This is the basis of Multiple-Input/Multiple-Output (MIMO) operation.
- Each **RF chain** and its **corresponding antenna** are responsible for transmitting a ***spatial stream***. A single frame can be broken up and
  multiplexed across multiple spatial streams, which are reassembled at the receiver.
- The shorthand **T × R : S** , where T and R are integers, used to refer to the number of **transmitter antennas** and the number of **receiver antennas** and S is no. of spatial streams, which should be less than or equal to T and R**.**

As per Shannon's Law, which is a mathematical relationship between the bit rate of a channel, as described by the bandwidth of the channel and its signal-to-noise ratio. Effectively, it states that the speed of a transmission
channel can be made as large as desired as long as the signal-to-noise ratio increases in tandem.

Antenna Diversity(in SISO) and MIMO Compared



Comparison of SISO transmission to MIMO transmission

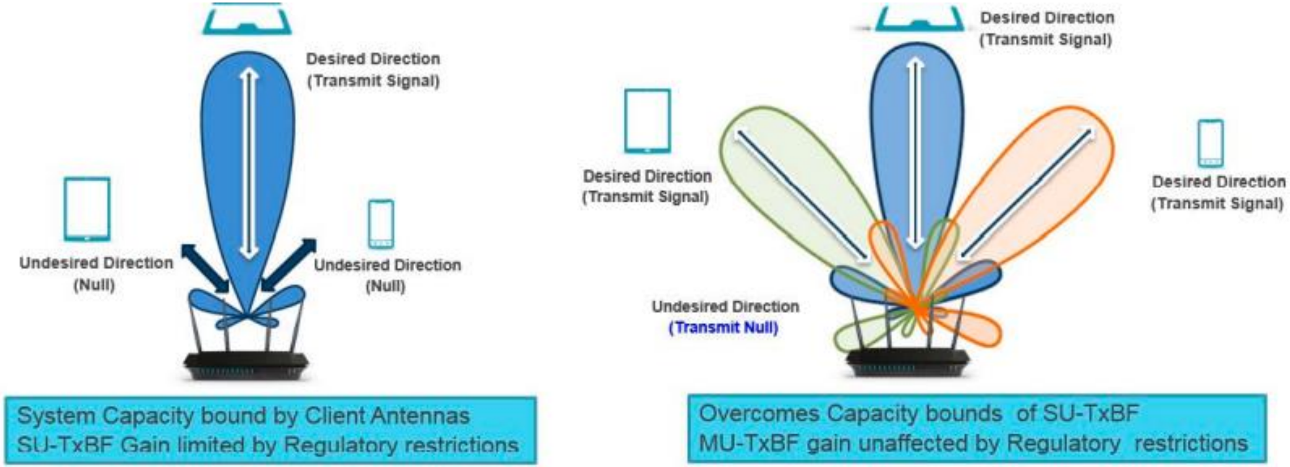
- 802.11a/b/g devices often had multiple antennas to take advantage of ***antenna diversity*****.** If an **802.11a/b/g SISO device has multiple physical antennas**, and **an 802.11n MIMO device has multiple antennas**, **what makes those two technologies different?**

  The answer lies in how the radio chip is laid out, and the complexity of the transceiver. In an antenna diversity system, there is really only one transceiver. Multiple antennas may feed into that one transceiver, but when the receiver is active, it must choose which of the antennas is connected to the electronics in the receive chain. Only one antenna can be connected to the receiver electronics, no matter how many antennas may sprout from the device.

Typically, 802.11a/b/g devices with diversity would choose the antenna that received the strongest signal.

- In MIMO, each antenna can be driven independently. Antenna One can transmit (or receive) a completely different set of bits from Antenna Two. Hence, Thought put is multiplied by the no. of Antenna’s or spatial streams.

SU-MIMO vs MU-MIMO



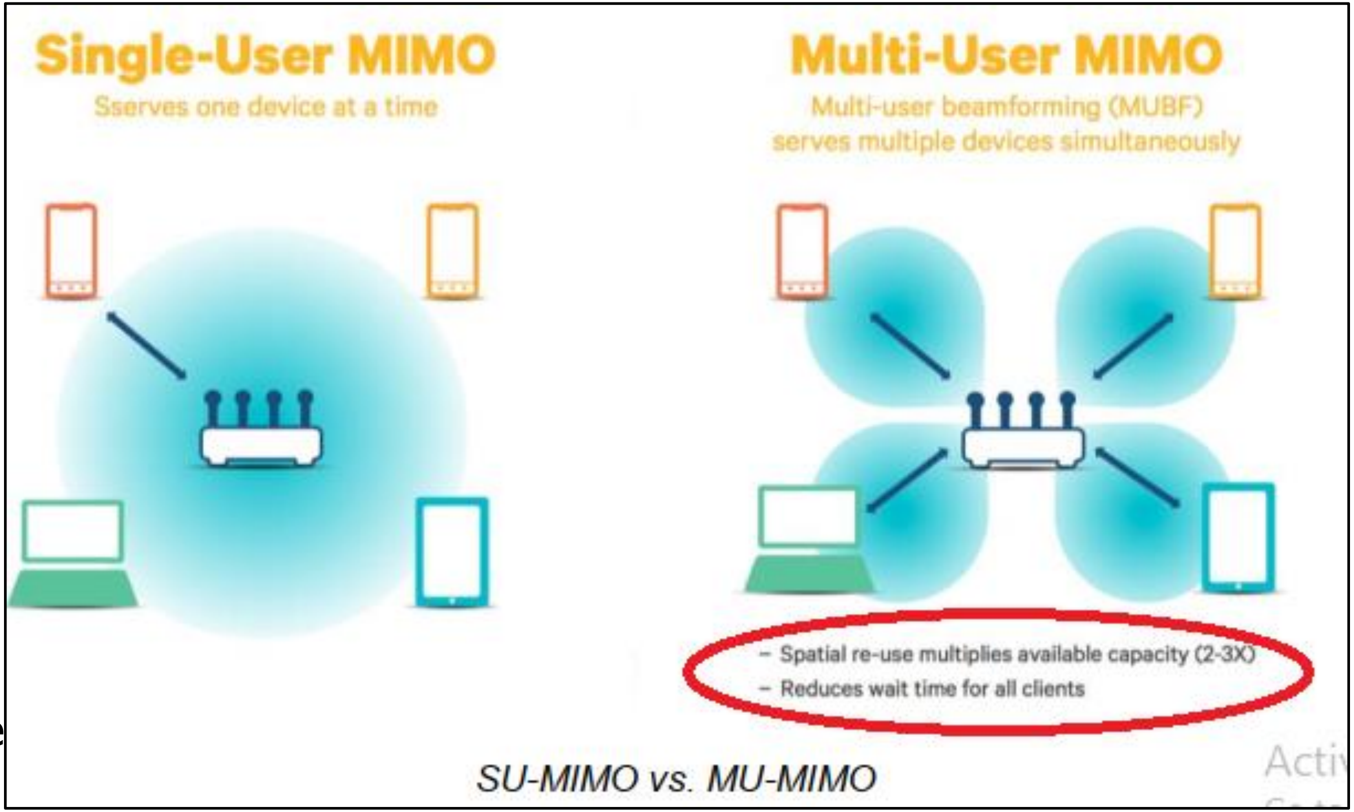
SU-MIMO TxBF vs. MU-MIMO TxBF

APs typically have 3-4 antennas, while most of the client devices they serve are limited to 1-2 antennas. As such, they cannot support the full range of MIMO channel operation, and the full AP capacity is rarely used. This difference is called the *MIMO gap*.

For example, a 3x3 Wi-Fi 11ac AP supports a peak physical layer (PHY) rate of 1.3 Gbps. But a smartphone or tablet with one antenna supports a peak rate of only 433 Mbps, leaving 867 Mbps capacity of the AP unused.

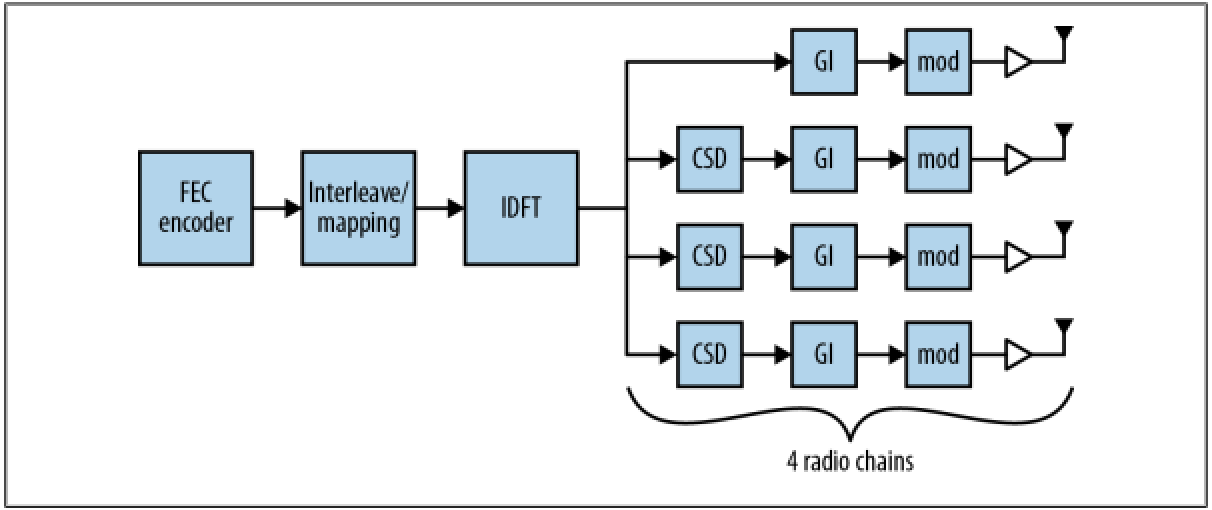
MU-MIMO facilitates Spatial Re-use

As we can see from this Diagram, MU-MIMO Technology facilitates Spatial Re-use and Hence, All the clients-AP communication Would happen in the same Air-time In a spatially diverse environment, There by serving high throughput to multiple clients, at the same time.



Single-User Transmit Beamforming

Radio Chains



4x4 802.11n interface block diagram

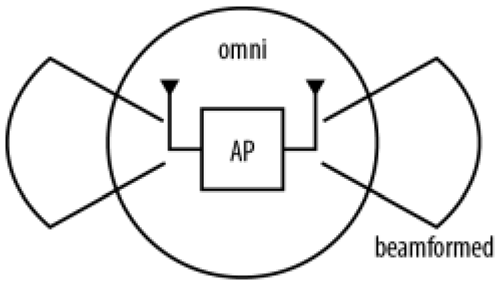
Between the operating system and antenna, an 802.11 radio interface has to perform
several tasks. **When transmitting a frame**, the main tasks are the **inverse Fourier transform** to turn the **frequency-domain encoded signal** into a **time-domain signal**, and **amplification** right before the signal hits the antenna so it has reasonable range.

On the receive side, the process must be reversed. Immediately after entering the antenna, **an amplifier boosts the faint signal** received into something substantial enough to work with, and **performs a Fourier transform** to extract the subcarriers. In an 802.11 interface, **these components are linked together and called a *radio chain*.**

Single-User Transmit Beamforming

With advanced radio chips, it is possible to **send transmissions** from the **MIMO antenna array in a particular direction** in a process called ***beamforming***.

MIMO can also be used to spread a single spatial stream across multiple transmitters for extra signal-processing gain at the receiver, and hence, longer range in a process called ***Space-Time Block Coding*** **(STBC)**



Conceptual process of beamforming

Beamforming is an **electrically** steerable antenna. When transmitting to a given receiver, the antenna is “pointed” in the direction of the receiver, but **the direction that the beam is focused can be controlled by subtly altering the phase shifts into the antenna system rather than mechanically moving the antenna.**

Whether implemented on the **radio chip or in the antenna array,** beamforming works by taking the radio signals to be transmitted and applying a mathematical transformation to them that changes the way they are transmitted.

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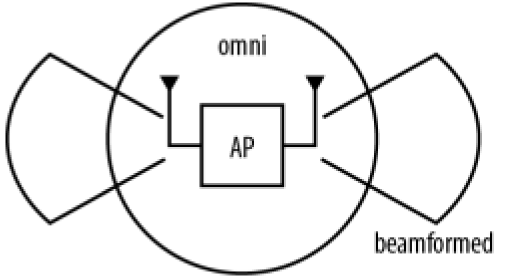

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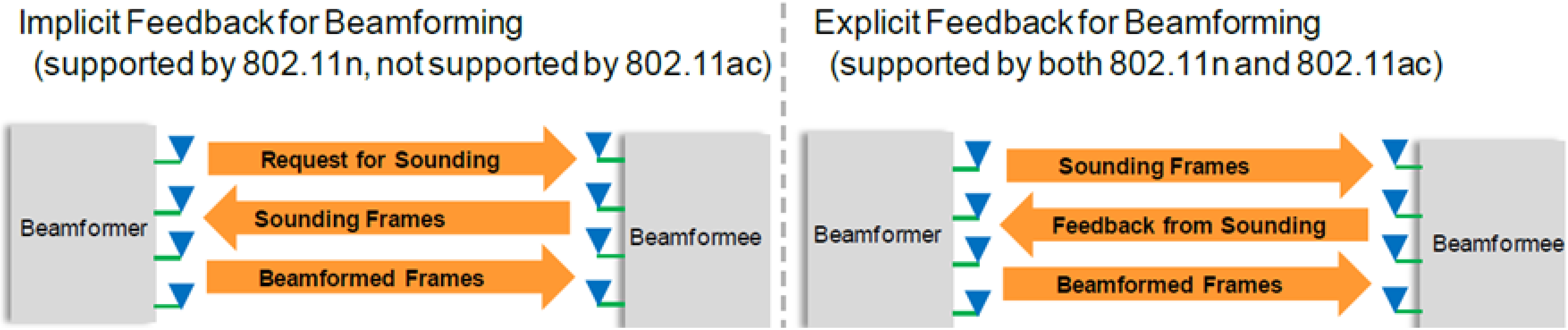
Channel Sounding/Beamforming Steps



Channel sounding consists of three major steps:

==

1. The **beamformer** begins the process by transmitting a **Null Data Packet Announcement frame**, which is used to **gain control of the channel** and identify **beamformees. Beamformees** will **respond to the NDP Announcement**, while all **other stations will simply defer channel access until** the **sounding sequence** is complete.
2. The **beamformer** follows the **NDP Announcement** with **a null data packet.** The value of an NDP is that the receiver can analyze the OFDM training fields to calculate the channel response, and therefore the **steering matrix**. For multi-user transmissions, multiple NDPs may be transmitted.
3. The **beamformee analyzes the training fields** in the **received NDP** and calculates **a feedback matrix**. The **feedback matrix** enables the **beamformer to calculate the steering matrix.**
4. The **beamformer receives the feedback matrix** and calculates the **steering matrix to direct transmissions toward the beamformee.**

The **steering matrix** is a precise mathematical description of **how the antenna array should use each individual element to select a spatial path for the transmission**, in short, a mathematical representation of ability to steer energy in certain direction of the receiver.

Types of Single-User Transmit Beamforming

Explicit beamforming (Channel Calibration procedure) 802.11

===================================

Before transmitting, **a device(Beamformer) actively measures the channel**, and uses the measurement to **compute the steering matrix** directly. **Active channel measurement** is accomplished by transmitting a ***sounding*** **frame** to the receiver (**Beamformee)**, which replies with a frame that indicates how the sounding frame was received. By comparing the known contents of the sounding frame to a representation of its contents at the receiver, the beamformer can compute **the steering matrix**. **"sounding" frames are either** signaled as such by the **sounding bit in the PLCP header.** Sounding can also be carried out by using ***Null Data Packets*** **(NDPs)**, which are frames that have **no data** but are designed to **enable detailed channel measurements.**

Implicit beamforming (only 802.11 n)

===================================

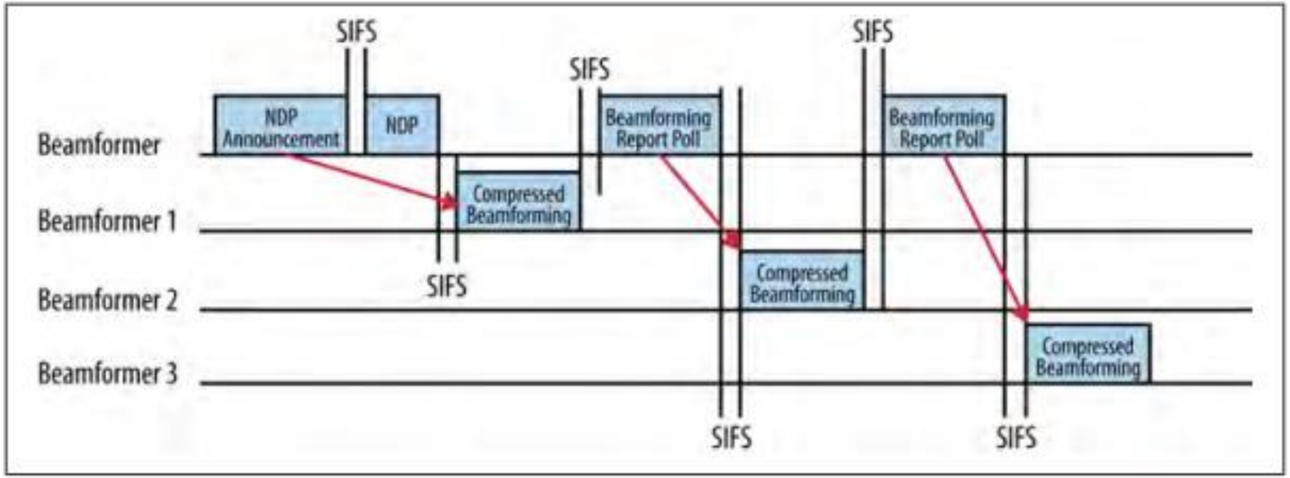
Devices estimate the beamforming matrix from received frames, or by inference from frames that are lost. Well known frames **such as ACKs or the data transmitted on pilot channels** can be used to **estimate the steering matrix**. **Implicit beamforming is based on less comprehensive measurements, and therefore, does not provide quite as high a level of performance.**

MU-MIMO DL

Multi-User Transmit Beamforming

Multi-user MIMO works by taking advantage of beam-forming to send frames to spatially diverse locations at the same time, building the first standardized version of an 802.11 “switch.”

Just as Ethernet switches reduced the scope for collisions from a large network down to a single port, multi-user MIMO reduces the spatial collision domain.
By using MU-MIMO, an AP may transmit to multiple receiving stations simultaneously.

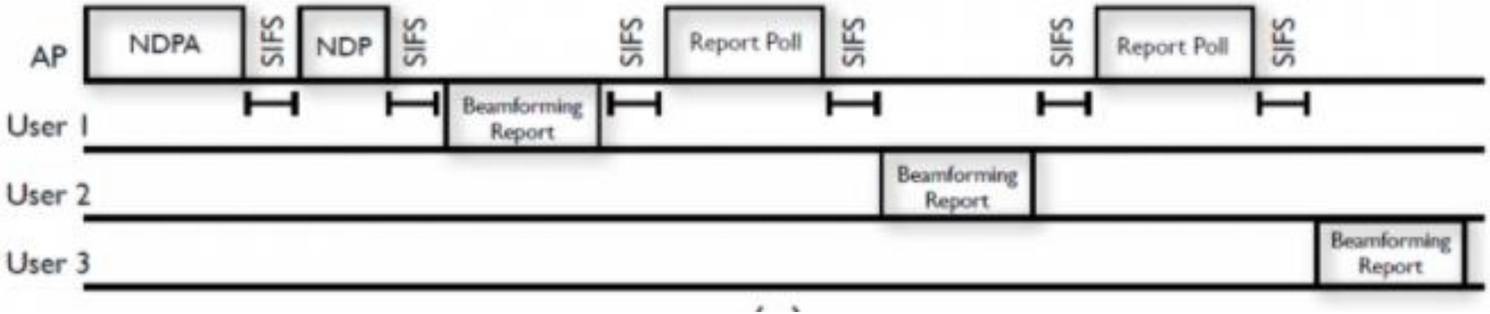


Multi-user channel sounding procedure

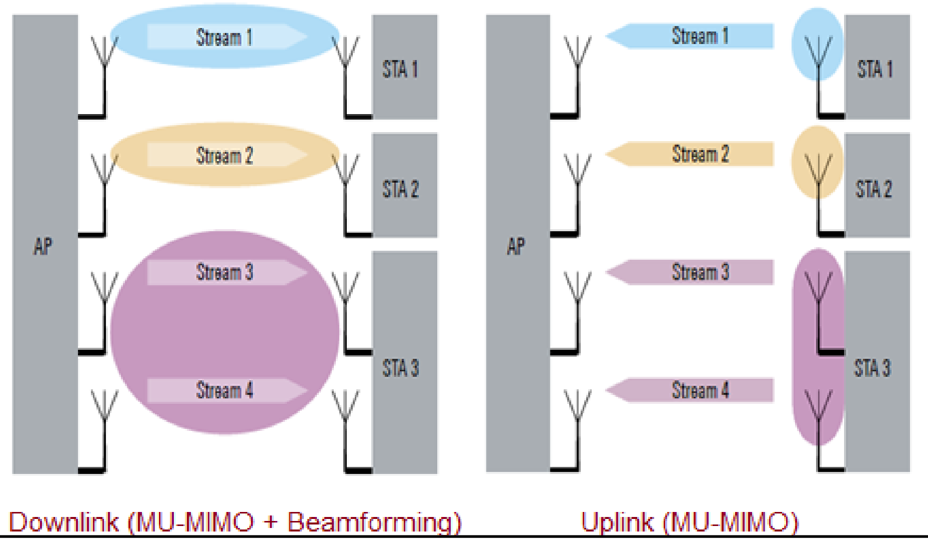
Sounding Procedure in MU-MIMO

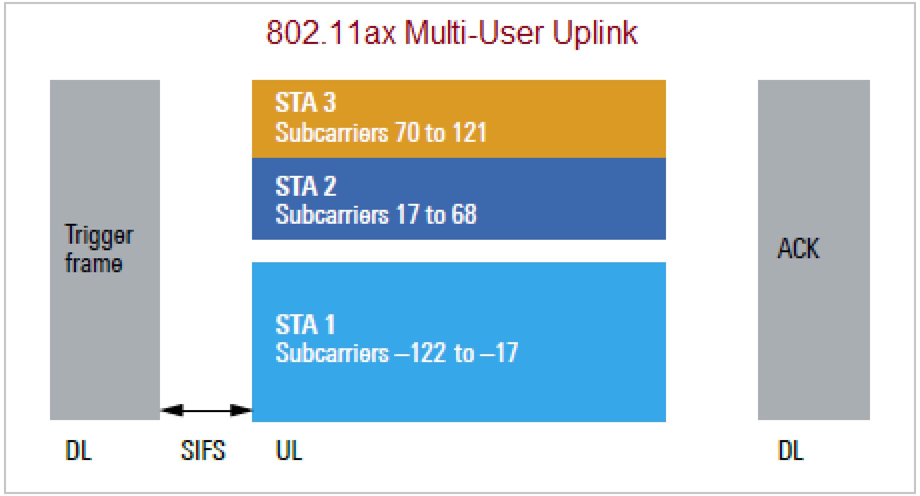
The sounding procedure starts off exactly as it did in the single-user case, with an **NDP Announcement control Frame** and **NDP packet** that put the transmission out to begin the **calibration.**

However, **to retrieve the feedback matrix from each beamformee**, the multiuser sounding procedure needs a **new frame, the Beamforming Report Poll frame**, to ensure that responses from all beamformees are collected. From the below figure we see that there are three beamformees, and therefore the beamformer must use **two poll frames to obtain the feedback matrices from the second and third beamformees**. (**No poll frame** is required for the **first station** as it is named in the **NDP Announcement frame**, but the second and subsequent beamformees must be polled.)
After receiving multiple responses (Beamforming Report), the beamformer will integrate all the responses together into a **master steering matrix.**



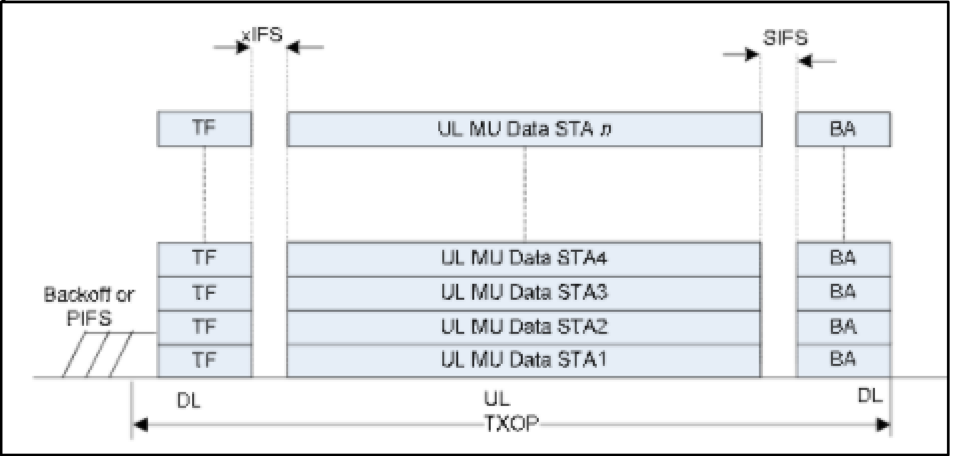
MU-MIMO UL





11ax supports Uplink MU-MIMO which 11ac doesn't.

If you notice in the 2 diagrams, the UL-MU-MIMO is similar to OFMDA(an another MU technology), with the only difference being clients using multiple spatial streams to communicate with separate antenna's of the 11ax RG.



An example of a TXOP containing an UL MU transmission with an DL MU transmission containing unicast BA frames acknowledging the frames received from the respective STAs"

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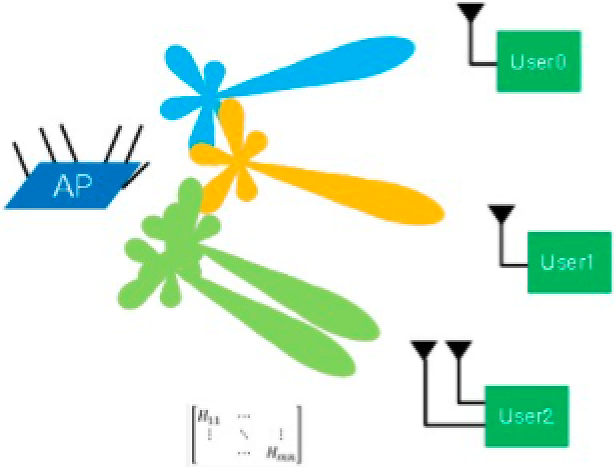
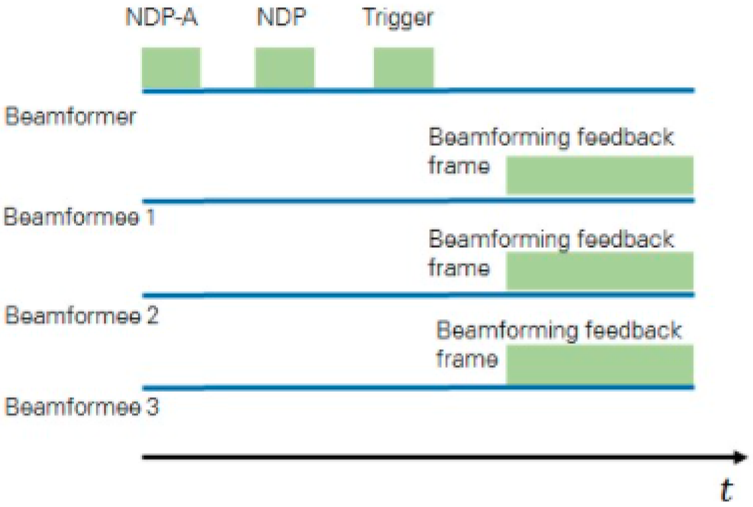
MU-MIMO UL transmission

As a new feature in the MU-MIMO Uplink direction, the AP will initiate a simultaneous uplink transmission from each of the STAs by means of a trigger frame. When the multiple users respond in unison with their own packets, **the AP applies the channel matrix to the received beams** and separates the information that each uplink beam contains. The AP may also initiate Uplink multi-user transmissions to receive beamforming feedback information from all participating STAs



AP using MU-MIMO beamforming to serve multiple users located in spatially diverse positions



A beamformer (AP) requesting channel information for MU-MIMO operation

MU-OFDMA and MU-MIMO in 11ax serve different purposes

Note: These 2 technologies in 11ax are generally confused to serve a single purpose. But that isn’t the case. The below table summarizes this.

MU-OFDMA and MU-MIMO Comparison

MU-OFDMA	MU-MIMO
Increased efficiency	Increased capacity
Reduced latency	Higher data rates per user
Best for low-bandwidth applications	Best for high-bandwidth applications
Best with small packets	Best with large packets

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Real Time OFDMA and MU-MIMO through test result for 5 Ghz Radio for 64-byte and 1500-byte packet sizes

From the Test data we would notice that for small packet sizes, the TCP and UDP transmissions in a 11ax enabled RG are done in OFDMA, as in the given Air-Time contention window, all the clients can download Or upload the data.

However, for larger packet sizes, the Air-Time needs be spatially split for Each MU-MIMO client And hence, MU-MIMO is selected by the 11ax RG.
Also, the time consumed in channel sounding in given airtime should be Compensated with pushing huge amount of traffic in given airtime. And Hence, MU-MIMO provides greater throughput efficiently to all clients in This scenario.

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For 64-byte TCP/UDP packet size,

the RG in 11ax selects "OFDMA" technology for transmission.

Conventions:
============

HE Features 15:
OFDMA enabled
MU-MIMO disabled

HE Features 31:
OFDMA enabled
MU-MIMO enabled

```
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@      64 byte packet size    @
@                             @
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

UDP 64-bytes he features 15

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:0C:51:E1	1200.8	90.1	93.2%	25.0%	0.1%	80	11.0	2	99.9%	0.0%
4C:1D:96:6F:12:9C	1200.9	90.2	92.8%	25.0%	0.3%	80	11	2	99.8%	0.0%
4C:1D:96:6C:C7:58	1200.7	90.1	93.2%	25.0%	0.4%	80	11.0	2	99.8%	0.0%
4C:1D:96:6D:2D:D8	1200.9	90.2	93.1%	25.0%	0.4%	80	11	2	100.0%	0.0%
(overall)	-	360.6	372.4%	-	-					

UDP 64-bytes he features 31

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:6F:12:9C	1200.9	90.2	93.1%	25.0%	0.3%	80	11	2	99.8%	0.0%
4C:1D:96:6C:C7:58	1200.9	90.2	93.0%	25.0%	0.2%	80	11	2	99.9%	0.0%
4C:1D:96:0C:51:E1	1200.7	90.2	92.8%	25.0%	0.4%	80	11.0	2	99.7%	0.0%
4C:1D:96:6D:2D:D8	1200.9	90.2	93.6%	25.0%	0.5%	80	11	2	100.0%	0.0%
(overall)	-	360.7	372.5%	-	-					

TCP 64-bytes he features 15

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:0A:8C:9C	1162.6	44.1	34.4%	25.0%	1.2%	80	10.7	2	96.7%	0.0%
4C:1D:96:48:D0:E1	1200.9	44.0	23.6%	25.0%	9.1%	80	11	2	19.4%	0.0%
4C:1D:96:A5:CA:58	1151.6	44.0	33.9%	25.0%	0.3%	80	10.6	2	98.8%	0.0%
4C:1D:96:F6:0C:D8	1078.4	44.0	32.0%	25.0%	0.8%	79.8	10.0	2.0	95.1%	0.0%
(overall)	-	176.1	123.9%	-	-					

TCP 64-bytes he features 31

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:F6:0C:D8	1076.8	46.2	33.0%	25.0%	1.4%	79.7	10.0	2.0	91.8%	0.0%
4C:1D:96:0A:8C:9C	1199.6	46.2	36.5%	25.0%	15.7%	80	11.0	2	70.7%	0.0%
4C:1D:96:A5:CA:58	1200.2	46.2	36.2%	25.0%	8.5%	80.0	11.0	2.0	85.4%	0.0%
4C:1D:96:48:D0:E1	1200.5	46.2	32.8%	25.0%	4.0%	80	11	2	74.8%	0.0%
(overall)	-	184.8	138.5%	-	-					

For 1500-byte TCP/UDP packet size,

the RG in 11ax selects “MU-MIMO” technology for transmission.

Conventions:

============

HE Features 15:
OFDMA enabled
MU-MIMO disabled

HE Features 31:
OFDMA enabled
MU-MIMO enabled

```
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@         1500 packet size  @
@                           @
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

UDP 1500-bytes he features 15

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:6C:C7:58	1198.1	251.1	97.6%	25.0%	0.0%	80	11	2	100.0%	0.0%
4C:1D:96:0C:51:E1	1198.1	251.1	97.7%	25.0%	0.0%	80	11	2	100.0%	0.0%
4C:1D:96:6F:12:9C	1198.1	251.2	97.6%	25.0%	0.0%	80	11	2	100.0%	0.0%
4C:1D:96:6D:2D:D8	1154.5	251.4	93.2%	25.0%	1.0%	77	10.6	1.9	96.0%	0.0%
(overall)	-	1004.8	386.1%	-	-					

UDP 1500-bytes he features 31

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:6C:C7:58	438.3	258.8	83.6%	25.0%	4.5%	79.9	8.2	1.0	0.0%	98.5%
4C:1D:96:6F:12:9C	386.0	258.9	88.3%	25.0%	0.4%	79.9	7.4	1	0.0%	99.7%
4C:1D:96:0C:51:E1	475.4	259.0	70.0%	25.0%	0.1%	80	8.9	1	0.0%	99.6%
4C:1D:96:6D:2D:D8	451.2	259.0	85.6%	25.0%	9.0%	79.5	8.3	1	0.0%	98.7%
(overall)	-	1035.8	327.5%	-	-					

TCP 1500-bytes he features 15

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:0A:8C:9C	1200.9	157.9	68.8%	25.0%	0.6%	80	11	2	99.4%	0.0%
4C:1D:96:48:D0:E1	1198.6	158.0	68.1%	25.0%	0.2%	79.8	11.0	2.0	99.6%	0.0%
4C:1D:96:A5:CA:58	1200.0	157.9	69.5%	25.0%	0.4%	80	11.0	2	99.6%	0.0%
4C:1D:96:F6:0C:D8	1058.1	157.8	71.1%	25.0%	8.4%	78.3	9.8	2.0	87.5%	0.0%
(overall)	-	631.5	277.5%	-	-					

TCP 1500-bytes he features 31

Station Address	PHY Mbps	Data Mbps	Air Use	Data Use	Retries	bw	mcs	Nss	ofdma	mu-mimo
4C:1D:96:F6:0C:D8	591.2	280.2	81.7%	26.2%	8.0%	80.0	7.9	1.3	0.0%	71.7%
4C:1D:96:0A:8C:9C	500.8	262.7	70.2%	24.6%	0.3%	80.0	9.3	1	0.0%	99.2%
4C:1D:96:A5:CA:58	569.5	263.1	60.8%	24.6%	2.3%	79.6	10.3	1	0.0%	97.3%
4C:1D:96:48:D0:E1	556.9	262.9	59.6%	24.6%	0.8%	79.5	10.2	1	0.0%	98.4%
(overall)	-	1068.9	272.3%	-	-					

Spatial Re-Use

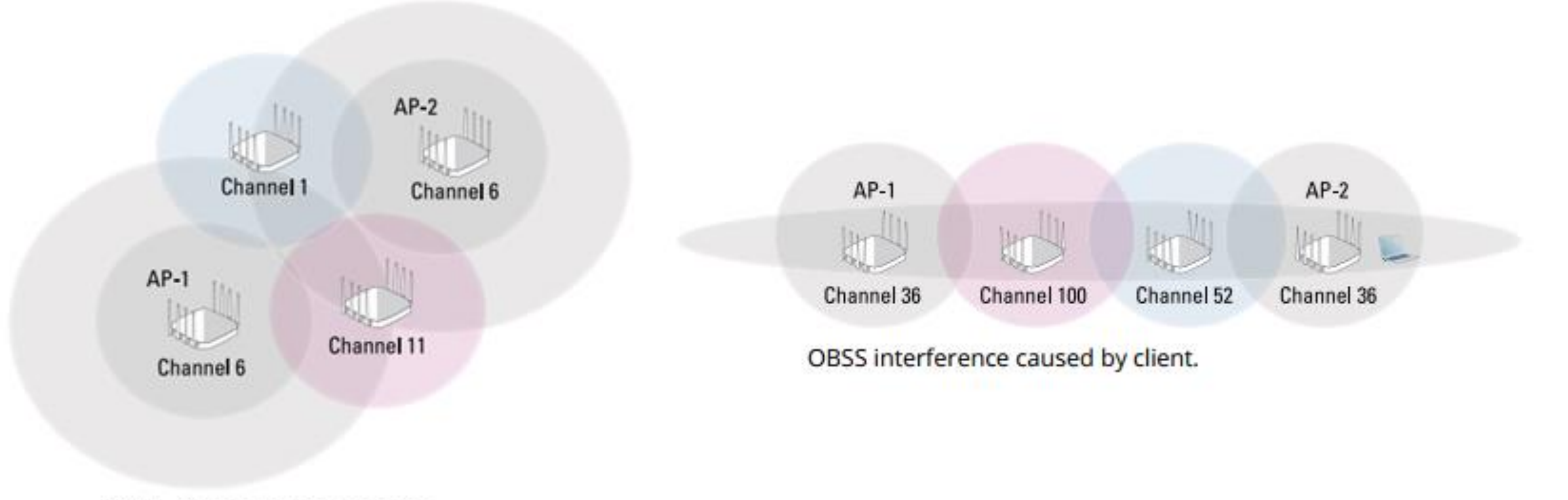
Overlapping BSS Issues

Carrier sense with multiple access collision avoidance (CSMA/CA) is the method used in Wi-Fi networks to ensure that only one radio can transmit on the same channel at any given time. An 802.11 radio will defer transmissions if it hears the physical (PHY) preamble transmissions of any other 802.11 radio at a *signal detect (SD)* threshold of just four decibels or more above the noise floor. CSMA/CA is necessary to avoid collisions; however, the deferral of transmissions also consumes valuable airtime.

OBSS creates medium contention overhead and consumes valuable airtime because you have two basic service sets (BSS) on the same channel that can hear each other thus, the term OBSS.

Even Client can also create OBSS interference as we can see below that a Client connected to AP-2 can make the client's connected to AP1 on the same channel to back off, as the client connected to AP1 would hear the PHY preamble of client connected to AP2.

OBSS cause a great deal of wastage of valuable airtime in 2.4 GHz Radio bandwidth when compared against 5 GHz.



OBSS – Overlapping basic service set.

OBSS interference caused by client.

11ax offers 2 solutions to OBSS problem:

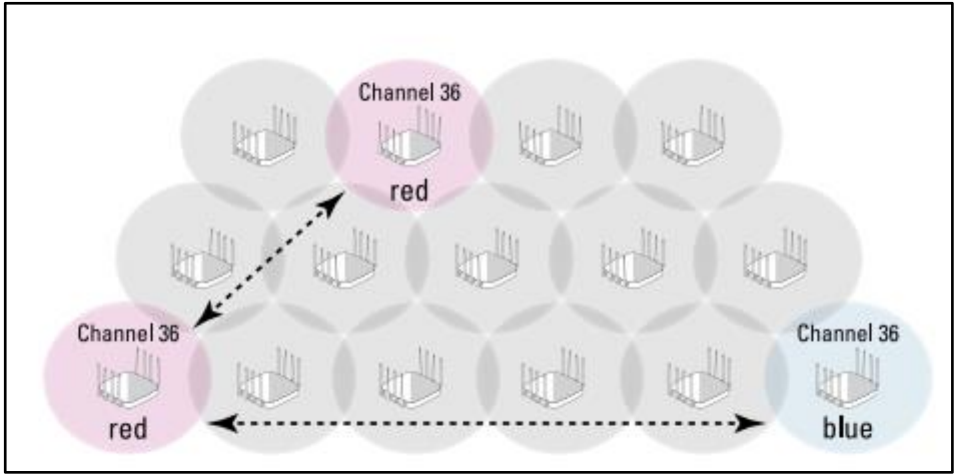
1. BSS coloring
2. Spatial Re-Use

BSS Coloring

The other name for 11ax is HE(High Efficiency) and the above 2 features In 11ax facilitates efficient use of the channel.

The IEEE 802.11ax standard defines a method that may increase the channel reuse by a factor of eight. *BSS color*, also known as BSS coloring, is a method for addressing medium contention overhead due to OBSS. BSS color is an identifier of the basic service set (BSS). In reality, the BSS color identifier is not a color, but instead is a numerical identifier. Wi-Fi 6 radios are able to differentiate between BSSs using a BSS color (numerical identifier) when other radios transmit on the same channel.
BSS color information is communicated at both the PHY layer and the MAC sublayer. In the preamble of an 802.11ax PHY header, the SIG-A field contains a 6-bit BSS color field. This field can identify as many as 63 BSSs. At the MAC sublayer, BSS color information is seen in 802.11 management frames. The HE operation information element contains a subfield for BSS color information.

Since, each AP has a BSS color associated with it, The AP's and client's operating in same channel can ignore the transmission from other BSS's and thus, the spatial re-use.



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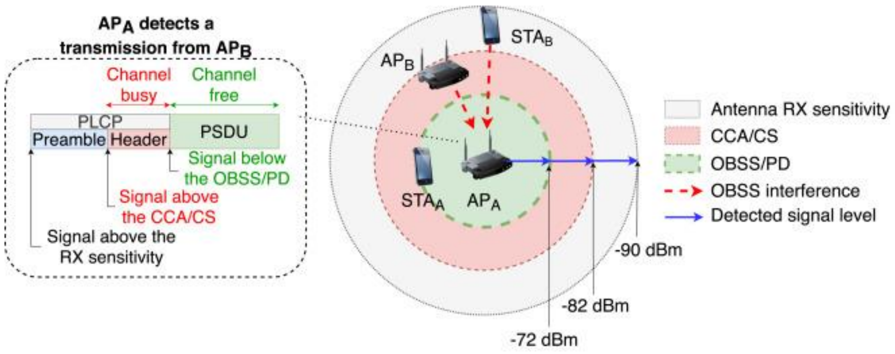
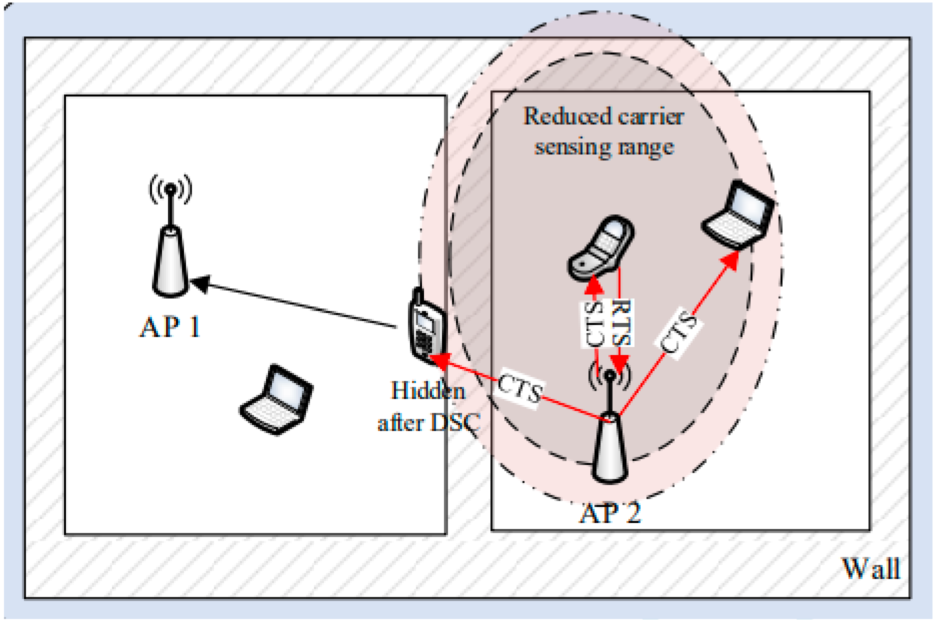
Spatial Re-use operation- Adaptive CCA

1. The Clear Channel Assessment (**CCA**) is a mechanism for determining whether the medium is idle or not. The **CCA** includes **carrier sensing and energy detection.**
2. This is performed by all Wi-Fi Radio's to check if the current channel is occupied with other RF transmissions or it's available for transmission/reception.



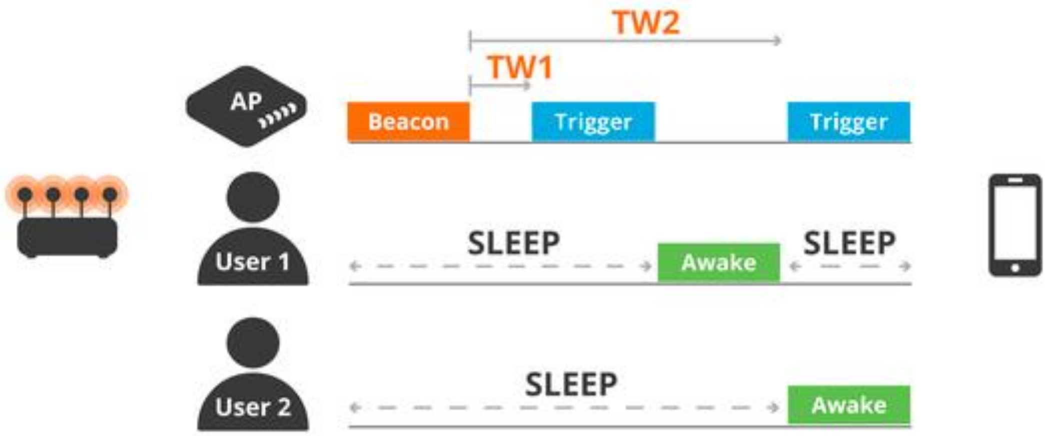


Based on the detected BSS color, Wi-Fi 6 radios can implement an adaptive CCA implementation that **can raise the signal detect threshold(or reduce carrier sending range) for inter-BSS frames** while maintaining lower threshold for intra BSS traffic .

Target Wake Time(TWT)

RESOURCE SCHEDULING SIGNIFICANTLY IMPROVES DEVICE BATTERY LIFE

TWT : Target Wake Time



- AP and devices negotiate and define a specific times to access the medium
- Reduced contention and overlap between users
- Significantly increases the device sleep time to reduce power consumption

REVISION HISTORY

Rev No.	Date	Description of Change	Author	Review and Approved By
1.0	9-Apr-21	Initial Draft	Neelkanth Reddy	Tanmoy B (L&D)

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