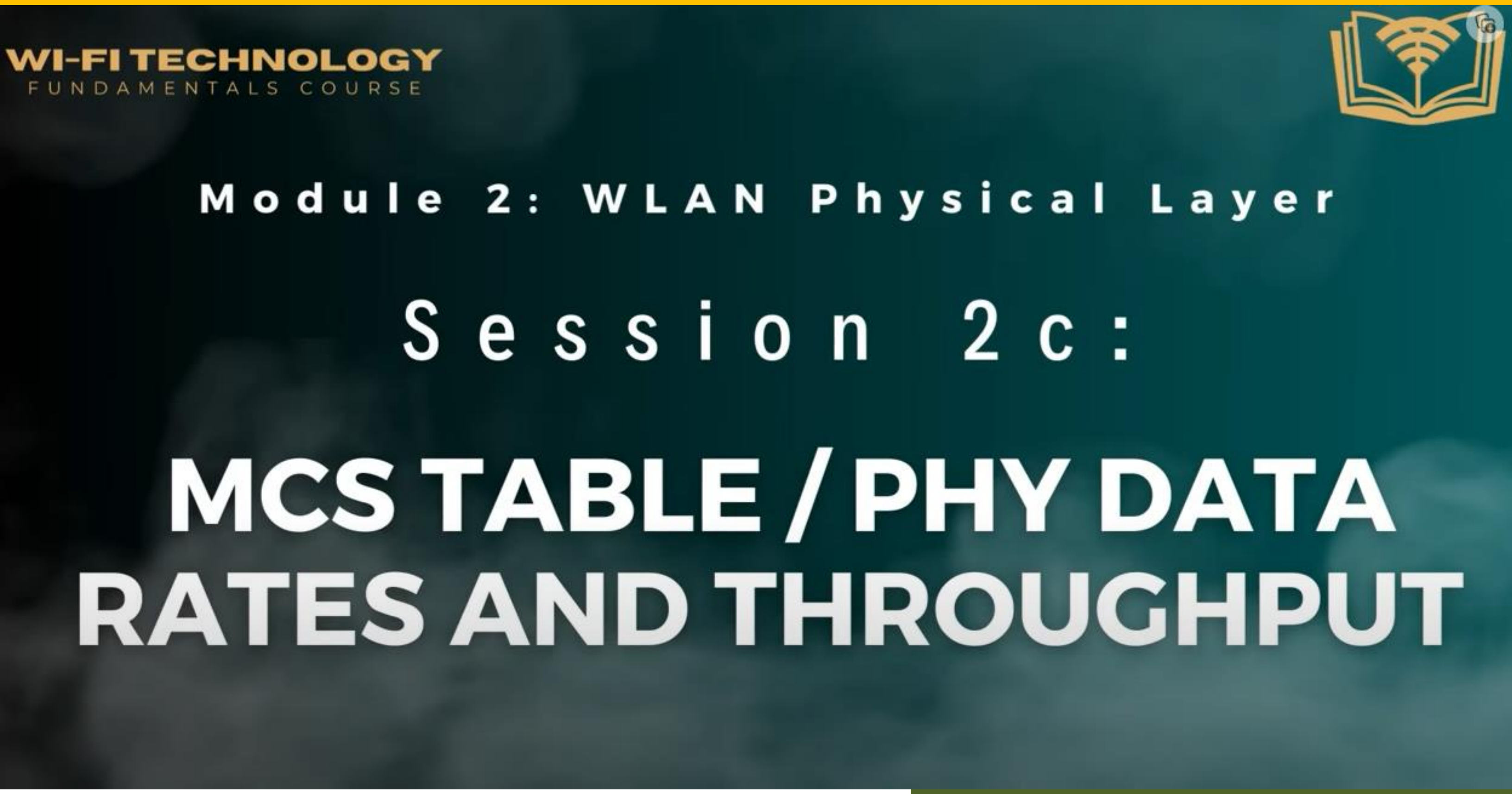

By

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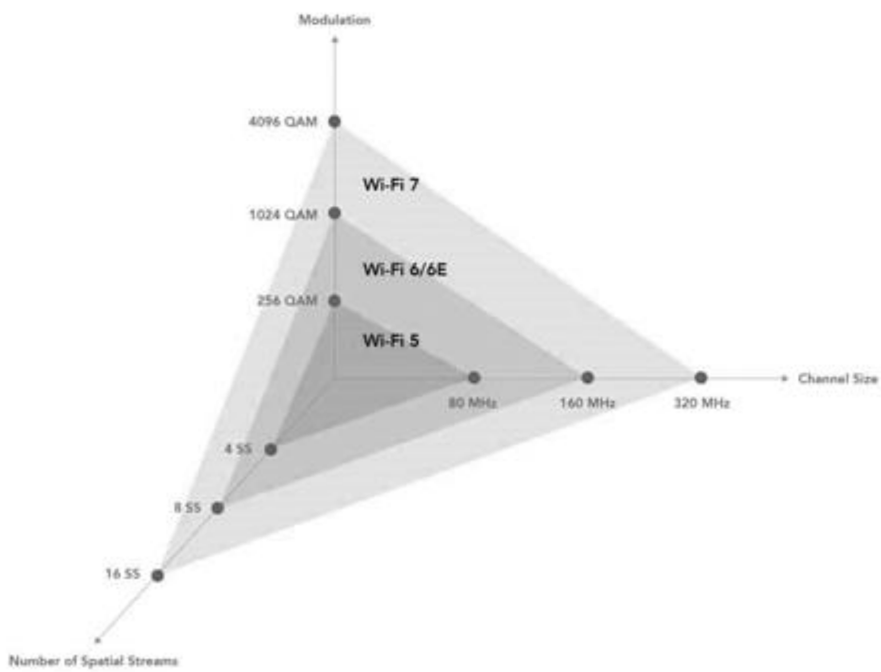
Wi-Fi Data Rates across generations

When we purchase a router, various throughput rates are typically mentioned on the packaging. The question is: how are these various throughput rates achieved? There are three main factors that can be manipulated to achieve different throughput rates:

1.Channel size
2.Modulation
3.Number of spatial streams



- **Channel size:** Throughput can be improved by changing the channel size. In Wi-Fi, available channels are typically divided into 20 MHz, 40 MHz, 80 MHz, and 160 MHz channels. The wider the channel, the better the throughput.
- **Modulation:** Modulation refers to how data is encoded and transmitted over the wireless channel. Different modulation schemes, such as QPSK, 16-QAM, and 64-QAM, represent various ways to encode data. More advanced modulation schemes allow for higher data rates, but they are more susceptible to interference and signal degradation over longer distances.
- **Number of spatial streams:** By increasing the number of spatial streams, throughput can be significantly improved. The number of spatial streams refers to the multiple data streams transmitted by the router's antennas. Multiple input, multiple output (MIMO) technology allows routers to transmit multiple spatial streams.

Note: It's not always advantageous to maximize these parameters. Manufacturers need to determine their values based on requirements, costs, and device compatibility, which also plays a significant role in selecting the values.

Generation	IEEE standard	Adopted	Maximum link rate (Mbit/s)	Radio frequency (GHz)
Wi-Fi 7	**802.11be**	(2024)	1376 to 46120	2.4/5/6
Wi-Fi 6E	802.11ax	2020	574 to 9608[1]	6[a]
Wi-Fi 6		2019		2.4/5
Wi-Fi 5	802.11ac	2014	433 to 6933	5[b]
Wi-Fi 4	802.11n	2008	72 to 600	2.4/5
*(Wi-Fi 3)**	802.11g	2003	6 to 54	2.4
	802.11a	1999		5
*(Wi-Fi 2)**	802.11b	1999	1 to 11	2.4
*(Wi-Fi 1)**	802.11	1997	1 to 2	2.4

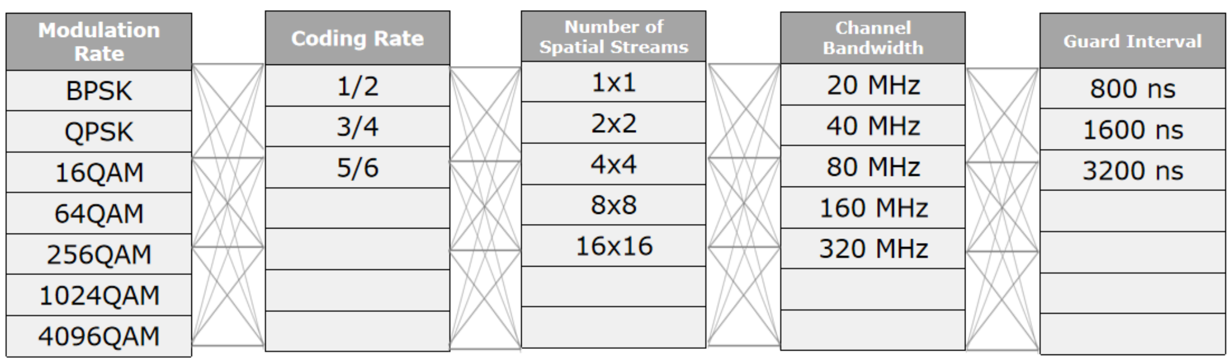
*Wi-Fi 1, 2, and 3 are by retroactive inference [2][3][4][5][6]

x 11.5 x 1.3 x 4.8

	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6/6E	Wi-Fi 7
Standard	802.11n	802.11ac	802.11ax	802.11be
Max Speed with 1 Spatial Stream	150 Mbps	866.7 Mbps	1.2 Gbps	2.9 Gbps
Max Speed with 2 Spatial Streams	300 Mbps	1.73 Gbps	2.5 Gbps	5.8 Gbps
Max Speed with Max # Spatial Streams	600 Mbps	6.92 Gbps	9.6 Gbps	46.4 Gbps

	Wi-Fi 4 (IEEE 802.11n)	Wi-Fi 5 (IEEE 802.11ac)	Wi-Fi 6 (IEEE 802.11ax)	Wi-Fi 6E (IEEE 802.11ax)	Wi-Fi 7 (IEEE 802.11be)
Frequency bands operations	2.4GHz (2.402 – 2.494) 5GHz (5.030 – 5.990)	5GHz (5.030 – 5.990)	2.4GHz (2.402 – 2.494) 5GHz (5.030 – 5.990)	2.4GHz (2.402 – 2.494) 5GHz (5.030 – 5.990) 6GHz (5.925 - 7.125)	2.4GHz (2.402 – 2.494) 5GHz (5.030 – 5.990) 6GHz (5.925 - 7.125)
Maximum bandwidth per channel	2.4GHz: 40MHz 5GHz: 40MHz	2.4GHz: 40MHz 5GHz: 80MHz	2.4GHz: 40MHz 5GHz: 160MHz	2.4GHz: 40MHz 5GHz: 160MHz 6GHz: 160MHz	2.4GHz: 40MHz 5GHz: 160MHz 6GHz: 320MHz
Maximum number of non-overlapping channels	2.4GHz: 2	5GHz: 5 (80MHz)	2.4GHz: 2 (40MHz) 5GHz: 2 (160MHz), or 5 (80MHz)	2.4GHz: 2 (40MHz) 5GHz: 2 (160MHz), or 5 (80MHz) 6GHz: 7 (160MHz), or 14 (80MHz)	2.4GHz: 2 (40MHz) 5GHz: 2 (160MHz), or 5 (80MHz) 6GHz: 3 (320MHz), or 7 (160MHz), or 14 (80MHz)
Maximum MIMO configuration	4x4	4x4	8x8	8x8	16x16
Highest modulation	64 QAM	256 QAM	1024 QAM (1K QAM)	1024 QAM (1K QAM)	4096 QAM (4K QAM)
Maximum PHY datarate	600 Mbps	1.7 Gbps	9.6 Gbps	9.6 Gbps	46.1 Gbps
Multi user MIMO (MU-MIMO)	N/A	Downlink (Wave 2 only)	Downlink Uplink	Downlink Uplink	Downlink Uplink
Multi user OFDMA (bandwidth sharing)	N/A	N/A	Yes	Yes	Yes
Target Wake Time (TWT)	N/A	N/A	Yes	Yes	Yes (improved)
Multi Link Operation / Multi Resource Unit	N/A	N/A	N/A	N/A	Yes

MCS table



- An MCS (Modulation and Coding Scheme) table is a lookup table or chart that provides a mapping of different combinations of parameters, such as modulation scheme, coding rate, guard interval, and other factors, to the expected data transfer rates or throughput in a wireless communication system. It helps in predicting the expected data rate based on the chosen configuration.
- In wireless communication, MCS tables are often used by devices or access points to dynamically adapt their transmission settings to optimize data transfer rates based on the current network conditions. By selecting the appropriate MCS from the table, the system can balance factors like data speed and reliability, taking into account the quality of the wireless signal and the potential for interference.
- So, the MCS table essentially serves as a reference guide to determine the most suitable configuration for transmitting data over a wireless network, given the prevailing

conditions, and it helps in making predictions about the expected data rate for a specific configuration.

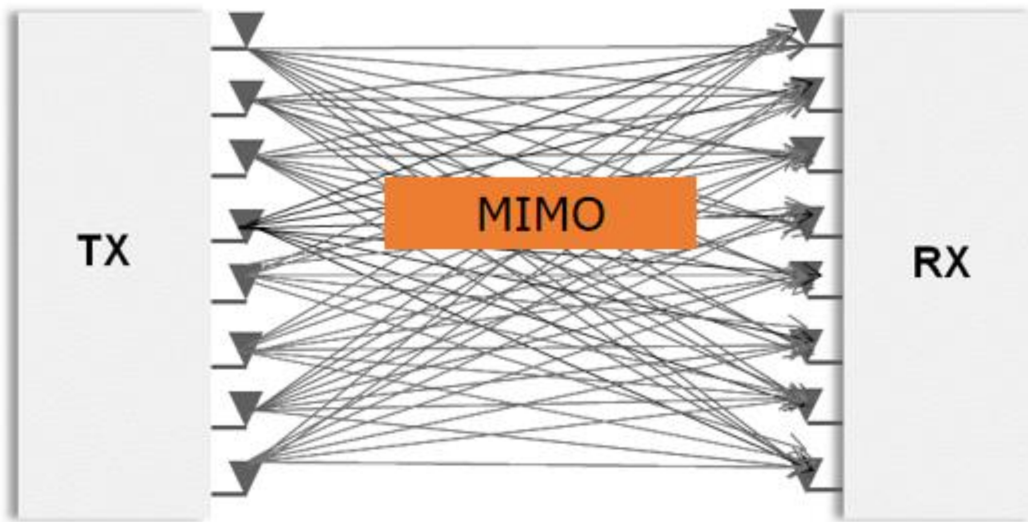
Data Rate Parameters

There are mainly four parameters which can be manipulated to alter the data rates.

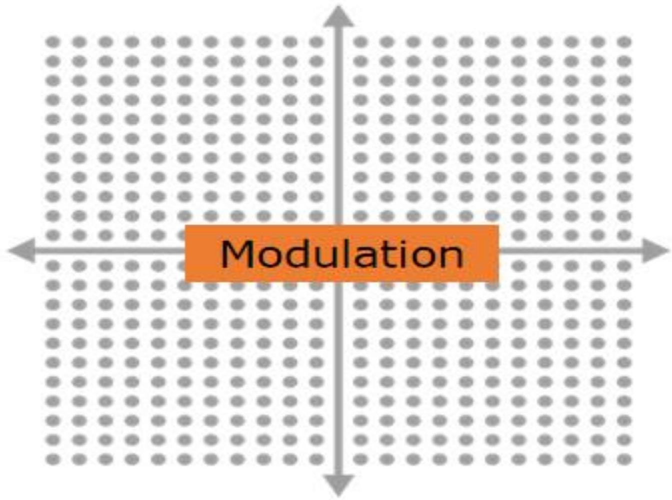
- **Channel bandwidth**
  Channel size refers to the available frequency bandwidth or spectrum allocated for data transmission. In wireless communication, the channel size is a fundamental factor affecting data rates. Wider channels can accommodate more data simultaneously, leading to higher data rates.

This can be better understood using the analogy of a highway. Here, the width of the highway is synonymous with the available bandwidth, and the number of vehicles represents the amount of data that can be transferred at a time. It is clear that when a wider highway is used, vehicles can travel without congesting the road, and more vehicles can be driven in parallel at the same time. Similarly, when a wider bandwidth is utilized, data rates are improved, and there is less overlap, ultimately enhancing the quality of the data rate. However, achieving a high data rate isn't always feasible, as it often involves a trade-off with transmission power.

- **MIMO**
  When transmitting data from a transmitter, the ideal scenario is for the data to reach the receiver without issues. However, various obstacles such as tall buildings and towers can weaken the signal and introduce errors and data loss, which is undesirable. This is where MIMO technology comes into play. MIMO, which stands for Multiple Input, Multiple Output, involves the use of multiple transmitters and receivers to send the same data. Each transmitter follows a different path to reach the receiver, and the resulting data is combined to obtain the actual data. This approach effectively reduces errors. The more transmitter and receiver pairs are used, the higher the data rate can be achieved



- **Modulation**
  Modulation is a technique used to represent data in a format suitable for transmission. Technically, modulation refers to the process of encoding digital information onto an analog carrier signal. Various modulation schemes are available, each offering different data rates. In previous sessions, we discussed some of these schemes, including QPSK, BPSK, 16-QAM, and others.

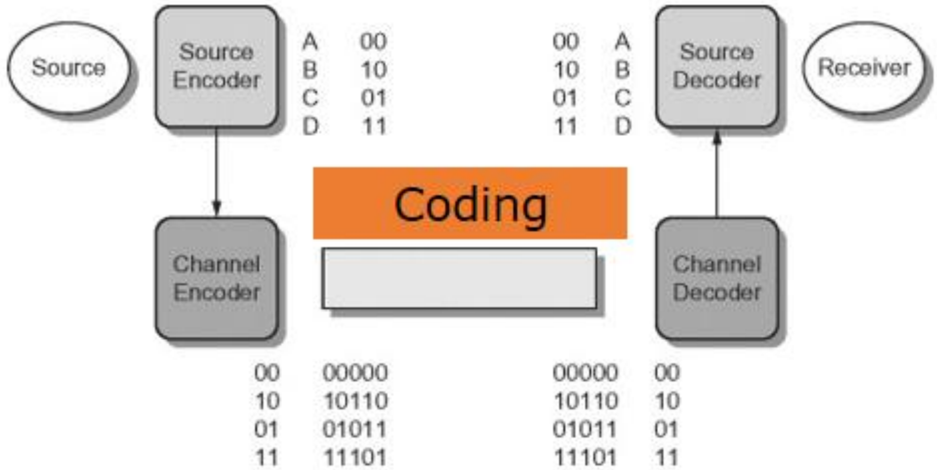


- **Coding**
  Coding in wireless communication involves the use of error-correcting codes to add redundancy to transmitted data. This redundancy allows the receiver to detect and correct errors that may occur during transmission, thereby improving data reliability.

  Adding redundancy, in the context of error-correcting codes in wireless communication, means introducing extra information (redundant bits) into the transmitted data. This extra information is not directly part of the original message but is derived from it in a specific way.

  The purpose of adding redundancy is to provide a means for error detection and correction. Redundant bits are used to verify the integrity of the received data and, if errors are detected, to recover the original data. This process is crucial for improving data reliability in noisy or error-prone wireless channels.

  In simple terms, it's like including extra information that helps in identifying and fixing errors, similar to having extra copies of important pages in a book. If some pages are damaged, you can use the extra copies to reconstruct the original content. This redundancy is what enables error correction in communication systems.

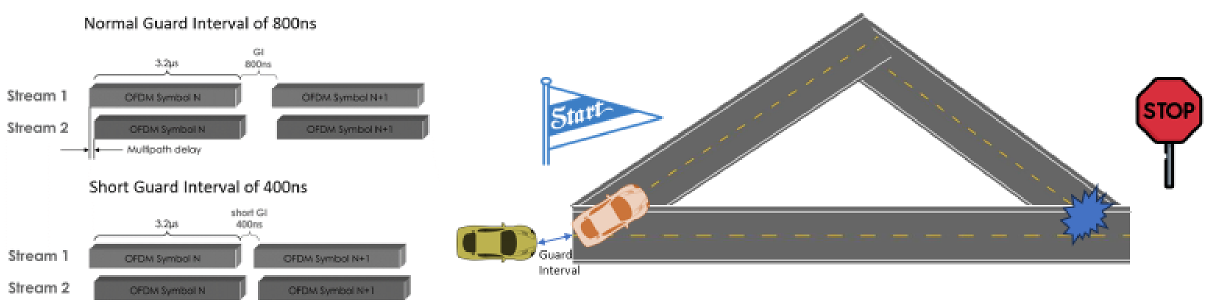


Guard Interval:

Guard Interval

Guard intervals are used to ensure that distinct transmissions do not interfere with one another, or otherwise cause overlapping transmissions. These transmissions may belong to different users (as in TDMA) or to the same user (as in OFDM).

In OFDM, the beginning of each symbol is preceded by a guard interval. As long as the echoes fall within this interval, they will not affect the receiver's ability to safely decode the actual data, as data is only interpreted outside the guard interval.



Description: The guard interval in wireless communication refers to the time gap between two consecutive OFDM (Orthogonal Frequency Division Multiplexing) symbols. It's used to prevent inter-symbol interference (ISI) caused by multipath propagation.
Purpose: The guard interval ensures that there's no overlap or collision between symbols due to echoes or reflections from previous symbols. This overlap can lead to data corruption. By introducing a guard interval, the receiver can distinguish between different symbols without confusion.

Short Guard Interval: Short guard intervals are used when maximizing throughput is a priority. They reduce idle time between symbols, allowing for higher data rates. However, they are less resilient to multipath interference.
Long Guard Interval: Long guard intervals are chosen when reliability and resistance to multipath interference are crucial. They increase the idle time between symbols, which reduces data throughput but helps maintain a stable connection in challenging environments.

802.11a/b/g MCS Rates:

802.11a/b/g MCS Rates

	Data rate (Mbps)	Encoding	Chip length	Bits encoded	Modulation
DSSS	1	Barker coding	11	1	DBPSK
DSSS	2	Barker coding	11	1	DQPSK

Base 802.11

	Data rate (Mbps)	Encoding	Chip length	Bits encoded	Modulation
DSSS	1	Barker coding	11	1	DBPSK
DSSS	2	Barker coding	11	1	DQPSK
HR-DSSS	5.5	CCK coding	8	4	DQPSK
HR-DSSS	11	CCK coding	8	8	DQPSK

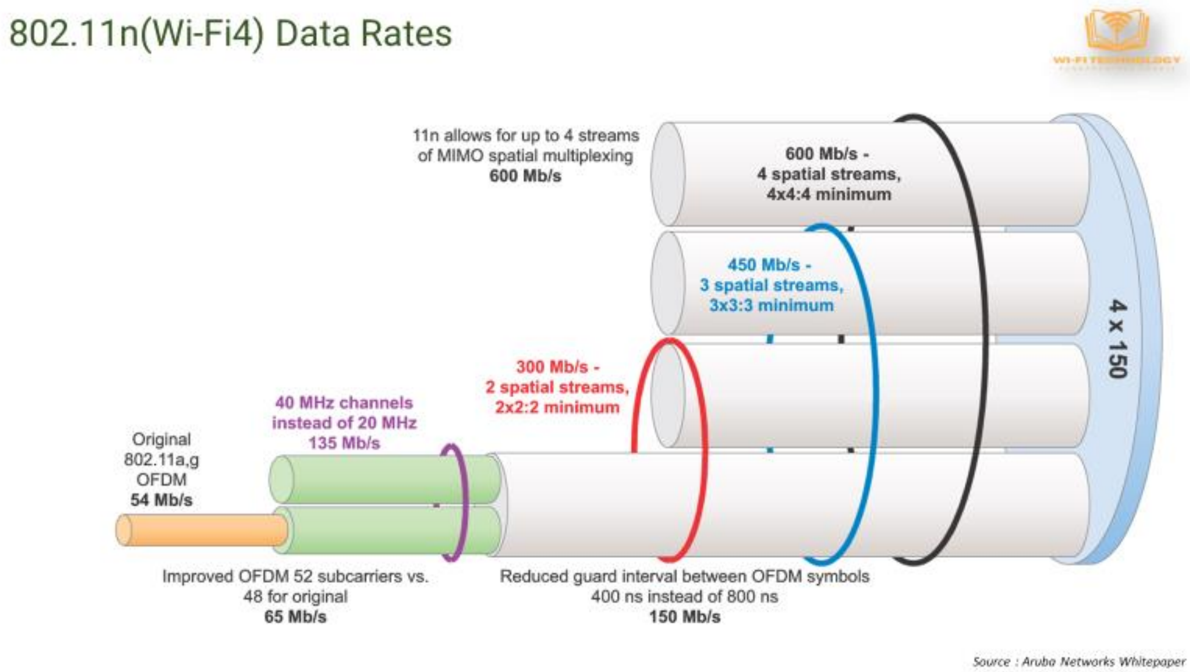
802.11b

Data rates (Mbps)	Modulation method	Coded bits per subcarrier	Data bits per OFDM symbol	Coded bits per OFDM symbol	Coding rate (data bits/ coded bits)
6	BPSK	1	24	48	1/2
9	BPSK	1	36	48	3/4
12	QPSK	2	48	96	1/2
18	QPSK	2	72	96	3/4
24	16-QAM	4	96	192	1/2
36	16-QAM	4	144	192	3/4
48	64-QAM	6	192	288	2/3
54	64-QAM	6	216	288	3/4

802.11a/g

Description: The MCS (Modulation and Coding Scheme) rates in the context of 802.11a, 802.11b, and 802.11g Wi-Fi standards define different combinations of modulation and coding used to achieve various data rates.
Data Rates: In 802.11b, the maximum data rate is 11 Mbps. In 802.11a and 802.11g, data rates go up to 54 Mbps.
Modulation Schemes: In 802.11b, DSSS (Direct Sequence Spread Spectrum) is used with a basic data rate of 1 Mbps. In 802.11a and 802.11g, OFDM (Orthogonal Frequency Division Multiplexing) is employed with different modulation schemes, including BPSK, QPSK, 16-QAM, and 64-QAM.
Coding Rates: The coding rates can vary. For example, 802.11b uses a coding rate of 1/2.

802.11n (Wi-Fi 4) Data Rates:



Description: The 802.11n (Wi-Fi 4) standard introduced advancements in Wi-Fi technology, including the use of OFDM and MIMO (Multiple Input, Multiple Output), which allowed for higher data rates.
Data Rates: Data rates in 802.11n range from 150 Mbps with one spatial stream to 600 Mbps with four spatial streams. These rates are achieved through combinations of spatial streams, modulation schemes, and coding rates.
MIMO: MIMO technology, which involves multiple antennas at both the transmitter and receiver, plays a crucial role in achieving higher throughput and improving signal robustness.
Modulation Schemes: Supported modulation schemes include BPSK (Binary Phase-Shift Keying), QPSK (Quadrature Phase-Shift Keying), 16-QAM (16 Quadrature Amplitude Modulation), and 64-QAM (64 Quadrature Amplitude Modulation).
Coding Rates: Coding rates in 802.11n range from 1/2 to 5/6, allowing for a balance between error correction and data throughput.

802.11n (Wi-Fi 4) MCS Table:

802.11n(Wi-Fi4) MCS Table

MCS index	Spatial streams	Modulation type	Coding rate	Data rate (Mbit/s) 20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.50	7.20	13.50	15.00
1	1	QPSK	1/2	13.00	14.40	27.00	30.00
2	1	QPSK	3/4	19.50	21.70	40.50	45.00
3	1	16-QAM	1/2	26.00	28.90	54.00	60.00
4	1	16-QAM	3/4	39.00	43.30	81.00	90.00
5	1	64-QAM	2/3	52.00	57.80	108.00	120.00
6	1	64-QAM	3/4	58.50	65.00	121.50	135.00
7	1	64-QAM	5/6	65.00	72.20	135.00	150.00
8	2	BPSK	1/2	13.00	14.40	27.00	30.00
9	2	QPSK	1/2	26.00	28.90	54.00	60.00
10	2	QPSK	3/4	39.00	43.30	81.00	90.00
11	2	16-QAM	1/2	52.00	57.80	108.00	120.00
12	2	16-QAM	3/4	78.00	86.70	162.00	180.00
13	2	64-QAM	2/3	104.00	115.60	216.00	240.00
14	2	64-QAM	3/4	117.00	130.00	243.00	270.00
15	2	64-QAM	5/6	130.00	144.40	270.00	300.00
16	3	BPSK	1/2	19.50	21.70	40.50	45.00
17	3	QPSK	1/2	39.00	43.30	81.00	90.00
18	3	QPSK	3/4	58.50	65.00	121.50	135.00
19	3	16-QAM	1/2	78.00	86.70	162.00	180.00
20	3	16-QAM	3/4	117.00	130.70	243.00	270.00
21	3	64-QAM	2/3	156.00	173.30	324.00	360.00
22	3	64-QAM	3/4	175.50	195.00	364.50	405.00
23	3	64-QAM	5/6	195.00	216.70	405.00	450.00
24	4	BPSK	1/2	26.00	28.80	54.00	60.00
25	4	QPSK	1/2	52.00	57.60	108.00	120.00
26	4	QPSK	3/4	78.00	86.80	162.00	180.00
27	4	16-QAM	1/2	104.00	115.60	216.00	240.00
28	4	16-QAM	3/4	156.00	173.20	324.00	360.00
29	4	64-QAM	2/3	208.00	231.20	432.00	480.00
30	4	64-QAM	3/4	234.00	260.00	486.00	540.00
31	4	64-QAM	5/6	260.00	288.80	540.00	600.00

Description: The MCS (Modulation and Coding Scheme) table for 802.11n lists various combinations of spatial streams, modulation schemes, coding rates, and their associated data rates.
Spatial Streams: The MCS table accommodates different numbers of spatial streams, ranging from 1x1 (one transmit and one receive antenna) to 4x4.
Modulation Schemes: The table includes various modulation schemes such as BPSK, QPSK, 16-QAM, and 64-QAM.
Coding Rates: Coding rates offered in the table vary from 1/2 to 5/6, providing different levels of error correction.
Data Rates: The MCS table maps these combinations to specific data rates, which range from 7.2 Mbps to 600 Mbps. The actual data rate depends on the selected MCS index, the number of spatial streams, and other factors.

These elements define the capabilities and data rates achievable within the 802.11n (Wi-Fi 4) standard, which served as a significant advancement in Wi-Fi technology by enabling higher throughput and reliability in wireless networks.

802.11ac(Wi-Fi5) MCS Table

Example 802.11ac configurations (all rates assume 256-QAM, rate 5/6)

Scenario	Typical Client Form Factor	PHY Link Rate	Aggregate Capacity
1-antenna AP, 1-antenna STA, 80MHz	Handheld	433 Mbit/s	433 Mbit/s
2-antenna AP, 2-antenna STA, 80MHz	Tablet, Laptop	867 Mbit/s	867 Mbit/s
1-antenna AP, 1-antenna STA, 160MHz	Handheld	867 Mbit/s	867 Mbit/s
2-antenna AP, 2-antenna STA, 160MHz	Tablet, Laptop	1.73 Gbit/s	1.73 Gbit/s
4-antenna AP, 4 1-antenna STAs, 160MHz (MU-MIMO)	Handheld	867 Mbit/s to each STA	3.47 Gbit/s
8-antenna AP, 160MHz (MU-MIMO) -- 1 4-antenna STA -- 1 2-antenna STA -- 2 1-antenna STAs	Digital TV, Set-top Box, Tablet, Laptop, PC, Handheld	3.47 Gbit/s to 4-antenna STA 1.73 Gbit/s to 2-antenna STA 867 Mbit/s to each 1-antenna STA	6.93 Gbit/s
8-antenna AP, 4 2-antenna STAs, 160MHz (MU-MIMO)	Digital TV, Tablet, Laptop, PC	1.73 Gbit/s to each STA	6.93 Gbit/s

Introduction of 11ac:

- **Channel Bandwidth**: It mentions that 802.11n was using 40 MHz channels, but with 802.11ac, they increased the channel bandwidth to 80 MHz and 160 MHZ. This wider channel bandwidth allowed for faster data transmission.
- **Spatial Streams:** It has an increase in the number of spatial streams. In 802.11n, it was 4x4 (four transmit and four receive antennas), but 802.11ac increased it to 8x8, which essentially means eight simultaneous data streams, further enhancing data throughput.
- **Modulation Schemes:** 802.11ac introduced newer modulation schemes, including 1024-QAM (Quadrature Amplitude Modulation). Modulation schemes affect how data is encoded and transmitted over the wireless medium. The higher the QAM value, the more data can be transmitted each time, improving overall speed.
- **Speed Improvement:** By increasing the channel bandwidth, the number of spatial streams, and introducing advanced modulation schemes, 802.11ac significantly improved Wi-Fi speeds. It reached speeds of almost 7 gigabits per second (Gbps), compared to the maximum of 600 Mbps in 802.11n. This is a substantial increase in data transfer rates.

Significance of Wi-Fi 5 (11ac):

- Wi-Fi 5 (11ac) marked a significant milestone as the first Wi-Fi standard to cross the gigabit per second speed barrier.
- This advancement excited many technology enthusiasts, as it represented a substantial improvement in wireless data transmission capabilities.

Channel bandwidth	Transmit – Receive antennas	Modulation and coding etc.	Typical client scenario	Throughput (individual link rate)	Throughput (aggregate link rate)
80 MHz	1x1	256-QAM 5/6, short guard interval	Smartphone	433 Mbps	433 Mbps
80 MHz	2x2	256-QAM 5/6, short guard interval	Tablet, PC	867 Mbps	867 Mbps
160 MHz	1x1	256-QAM 5/6, short guard interval	Smartphone	867 Mbps	867 Mbps
160 MHz	2x2	256-QAM 5/6, short guard interval	Tablet, PC	1.73 Gbps	1.73 Gbps
160 MHz	4x Tx AP, 4 clients of 1x Rx	256-QAM 5/6, short guard interval	Multiple smartphones	867 Mbps per client	3.47 Gbps
160 MHz	8x Tx AP, 4 clients with to-tal of 8x Rx (with multi-user MIMO)	256-QAM 5/6, short guard interval	Digital TV, set-top box, tablet, PC, smartphone	867 Mbps to two 1x clients 1.73 Gbps to one 2x client 3.47 Gbps to one 4x client	6.93 Gbps
160 MHz	8x Tx AP, 4 clients of 2x Rx (with multi-user MIMO)	256-QAM 5/6, short guard interval	Multiple set-top boxes, PC	1.73 Gbps to each client	6.93 Gbps

Impact of Changes:

- By increasing channel bandwidth from 40 MHz to 660 MHz, the data transfer capacity significantly increased.
- By increasing the number of spatial streams from 4 to 8, more data paths were available for transmitting information simultaneously.
- Introducing a higher order modulation rate of 256 QAM allowed for more data to be encoded in the same amount of spectrum.

Performance Improvement:

11n: Maximum speeds were around 600 Mbps.
11ac: Achieved speeds close to 7 Gbps, surpassing the gigabit boundary.

MCS	Lowest rates Mbps (20 MHz channel, 1x SS)		Channel width	Spatial streams	Highest rates Mbps (160 MHz channel, 8x SS)	
	Long GI	Short GI			Long GI	Short GI
0	6.5	7.2	x2.1 for 40 MHz x4.5 for 80 MHz x9.0 for 160 MHz	x2 for 2 SS x3 for 3 SS x4 for 4 SS x5 for 5 SS x6 for 6 SS x7 for 7 SS x8 for 8 SS	468.0	520.0
1	13.0	14.4			939.0	1040.0
2	19.5	21.7			1404.0	1560.0
3	26.0	28.9			1872.0	2080.0
4	39.0	43.3			2808.0	3120.0
5	52.0	57.8			3744.0	4160.0
6	58.5	65.0			4212.0	4680.0
7	65.0	72.2			4680.0	5200.0
8	78.0	86.7			5616.0	6240.0
9	(86.7)	(96.3)			6240.0	6933.3

Data rates for various 802.11ac configurations

In summary, the improvements in Wi-Fi 5 (11ac) were achieved through a combination of wider channel bandwidth, increased spatial streams, and advanced modulation schemes. These changes collectively allowed for a remarkable increase in data transfer speeds, making it a pivotal moment in the evolution of Wi-Fi technology.

802.11ax(Wi-Fi6 Data Rates)

Modulation and coding schemes for single spatial stream

MCS index[a]	Modulation type	Coding rate	Data rate (in Mbit/s)[b]							
			20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			1600 ns GI[c]	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

Notes

a. ^ MCS 9 is not applicable to all channel width/spatial stream combinations.
b. ^ A second stream doubles the theoretical data rate, a third one triples it, etc.
c. ^ GI stands for the guard interval.

Modulation Schemes:

- 11ac: Introduced advanced modulation schemes, like 256 qu.
- 11ax: Added an even higher-order modulation rate, 1024 qu.

Channel Bandwidth:

- 11ac: Stayed at 160 MHz channel bandwidth.
- 11ax: Also maintained the 160 MHz channel bandwidth.

Efficiency vs Throughput:

- 11ac: Focused on improving throughput and surpassed the gigabit boundary, reaching almost 6 Gbps.
- 11ax: Concentrated on efficiency due to the expected increase in the number of connected devices. Throughput improvements were minimal.

Throughput Improvement:

- 11ax: While the focus was on efficiency, there was still a moderate improvement in throughput, reaching up to 9.6 Gbps. This improvement was achieved through the introduction of higher order modulation without changing channel bandwidth or spatial streams.

Techniques Introduced:

- OFDMA (Orthogonal Frequency Division Multiple Access): Allows multiple devices to share the same channel simultaneously, improving efficiency by dividing the channel into smaller sub-channels.
- MU-MIMO (Multi-User Multiple Input Multiple Output): Enables simultaneous communication with multiple devices using multiple antennas, enhancing efficiency by serving multiple users at once.
- Other Efficiency Measures: Various other techniques were introduced to optimize channel usage and minimize interference, ensuring better overall performance in crowded network environments.

In summary, 11ax (Wi-Fi 6) shifted its focus from purely throughput improvements to efficiency due to the increasing number of devices on networks. This was achieved through the introduction of techniques like OFDMA and MU-MIMO.

802.11be (Wi-Fi7) Data Rates

MCS index[i]	Modulation type	Coding rate	Data rate (Mbit/s)[ii]														
			20 MHz channels			40 MHz channels			80 MHz channels			160 MHz channels			320 MHz channels		
			3200 ns GI[iii]	1600 ns GI	800 ns GI	3200 ns GI	1600 ns GI	800 ns GI	3200 ns GI	1600 ns GI	800 ns GI	3200 ns GI	1600 ns GI	800 ns GI	3200 ns GI	1600 ns GI	800 ns GI
0	BPSK	1/2	7	8	9	15	16	17	31	34	36	61	68	72	123	136	144
1	QPSK	1/2	15	16	17	29	33	34	61	68	72	122	136	144	245	272	288
2	QPSK	3/4	22	24	26	44	49	52	92	102	108	184	204	216	368	408	432
3	16-QAM	1/2	29	33	34	59	65	69	123	136	144	245	272	282	490	544	577
4	16-QAM	3/4	44	49	52	88	98	103	184	204	216	368	408	432	735	817	865
5	64-QAM	2/3	59	65	69	117	130	138	245	272	288	490	544	576	980	1089	1153
6	64-QAM	3/4	66	73	77	132	146	155	276	306	324	551	613	649	1103	1225	1297
7	64-QAM	5/6	73	81	86	146	163	172	306	340	360	613	681	721	1225	1361	1441
8	256-QAM	3/4	88	98	103	176	195	207	368	408	432	735	817	865	1470	1633	1729
9	256-QAM	5/6	98	108	115	195	217	229	408	453	480	817	907	961	1633	1815	1922
10	1024-QAM	3/4	110	122	129	219	244	258	459	510	540	919	1021	1081	1838	2042	2162
11	1024-QAM	5/6	122	135	143	244	271	287	510	567	600	1021	1134	1201	2042	2269	2402
12	4096-QAM	3/4	131	146	155	263	293	310	551	613	649	1103	1225	1297	2205	2450	2594
13	4096-QAM	5/6	146	163	172	293	325	344	613	681	721	1225	1361	1441	2450	2722	2882

Wi-Fi 7:

- Wi-Fi 7 is the latest standard that is yet to be released.
- Wi-Fi 7 is expected to focus on speed improvements, continuing the trend of pushing for higher data transfer rates.

Modulation Rate:

- Introduces a higher modulation rate, specifically 4096QAM (quadrature amplitude modulation). This means 12 bits are transmitted per symbol, allowing for more data to be encoded and transmitted within the same channel.

Channel Bandwidth:

- Increases channel bandwidth from 160 MHz to 320 MHz. This expansion is made possible by the availability of the 6 GHz spectrum, which provides more unlicensed spectrum for Wi-Fi networks.

Spatial Streams:

- Enhances MIMO (Multiple Input, Multiple Output) technology from 8x8 to 16x16. This means there are now 16 spatial streams, allowing for parallel data transmission and reception, significantly improving the overall data throughput.

Impact on Data Rates:

- These changes in modulation rate, channel bandwidth, and spatial streams led to a substantial increase in data rates. While the passage provides data rates for a single spatial stream (around 2.8 Gbps), these rates can be multiplied by the number of spatial streams supported (up to 16), resulting in close to 50 Gbps data rates.

Throughput Improvement:

- Wi-Fi 7: By changing the modulation rate, increasing channel bandwidth, and the number of spatial streams, Wi-Fi 7 achieves substantial throughput improvements.
- Data Rates: For one spatial stream, the maximum data rate reaches around 2.8 gigabits per second. When multiplied by 16 spatial streams, the data rates can reach close to 48 gigabits per second, representing a significant increase in wireless data transfer speeds.

MCS Indexing and Notation Changes:

- Wi-Fi 7: The method of MCS (Modulation and Coding Scheme) indexing has changed. Instead of a linear progression from 0 to 31, the notation now combines the number of spatial streams (NSS) with the MCS rate.
- Notation Example: For instance, an F data rate could be represented as NSS2 (two spatial streams) combined with MCS11 (1024QAM modulation). Another combination might be NSS4 (four spatial streams) with MCS11 (1024QAM modulation). This new notation system provides a more organized and scalable way to represent high data rates.

In summary, Wi-Fi 7 (the latest standard) focuses on pushing the boundaries of speed by introducing even higher modulation rates, wider channel bandwidth, and increased spatial streams. These changes lead to significantly higher data rates, close to 50 Gbps, and a new notation system that combines the number of spatial streams with the MCS rate to represent data rates more efficiently and accurately.

PHY Data Rates Calculation

Each value in the MCS table is defined as a Data rate or PHY rate. The Phy Rate represents the theoretical maximum speed at which data can be transmitted between a wireless router or access point (AP) and a WiFi client device.The following is the formulae for calculating a phy rate.Here is the formula we can use to calculate which data rate is used for both 802.11n and 802.11ac:

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

- N_{SD}: *Number of Data Subcarriers*
- N_{BPSCS}: *Number of Coded Bits per Subcarrier per Stream*
- R: *Coding*
- N_{SS}: *Number of Spatial Streams*
- T_{DFT}: *OFDM Symbol Duration*
- T_{GI}: *Guard Interval Duration*

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								

PHY	Modulation		R	N_{SS}	N_{SD}				T_{DFT}	T_{GI}		
	Name	N_{BPSCS}			20MHz	40MHz	80MHz	160MHz		Long	Medium	Long
802.11ax (HE)	BPSK	1	1/2	1 to 8	234	468	980	1960	12.8 μs	0.8 μs	1.2 μs	3.2 μs
	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									
	1024-QAM	10	3/4 & 5/6									

Now, the formula doesn't change much with 802.11ax. However, some new features will impact the way we calculate data rate for 802.11ax:

- A new symbol duration is used: 12.8μs

- Different Guard Intervals are used: 0.8µs, 1.6µs and 3.2µs

- The size and number of data subcarriers is not the same (especially with the different RU sizes introduced by OFDMA.

Even though the formula doesn't change much, the IEEE does define 2 different formulas depending on if OFDMA is used or not. When OFDMA is not used, we can use the formula previously presented above. Here is the formula we can used when OFDMA is used (it is pretty much the same except that we define the number of data subcarriers per RU and not per

channel):

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*

PHY	Modulation		R	N_{SS}	N_{SD}				T_{DFT}	T_{GI}		
	Name	N_{BPSCS}			20MHz	40MHz	80MHz	160MHz		Long	Medium	Long
802.11ax (HE)	BPSK	1	1/2	1 to 8	234	468	980	1960	12.8 µs	0.8 µs	1.2 µs	3.2 µs
	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									
	1024-QAM	10	3/4 & 5/6									

This table details the parameters used when OFDMA is not used.

PHY	Modulation		R	N_{SS}	N_{SD}						T_{DFT}	T_{GI}		
	Name	N_{BPSCS}			26-tone	52-tone	106-tone	242-tone	484-tone	996-tone		Long	Medium	Long
802.11ax (HE)	BPSK	1	1/2	1 to 8	24	48	102	234	468	980	12.8 µs	0.8 µs	1.2 µs	3.2 µs
	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											
	1024-QAM	10	3/4 & 5/6											

This table details the parameters when OFDMA and resource units are used.

Example

The following is an example to identify the data rate of a particular phone using.The phone is a Samsung GS10 which supports 802.11ax and up to 2 spatial streams. The AP used is an Aerohive AP630. I have configured it with an 80MHz wide channel. OFDMA is not used here because ODFMA was not activated at the time of this capture.

So based on this information, we can determine some of the variables required to calculate the data rate and narrow down the data rates that will be used by this device:

- Number of Data Subcarriers for an 80MHz wide channel: 980

- Number of Coded bit per subcarrier (Modulation): we don't know yet

- Coding: we don't know yet

- Number of Spatial Streams: 2

- OFDM Symbol Duration: 12.8µs

- Guard Interval: we don't know yet

So here is the list of possible data rates used by this device when connecting to this AP:

MCS Index	Spatial Stream	Modulation	Coding	OFDM (802.11ax) 80MHz 0.8µs GI	1.6µs GI	3.2µs GI
0	1	BPSK	1/2	36.0	34.0	30.6
1	1	QPSK	1/2	72.1	68.1	61.3
2	1	QPSK	3/4	108.1	102.1	91.9
3	1	16-QAM	1/2	144.1	136.1	122.5
4	1	16-QAM	3/4	216.2	204.2	183.8
5	1	64-QAM	2/3	288.2	272.2	245.0
6	1	64-QAM	3/4	324.3	306.3	275.6
7	1	64-QAM	5/6	360.3	340.3	306.3
8	1	256-QAM	3/4	432.4	408.3	367.5
9	1	256-QAM	5/6	480.4	453.7	408.3
10	1	1024-QAM	3/4	540.4	510.4	459.4
11	1	1024-QAM	5/6	600.5	567.1	510.4
0	2	BPSQ	1/2	72.1	68.1	61.3
1	2	QPSK	1/2	144.1	136.1	122.5
2	2	QPSK	3/4	216.2	204.2	183.8
3	2	16-QAM	1/2	288.2	272.2	245.0
4	2	16-QAM	3/4	432.4	408.3	367.5
5	2	64-QAM	2/3	576.5	544.4	490.0
6	2	64-QAM	3/4	648.5	612.5	551.3
7	2	64-QAM	5/6	720.6	680.6	612.5
8	2	256-QAM	3/4	864.7	816.7	735.0
9	2	256-QAM	5/6	960.8	907.4	816.7
10	2	1024-QAM	3/4	1080.9	1020.8	918.8
11	2	1024-QAM	5/6	1201.0	1134.3	1020.8

Because we know that the data rate used was 1200.95 Mbps (as indicated on the picture above), we can now determine that:

- MCS 11 was used

- 1024QAM with a coding of 5/6 was being used

- A guard interval of 0.8µs was used

Difference between PHY Data Rates and Throughput

The actual Throughput under ideal conditions is expected to be around 60-70% of the PHY data rates.

PHY Data Rates and Throughput are two different metrics used in wireless communication to measure the performance and capacity of a network. They are related but represent distinct aspects of network performance:

1.PHY Data Rates (Physical Layer Data Rates):

- PHY data rates represent the maximum transmission speed or capacity at the physical layer of a wireless network. These rates are typically measured in bits per second (bps) or megabits per second (Mbps).

- PHY data rates consider the signaling rate or modulation and coding scheme (MCS) used to transmit data. They reflect the raw data transfer rate before considering any overhead or losses.

- PHY data rates are theoretical maximum values and don't account for various real-world factors that can reduce the effective data transfer speed.

2.Throughput:

- Throughput, on the other hand, represents the actual data transfer rate achieved at the application layer. It measures how much useful data is successfully transmitted and received over the network.

- Throughput considers various factors that affect data transmission, including protocol overhead, retransmissions, network congestion, interference, and other environmental factors.

- Throughput is often measured in bits per second (bps) or megabits per second (Mbps) and provides a more practical view of network performance for end-users.

Key Differences:

- PHY Data Rates are theoretical and represent the maximum physical layer speed, while Throughput is the actual data rate experienced by users.

- PHY Data Rates don't account for protocol overhead, errors, and other real-world constraints, while Throughput considers these factors.

- Throughput is typically lower than PHY Data Rates because it considers the practical limitations of the network.

- PHY Data Rates are used for specification and design purposes, while Throughput is a more meaningful metric for evaluating real-world network performance.

1. Wi-Fi Overhead: Wi-Fi overhead refers to the non-user data portions of Wi-Fi frames. It includes control information, preamble, headers, and gaps between frames. Overhead reduces the available bandwidth for user data transmission.

2. Interframe Spaces (IFS):IFS are time intervals between Wi-Fi frame transmissions. They allow for channel access coordination and priority handling of different frame types. Shorter IFS times are given higher priority.

3. Management and Control Frames: Management frames are used for network management tasks, such as association, disassociation, and scanning.

Control frames manage data frame transmission, acknowledge receipt, and handle flow control.

4. Random Backoff: Random backoff is a mechanism used to avoid collisions in wireless networks. Before transmitting, devices choose a random time to wait, reducing the likelihood of simultaneous transmissions.

5. PHY Signaling: PHY (Physical Layer) signaling refers to the transmission of signals that encode data. This includes modulation and coding schemes used to represent data on the wireless channel.

6. Interference: Interference occurs when unwanted signals disrupt the intended communication in a wireless network. It can be caused by other Wi-Fi devices, electronic devices, or physical obstacles.

7. MAC Header: The MAC (Media Access Control) header contains control information for data frames, including source and destination addresses, frame type, and error-checking information.

8. Guard Intervals: Guard intervals are time intervals inserted between symbols or frames to prevent interference and maintain signal separation. They ensure reliable data transmission.

9. Virtual Carrier Sensing: Virtual carrier sensing is a technique used by Wi-Fi devices to sense the channel's availability without physically transmitting a signal, reducing the chances of collisions.

10. Backward Compatibility/Legacy Mode: Backward compatibility allows newer Wi-Fi devices to work with older Wi-Fi standards. Legacy mode enables them to communicate with older devices using older protocols.

11. Acknowledgments: Acknowledgements (ACKs) are short frames sent by the receiving device to confirm the successful reception of a data frame. They ensure data integrity.

12.Retransmissions: Retransmissions occur when data frames are not acknowledged or are received with errors. The sender resends the data frame to ensure successful delivery.

13. Rate Adaptation: Rate adaptation is the process of dynamically adjusting the data transmission rate based on the current wireless channel conditions to optimize throughput.

14.Packet sizes/Frame sizes: Packet or frame sizes refer to the size of data units transmitted over a network. Smaller frames are more efficient for short data transfers, while larger frames are better for bulk data.

15. Half Duplex: Half duplex communication allows data to be transmitted and received but not simultaneously. Devices take turns sending and receiving data on the same channel. It's like a walkie-talkie where you can either talk or listen but not do both simultaneously.

802.11ac Throughput Calculator

- This calculator can help measure throughput for various options in wireless communication.

- It allows users to input different parameters to estimate the expected throughput for specific configurations.

- The calculator mentioned is designed for 802.11ac (11ac) and requires inputs such as MCS index, channel bandwidth, guard interval, and the number of spatial streams.

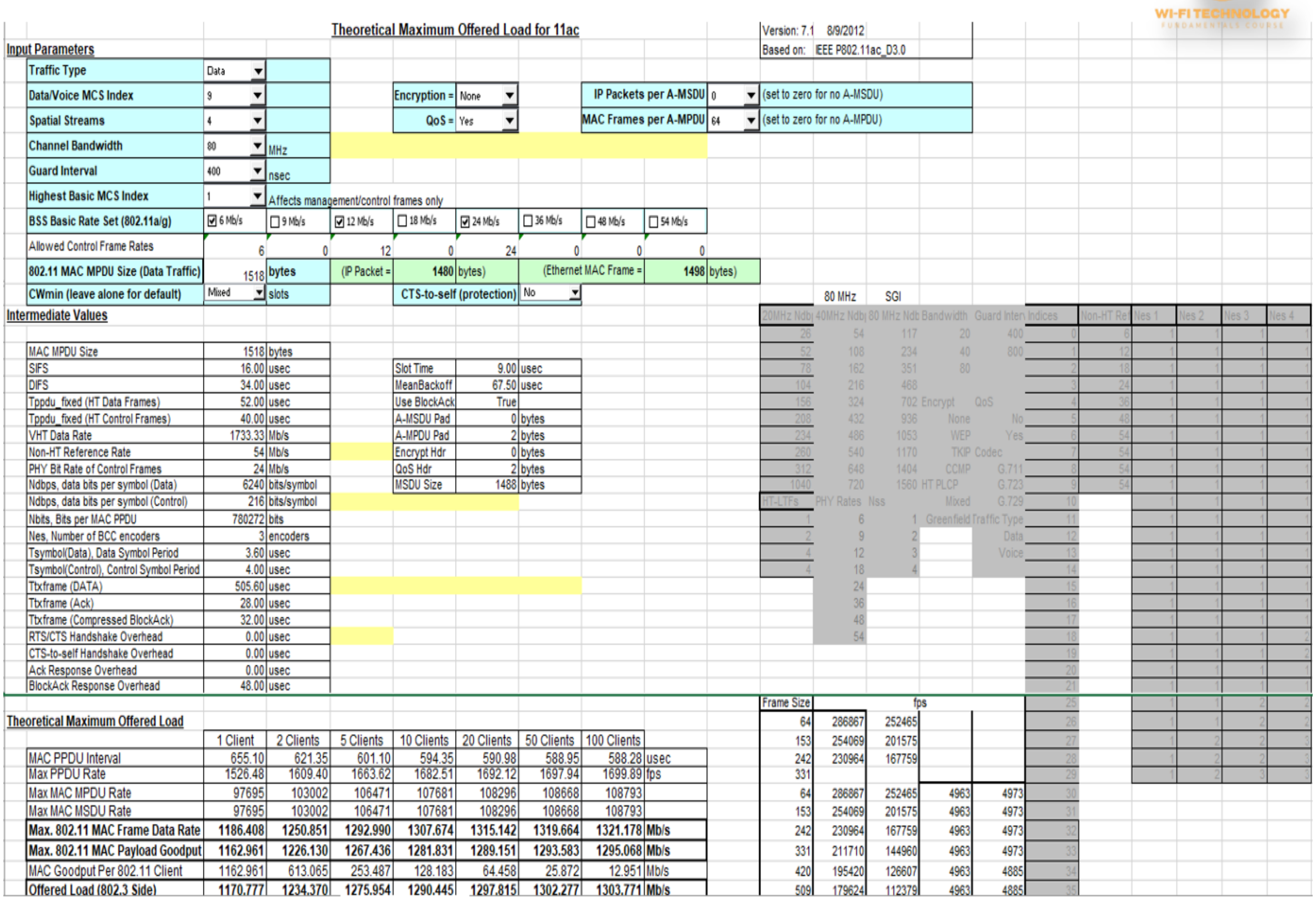
- It can calculate the possible data rate, which corresponds to the specifications mentioned on the device's box (e.g., 1.8 Gbps).

- However, the actual throughput, which factors in overhead and protocol-related inefficiencies, may be significantly lower (e.g., around 1.162 Gbps).

- The calculator also demonstrates how changing parameters, such as the MCS index or frame size, affects throughput.

- It's noted that the calculator hasn't been updated for 802.11ax (11ax) and 802.11b (11b) yet.

802.11ax Throughput Calculator



Theoretical Maximum Offered Load for 11ac

Version: 7.1 8/9/2012
Based on: IEEE P802.11ac_D3.0

Input Parameters

Traffic Type	Data		
Data/Voice MCS Index	9		
Spatial Streams	4		
Channel Bandwidth	80	MHz	
Guard Interval	400	nsec	
Highest Basic MCS Index	1	Affects management/control frames only	
802.11 MAC MPDU Size (Data Traffic)	1518	bytes	
CWmin (leave alone for default)	Mixed	slots	

Encryption = None; QoS = Yes; IP Packets per A-MSDU 0 (set to zero for no A-MSDU); MAC Frames per A-MPDU 64 (set to zero for no A-MPDU); (IP Packet = 1480 bytes); (Ethernet MAC Frame = 1498 bytes); CTS-to-self (protection) No

BSS Basic Rate Set (802.11a/g)	☑ 6 Mb/s	☐ 9 Mb/s	☑ 12 Mb/s	☐ 18 Mb/s	☑ 24 Mb/s	☐ 36 Mb/s	☐ 48 Mb/s	☐ 54 Mb/s
Allowed Control Frame Rates	6	0	12	0	24	0	0	0

Intermediate Values

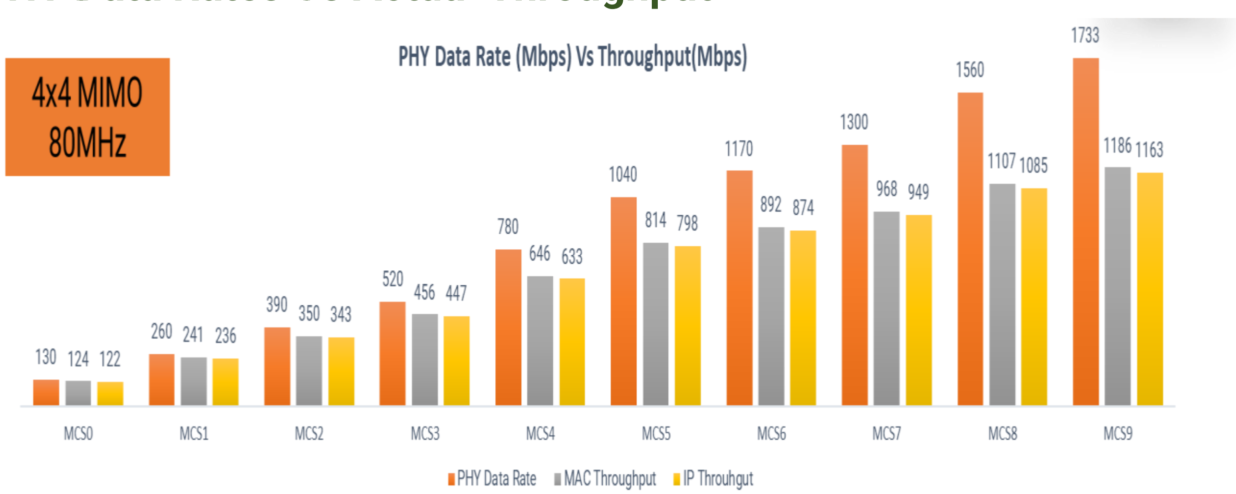
MAC MPDU Size	1518	bytes
SIFS	16.00	usec
DIFS	34.00	usec
Tppdu_fixed (HT Data Frames)	52.00	usec
Tppdu_fixed (HT Control Frames)	40.00	usec
VHT Data Rate	1733.33	Mb/s
Non-HT Reference Rate	54	Mb/s
PHY Bit Rate of Control Frames	24	Mb/s
Ndbps, data bits per symbol (Data)	6240	bits/symbol
Ndbps, data bits per symbol (Control)	216	bits/symbol
Nbits, Bits per MAC PPDU	780272	bits
Nes, Number of BCC encoders	3	encoders
Tsymbol(Data), Data Symbol Period	3.60	usec
Tsymbol(Control), Control Symbol Period	4.00	usec
Ttxframe (DATA)	505.60	usec
Ttxframe (Ack)	28.00	usec
Ttxframe (Compressed BlockAck)	32.00	usec
RTS/CTS Handshake Overhead	0.00	usec
CTS-to-self Handshake Overhead	0.00	usec
Ack Response Overhead	0.00	usec
BlockAck Response Overhead	48.00	usec

Slot Time	9.00	usec
MeanBackoff	67.50	usec
Use BlockAck	True	
A-MSDU Pad	0	bytes
A-MPDU Pad	2	bytes
Encrypt Hdr	0	bytes
QoS Hdr	2	bytes
MSDU Size	1488	bytes

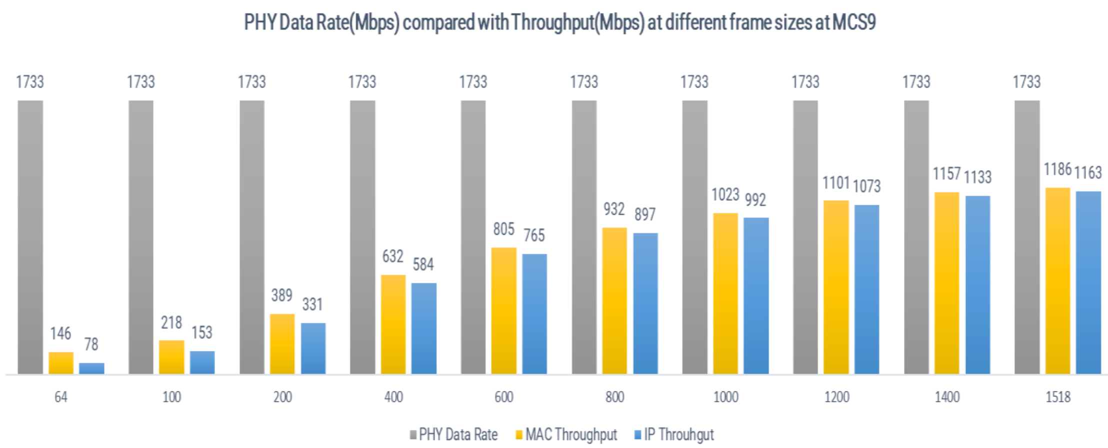
Theoretical Maximum Offered Load

	1 Client	2 Clients	5 Clients	10 Clients	20 Clients	50 Clients	100 Clients	
MAC PPDU Interval	655.10	621.35	601.10	594.35	590.98	588.95	588.28	usec
Max PPDU Rate	1526.48	1609.40	1663.62	1682.51	1692.12	1697.94	1699.89	fps
Max MAC MPDU Rate	97695	103002	106471	107681	108296	108668	108793	
Max MAC MSDU Rate	97695	103002	106471	107681	108296	108668	108793	
Max. 802.11 MAC Frame Data Rate	**1186.408**	**1250.851**	**1292.990**	**1307.674**	**1315.142**	**1319.664**	**1321.178**	**Mb/s**
Max. 802.11 MAC Payload Goodput	**1162.961**	**1226.130**	**1267.436**	**1281.831**	**1289.151**	**1293.583**	**1295.068**	**Mb/s**
MAC Goodput Per 802.11 Client	1162.961	613.065	253.487	128.183	64.458	25.872	12.951	Mb/s
Offered Load (802.3 Side)	**1170.777**	**1234.370**	**1275.954**	**1290.445**	**1297.815**	**1302.277**	**1303.771**	**Mb/s**

PHY Data Rates Vs Actual Throughput



Understanding the theoretical PHY data rates and the actual achievable throughput at the MAC layer or IP layer is crucial for assessing the performance of Wi-Fi routers, especially for test engineers. By referring the calculated graphs based on MCS rates, such as the one presented for a four-by-four 80 MHz configuration, engineers can effectively benchmark the performance of their Wi-Fi routers. For instance, if the actual throughput reaches the theoretical maximum, as depicted by the graph, it indicates that the access point is performing exceptionally well. Conversely, if the achieved throughput falls significantly below the theoretical limit, at around 900 Mbps, for instance, it might indicate underlying issues that require attention. Therefore, utilizing such calculators can significantly aid in accurately evaluating the performance of Wi-Fi routers.



Certainly, the impact of packet size on throughput is a critical factor to consider. As evident from the comparison chart, variations in packet sizes can significantly influence the achieved throughput. For instance, when using a 158-byte packet size, the throughput remains stable at 1.1 Gbps under the same conditions. However, reducing the packet size to 64 bytes results in a dramatic drop in throughput, plummeting to 146 Mbps.

The reason for the drop in throughput with smaller packet sizes is due to the extra stuff that needs to be sent along with the actual data. This extra stuff, known as overhead, takes up a larger portion of the smaller packets, leaving less room for the actual useful information. This means that the smaller the packet, the more it is filled with this extra stuff, resulting in less useful data being sent. Understanding this relationship is crucial for making Wi-Fi work better and figuring out how to make networks run more efficiently.

The Real Throughput

1. Device Limitations: Despite having a high-end Wi-Fi router with advanced features such as 4x4 MIMO and an 80 MHz channel bandwidth, the actual performance of the network can be limited by the capabilities of the connected devices.

2. Reduced Speed: If your device, like a laptop, supports only 2x2 MIMO and a 40 MHz channel, the connection speed will drop significantly from the router's advertised speed, potentially impacting your online experience.

3. Signal Distance: A further reduction in speed can occur when the distance between your device and the router increases, leading to a weaker signal and a subsequent decrease in data transmission rates.

4. Overhead Impact: Various protocol-related overheads and the influence of small packet sizes on overall throughput can contribute to a noticeable drop in the actual achievable speed.

5. Shared Bandwidth: As more devices connect to the Wi-Fi network, the available bandwidth is divided among them, resulting in a reduced speed for each connected device.

6. Advanced Solutions: To tackle these challenges, modern standards have introduced sophisticated techniques like MU-MIMO (Multi-User MIMO) and OFDMA (Orthogonal Frequency Division Multiple Access), enabling the router to communicate with multiple devices simultaneously and optimize the utilization of available resources.

These advancements ensure that the Wi-Fi network performs efficiently, providing the best possible speeds and a seamless online experience for all connected devices.

Real-time example available on YouTube at the timestamp 50:07. Follow the link for a practical demonstration (https://www.youtube.com/watch?v=FrwdbnUPSfE)