Chapter 5

Mainstream WiFi Standards

Since the introduction of the basic 802.11 wireless LAN in 1997, there have been many amendments and advancements to date to address the requirements of new applications and demands. While some of these amendments sought to improve the capacity and efficiency of the mainstream WiFi used by billions of people to access the Internet, others targeted some niche applications to further enhance the utility of the technology. In this chapter, we will focus on the mainstream WiFi standards while the niche standards will be examined in the following chapter.

5.1 802.11 Amendments and WiFi Evolution

Since its first appearance in 1997, WiFi has gone through significant evolutions increasing its efficiency and data rates to meet the growing demand for wireless connectivity. Table 5.1 provides a chronological list of the major amendments along with the key enhancements and the maximum data rates they can support. As we can see, WiFi data rate has increased from a mere 2 Mbps in 1997 to a whopping 9.6Gbps in 2020, approximately a 5-fold increase in 23 years. Interestingly, the next version of WiFi is striving to achieve another 3-fold increase to 30 Gbps in just 4 years, possibly beating the speed of wired wireless LANs for the first time in history.

While it is easy to see the benefits of higher data rates, the details that contribute to data rate increase is less trivial to understand. In the rest of this chapter, we shall examine the factors that contribute to data rate enhancements for each of these amendments.

Table 5.1 Chronological list of mainstream IEEE 802.11 amendments

802.11 Amendment	Key Enhancements	Max. Data Rate
802.11-1997	Legacy WiFi in 2.4GHz (now extinct!)	2 Mbps
802.11b-1999	Higher speed modulation in 2.4GHz	11 Mbps

802.11a-1999	Higher speed PHY (OFDM) in 5GHz	54 Mbps
802.11g-2003	Higher speed PHY (OFDM) in 2.4GHz	54 Mbps
802.11n-2009	[illegible]put in 2.4/5GHz	600 Mbps
802.11ac-2013	[illegible]ghput in 5GHz	~7 Gbps
802.11ax-2020	[illegible] in 2.4/5GHz	~9.6 Gbps
802.11be-2024 (expected)	Extremely high throughput in 2.4/5/6GHz	~30 Gbps

5.2 Basics of WiFi Data Rates

Each WiFi version supports a range of specific data rates. For example, 802.11a [802-11a] supports 8 different data rates: 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. Fundamentally, data rate of WiFi or for any other communications technology is derived as:

Data rate = symbol rate x data bits per symbol

While the symbol rate is defined by the PHY, the number of data bits carried in a symbol depends on the choice of modulation and coding. It should be noted that only 802.11b used DSSS, while all subsequent WiFi amendments used OFDM as their PHY. Usually, many different combinations of modulation and coding are available for a given PHY, which leads to a range of specific available data rates for a given WiFi. When MIMO is employed, data rates can be further increased linearly with the number of independent spatial streams supported by the MIMO system. Next, we are going to examine each of the mainstream WiFi amendments, discuss the main enhancements they introduce compared to their predecessor, and how these enhancements increase their achievable data rates.

5.3 Data Rate in DSSS-based WiFi: IEEE 802.11-1997 and 802.11b-1999

Recall that the original 802.11 released in 1997 supported only 2 Mbps for 22 MHz channels using the Direct Sequence Spread Spectrum (DSSS) technique at the physical layer. In this section, we will examine how the data rate for DSSS is computed and how the 802.11b was able to increase the DSSS rate to 11 Mbps for the same 22 MHz channel.

First, let us look at the use of chips in a DSSS system as illustrated in Figure 5.1, where a binary coded symbol (single bit per symbol) is spread with 10 chips. Both the original 802.11 and 802.11b [802-11b] operate at 1/2 chip per Hz, which gives a chip rate of 11Mchips/s for the 22MHz channel. Second, we note that 802.11 uses a Barker code, which uses 11 chips per symbol. On the other hand, to increase the data rate, 802.11b employs Complementary Code Keying (CCK), which employs only 8 chips to code a symbol. This means we have a symbol rate of 1Msps (mega symbol per second) for the 2Mbps rate and 1.375 Msps for the 11 Mbps data rate. The third factor that determines the final data rate is the symbol coding, which determines how many data bits are co[illegible] For 2-Mbps rate, 802.11 uses 2 bits per symbol, whereas for the [illegible]ts per symbol.

Now we can ve[illegible]es by multiplying the symbol rates with the bits per symbol for [illegible]ecifically, for the 2 Mbps, we have 1Msps x 2bits/symbol=2M[illegible]Mbps, we have 1.375 Msps x 8 bits/symbol = 11Mbps

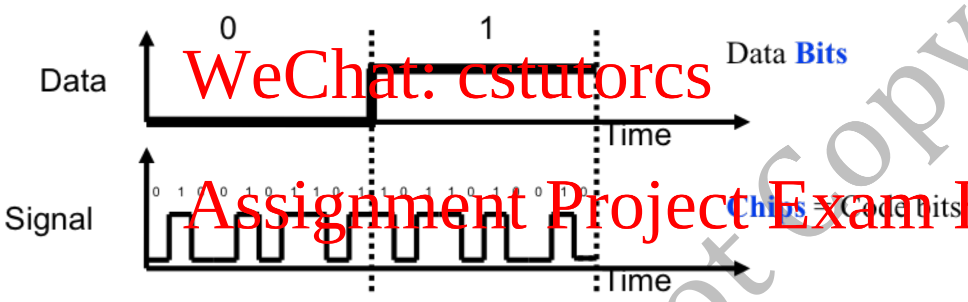

Figure 5.1 An example of DSSS with binary modulated symbols spread with a chip rate of 10 chips per symbol.

Example 5.1:

A WLAN standard is employing a spread spectrum coding with only ½ rate, which produces chips at a rate of ½ chips per Hz. It uses **8 chips to code a symbol** and 16 QAM modulation to modulate the symbol stream. What would be the data rate for 22 MHz channels?

Solution:

Chip rate = ½ x 22 = 11 Mcps (cps = chips per second)
Symbol rate = 11/8 = 1.375 Msps (sps = symbols per second)
Bits per symbol = $\log_2(16)$ = 4 [16 QAM produces 4 bits per symbol]
Data rate = symbol rate x bits per symbol = 1.375 x 4 = 5.5 Mbps

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5.4 Data Rate in OFDM-based WiFi

OFDM, which was adopted in WiFi from 802.11a onwards, has a completely different structure than its predecessor, DSSS. The symbol rate in OFDM is obtained as the inverse of the symbol interval (a.k.a. symbol length or duration), which includes a data interval followed by a guard interval. The actual symbol is contained within the data interval, whereas the guard interval is used to avoid inter-symbol interference. The longer the delay spread, the longer the guard interval and the lower the symbol rate.

The number of bits carried in an OFDM symbol depends on the subcarrier structure and the modulation order of the symbol. OFDM divides a WiFi channel into many subcarriers. All these subcarriers are divided into three categories: data subcarriers, pilot subcarriers, and guard subcarriers. Only the data subcarriers carry the OFDM symbols. Pilots [illegible]s channel, while the guards protect the symbol against interfere[illegible]ent channels. The guard subcarriers are thus equally distribut[illegible]ar of the middle subcarriers.

Although the all[illegible]rs to pilot and guard reduces the total number of data subcarriers, [illegible]note that each OFDM symbol is carried over all the data subcar[illegible]hich significantly boosts the effective bits per symbol. For example, an OFDM with N data subcarriers each applying M-ary modulation, the effective number of bits sent per symbol is obtained as $N\mathrm{x}\log_2 M$.

Finally, the actual number of data bits per symbol is affected by the choice of error correcting codes and their coding rates. For example, with a coding rate of ¾, 4 bits are actually transmitted for every 3 data bits. Similarly, a coding rate of 2/3 implies 2 data bits for every 3 bits transmitted, and so on. The number of data bits per OFDM symbol therefore is obtained as:

Data bits per OFDM symbol = *coding rate* ✗ $\log_2 M$ ✗ *#-of-data-subcarriers*

Example 5.2:

What is the data rate of an OFDM WiFi applying 64-QAM and a coding rate of ¾ to its 48 data subcarriers? Assume a symbol interval of 4µs.

Solution:

$\mathrm{Log}_2 M = \log_2 64 = 6$
Coded bits per symbol = $\log_2 M$ ✗ #-of-data-subcarriers = 6x48 = 288
Data bits per symbol = coding rate x 288 = ¾ x 288 = 216
Symbol rate = 1/symbol-interval = ¼ Msps (0.25 million symbols per sec.)
Data rate = symbol rate x data bits per symbol = 216 x ¼ Mbps = **54 Mbps**

Table 5.2 summarises the 5 key parameters that affect data rates in OFDM-based WiFi. In the rest of this chapter, we will examine how the successive amendments exploited these parameters to enhance the data rates from their predecessors.

Table 5.2 Five key parameters affecting WiFi data rates

Parameter	**Description**
Modulation	Affects the number of bits per symbol; $\mathrm{Log}_2 M$ bits per symbol for M-ary modulation; usually multiple modulation option are available
Coding	Error correcting coding affects the actual number of data bits per symbol; usually multiple coding options are available; an integer number, called MCS (modulation and coding system), defines a particular combination of modulation and coding;
Guard interval	Affects symbol rate; the longer the interval, the lower the

	symbol rate and vice versa.
Channel Width	Affects the number of achievable OFDM subcarriers and hence ultimately the data rate; channel width can be increased by combining multiple channels into a single one [illegible]onding), an option available from 802.11n
MIMO streams	[illegible]pendent data streams that can be sent in [illegible]treams means higher achievable data rates, [illegible]MIMO available from 802.11n onwards; newer [illegible]ve increased number of MIMO streams [illegible]eir predecessor

5.5 IEEE 802.11a 1999

802.11a is the first amendment to use OFDM, which allowed it to push the date rates to 54 Mbps. Actually, 802.11a supports 8 different data rates, from a mere 6 Mbps up to 54 Mbps, by selecting a combination of modulator and coding to dynamically adjust for the noise and interference.

802.11a divides the 20 MHz channel bandwidth into 64 subcarriers. Out of these 64 subcarriers, 6 at each side are used as guards (a total of 12 guards) and 4 as pilot, which leaves 48 of them to be used to carry data.

802.11a OFDM has a symbol length of 4 microsecond, which gives a symbol rate of 0.25 M symbols/s. Therefore, with a modulation of BPSK for example, there will be 1 coded bit per subcarrier for each OFDM symbol, or 48 coded bits per OFDM symbol in total as the symbol is transmitted over all of the 48 subcarriers in parallel. The actual data bits transmitted per symbol will however depend on the coding used. 802.11a supports three coding rates, 1/2, 2/3, and 3/4.

The modulation schemes are fixed and cannot be changed i.e., to operate at a particular data rate, the corresponding combination of modulation and coding scheme (MCS) has to be selected. Table 5.3 shows the MCS combinations of each data rate in 802.11a. Note that the *data bits per symbol* has to be multiplied by the *symbol rate* of 0.25 M symbols/s to obtain the final net data rate shown in the last column.

Table 5.3 Modulation, coding, and data rates for 802.11a

Modulation	**Coding Rate**	**Coded bits per subcarrier**	**Coded bits per symbol**	**Data bits per symbol**	**Data Rate (Mbps)**
BPSK	1/2	1	48	24	6
BPSK	3/4	1	48	36	9

QPSK	1/2	2	96	48	12
QPSK	3/4	2	96	72	18
16-QAM	1[illegible]	[illegible]	192	96	24
16-QAM	3[illegible]	[illegible]	192	144	36
64-QAM	2/3	6	288	192	48
64-QAM	3/4	6	288	216	54

5.6 IEEE 802.11g-2003

Although 802.11a was able to push the date rates to 54 Mbps, it used the 5 MHz band and was not compatible with the previous version (802.11b), which was operating in the 2.4GHz and at 11 Mbps. 802.11g [802-11g] achieved 54 Mbps at 2.4 GHz using OFDM, but it could fall back to 802.11b data rates using CCK modulation. More specifically, 802.11g OFDM data rates are identical with 802.11a, i.e., it supports 6, 9, 12, 18, 24, 36, 48, 54 Mbps as per Table 5.3, while CCK supports data rates of 1, 2, 5.5, and 11 Mbps. This seamless backward compatibility made 802.11g very popular, because previous hardware designed to operate in the 2.4GHz band can now benefit from the higher data rates without having to switch to a new spectrum.

5.7 IEEE 802.11e-2005 (Enhanced QoS)

While amendments 802.11a and 802.11g were racing to increase the data rates through enhancements in the PHY layer, 802.11e [802-11e] was released in 2005 to enhance the WiFi medium access control (MAC) for supporting quality of service (QoS). To achieve QoS, delay sensitive traffic, such as voice and video, must be given priority over delay-tolerant traffic, such as web browsing and file transfer. 802.11e provided the necessary protocol support at the MAC layer to achieve that.

802.11e achieves QoS by introducing a Hybrid Coordination Function (HCF) for MAC. HCF allows both contention-free access using a Point Cordination Function (PCF), where the stations are polled by the access point. When PCF is used, stations cannot attempt to access the channel unless the AP provides access to it, which eliminates contentions. On the other hand, the stations can also use a contention-based access, called Enhanced Distributed Control Function (EDCF), where they can contend for the medium access, but with priority assigned for each packet based on the type of service.

Basically, EDCF achieves priority by implementing four separate priority queues within the station (see Figure 5.2). When a packet is delivered to the MAC from the upper layer, it is queued in the appropriate queue based on the priority required for the service. Each queue has separate values for the transmission parameters, such as the minim and maximum congestion window values.

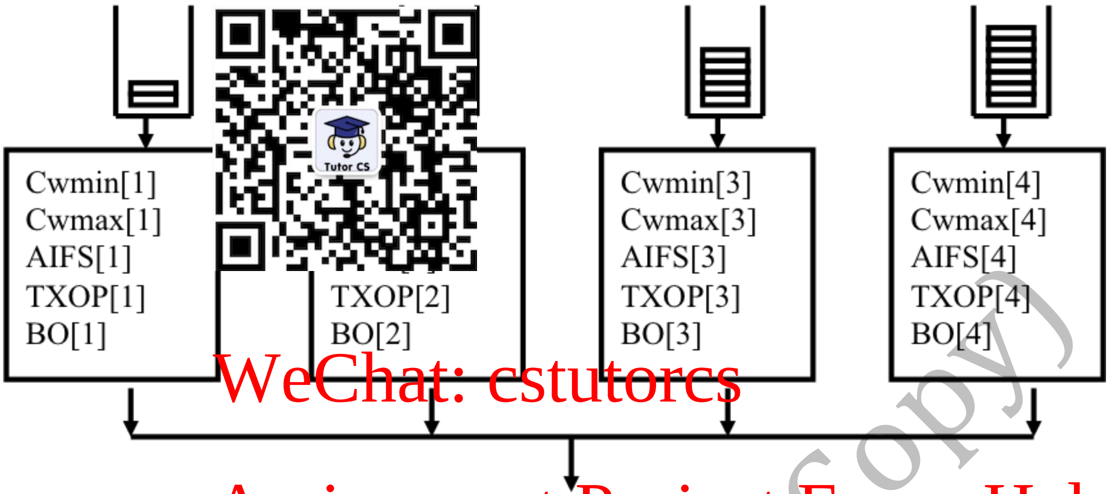

Figure 5.2 Priority queuing in enhanced DCF

Frame Bursting

802.11e also introduces batch transmission of multiple frames, which is called frame bursting. Instead of sending one frame at a time, a station can request, in an RTS packet for example, for a maximum transmission opportunity (TXOP) duration and send multiple frames back-to-back within that time. The receiver can then acknowledge all the frames together instead of acknowledging them one by one. Voice or gaming has high priority, but allowed to use small TXOP. In contrast, data has low priority but can access long TXOP to send many frames in burst. Figure 5.3 shows how EDCF TXOP works.

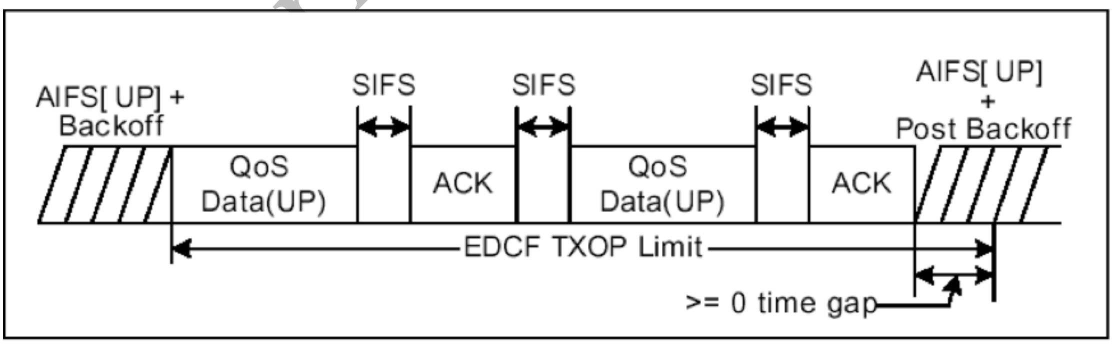

Figure 5.3 Frame bursting with TXOP

Direct Link

Another new feature allowed in 802.11e is to allow stations to send packets directly to another station within the same BSS without going through the BS. Figure 5.4 illustrates this feature. This will further reduce the latency for some delay-sensitive communication.

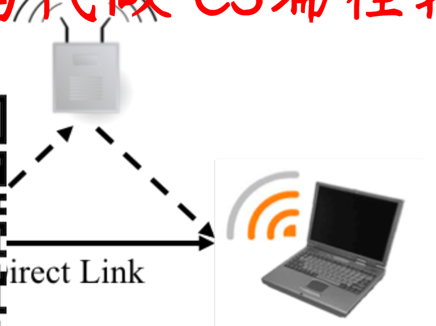

Figure 5.4 The direct link feature in 802.11e

5.8 IEEE 802.11n-2009

The data rate of 54 Mbps achieved in 1999 with 802.11b served the application demands well at that time. Since then, demand for more bandwidth continued to soar fueled by more devices being connected to the LAN, growing popularity of on-demand video streaming, and so on. In late 2000, it became apparent that new amendments must come forth to boost the speed and capacity of wireless LANs. In fact, some vendors already started to release products with some proprietary enhancements to meet the market demand. It was time to standardize these developments.

In 2009, IEEE introduced 802.11n [802-11n] to significantly increase the data rates of wireless LAN from the previous versions of 802.11a/b/g. The target was to break the 100 Mbps mark and go well beyond that. To achieve this major WiFi data rate boost in history, 802.11n introduced five important techniques, which promised a massive maximum data rate of 600 Mbps.

First, it employed the MIMO technology in WiFi history for the first time to capitalize on the potential of multiple independent streams existing over the same frequency. Second, it reduced the *coding overhead* by employing a 5/6 coding rate which is much lower than the previous minimum allowed rate of ¾ used in 802.11a. Third, the *guard interval* and *inter-frame spacing* were reduced to increase the number of OFDM sub-carriers that can carry data. Fourth, it allowed a new physical layer mechanism, called *channel bonding*, to combine two consecutive 20-MHz channels into a single 40-MHz channel without any guard intervals between them. Fifth, it promoted reduction of MAC layer overhead by packing multiple frames inside a single frame, called *frame aggregation*, thereby amortizing the frame header bits over many data bits.

5.8.1 MIMO: Number of antennas and number of streams

Recall from our earlier discussion on MIMO that multiple antennas at the transmitter and the receiver help transmit data in multiple simultaneous *independent* streams. Clearly, the larger the number of these independent streams, the higher the effective data rates. However, the maximum number of independent streams are limited by the minimum number of antennas available at the transmitter or receiver. The individual implementations may further reduce the number of independent streams limiting the total capacity of the MIMO infrastructure.

The convention n x m: k is used to describe the number of antennas and streams in a given system, w[illegible] of available antennas in the transmitter and m is the number of a[illegible]ver. The number of streams is represented by k, where k is less t[illegible]xample, 4 x 2: 2 means that the transmitter has 4 antennas, but th[illegible]. Only 2 parallel streams are used to transmit the data in this confi[illegible]

802.11n allows [illegible]: 4 configurations. When there are more receive antennas than the number of streams, then the throughput can be maximized by selecting the best subset of antennas. For example, with a 4 x 3: 2 configuration, the best 2 receive antennas should be selected for processing the received data.

5.8.2 Reduction of Coding Overhead

Recall that the coding rate directly affects the net data rates. Given the raw bit rate, C_raw, of a channel, which shows the number of coded bits transmitted per second, the net data rate, C_data, is derived as C_data = C_raw x C_rate, where C_rate is the fraction representing the coding rate.

Previously, ¾ was the minimum coding rate allowed in any 802.11 amendments. 802.11n allows a coding rate as low as 5/6, which directly increases net data rate by a factor of (5/6)/(3/4) = 11%. Of course, this 11% increase in data rate is entirely due to the reduction of the coding rate. As we will see in the remaining of this section, the ultimate data rate boost will be much more than this, once all other techniques are employed simultaneously.

5.8.3 Reduction of Guard Interval and Increase of Data Sub-carriers

Guard intervals are time-domain guards used between every two consecutive data symbol transmissions to overcome the effect of multipath or inter-symbol interference at the receiver. A direct consequence of guard interval is the reduction of data rates, as no data can be transmitted during the guard interval. Clearly, data rate can be increased by using shorter guard intervals between two data symbols. Figure 5.5 illustrates how by reducing the guard interval slightly, 6 data symbols can be transmitted instead of 5 during the same time interval. 802.11n therefore targets reduction of guard interval as another means for increasing the net data rate.

The rule of thumb is to allow a guard interval four times the multi-path delay spread. Initial 802.11a design assumed 200ns delay spread, which lead to 800 ns guard interval. For 3200 ns data blocks, this incurs a overhead of 800/(800+3200)=20%. Detailed experimental analysis revealed that most indoor environments have a delay spread in the range of 50-75 ns. 802.11n therefore selects a guard interval of 400 ns, which is more than four times this value. Now the guard interval related overhead is reduced from 20% to only 11%.

With reduced guard intervals in time domain, the number of sub-carriers used for guard is reduced from 6 to 4 on either side of the data subcarrier block. This directly increases the data sub-carriers from 48 to 52 for the legacy 20-MHz channels, which will directly increase the number of data bits per OFDM symbol and hence the ultimate net data rates.

Finally, 802.11n [illegible] ving option for MIMO, which allows putting antennas to slee[illegible] ay the power saving is extended beyond stations, i.e., the antenna [illegible] activated even when the station is awake.

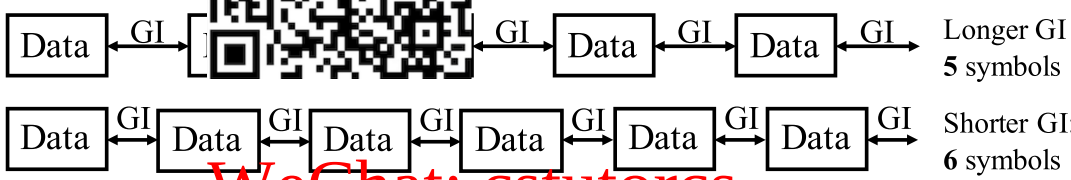

Figure 5.5 Increasing data rate by decreasing guard interval

5.8.4 Reduction of Inter-frame Spacing

At the MAC layer, frame spacing is needed to improve medium access control, but it directly reduces net data rates. It is therefore possible to improve data rates by reducing the inter-frame spacing. 802.11n reduces the inter-frame spacing (SIFS) from 10 microsecond to 2 microsecond.

5.8.5 Channel Bonding

The Channel Bonding option in 802.11n refers to the mechanism to combine two 20-MHz channels into a single 40-MHz channel. The bonding therefore directly doubles the bandwidth of the channel. This means that the data rate will be at least double the legacy 20-MHz channel. This will allow very high-speed links, which may be required to watch a very high-resolution video, such as 4K, over the wireless LAN. We will see shortly that the channel bonding actually increases data rate by more than a factor of two!

In the frequency-domain, guard bands are used between two consecutive channels to reduce interference. One way to reduce this guard overhead is to use wider channels, so the guard overhead is amortized over a larger bandwidth. This bonded 40-MHz channel can be operated with 108 data subcarriers plus 6 pilots. Note that, without channel bonding, only 52 data subcarriers can be used with 4 pilots. Therefore, combining two channels with channel bonding actually provides more than double the performance (108 data subcarriers instead of 52+52=104 subcarriers)!

Example 5.3

Compared to 802.11a/g, 802.11n has higher coding rate, wider channel bandwidth, lower coding overhead, and reduced guard interval. On top of this, 802.11n uses MIMO multiplexing to further boost the data rate. Given that 802.11a/g has a maximum data rate of 54 Mbps, can you estimate the maximum data rate for 802.11n that uses 4 MIMO streams (assume 64 QAM for both of them, i.e., there is no improvement in modulation)?

Solution:

Let us first estimate the maximum data rate of 802.11n by adding up the various factors that increase data rates compared to 802.11a/g.

54 Mbps is achi… or 3200 Data+800 GI for a/g, which basically uses a single stre…
802.11n has the … ent factors:

Streamin…

Coding f… ~1.11

OFDM s… bandwidth) factor = (108/48) = 2.25

Guard interval factor = (3200+800)/(3200+400) = ~1.11

Total improvement factor = 4x1.11x2.25x1.11 = ~**11.1**

Improved data rate for 802.11n =
4×[(5/6)/(3/4)]×(108/48)×[(3200+800)/(3200+400)]×54 = **600 Mbps**

We can also arrive at the 600 Mbps rate by directly calculating the data rate for 802.11n from its various parameters as follows: Minimum guard interval: 400ns (data interval=3200ns) → 3.6μs symbol interval

Maximum modulation: 64 QAM
Maximum coding: 5/6
Maximum # of MIMO streams: 4 (4x4 MIMO)
Maximum # of data carriers: 108 (for 40MHz bonded channels)
Coded bits per symbol = $\log_2 64$ ✗ #-of-data-subcarriers = 6x108 = 648
Data bits per symbol = coding rate x 648 = 5/6 x 648 = 540
Symbol rate = 1/symbol-interval = 1/3.6Msps
Data rate (single MIMO stream) = symbol rate x data bits per symbol = 1/3.6 x 540 Mbps = **150 Mbps**
Data rate with 4 streams = 4 x 150 = 600 Mbps

Available data rates for 802.11n for a single stream is shown in Table 5.4. These data rates will increase linearly with increasing number of streams. For example, with 3 streams, the data rate for MCS 3 would be 3x26=78 Mbps for 20 MHz channel with 800ns symbol interval.

Table 5.4 Modulation, coding, and data rates for 802.11n: Single Stream

MCS index	Spatial streams	[illegible]	[illegible]	Data rate (Mbit/s)			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	[illegible]	[illegible]	6.5	7.2	13.5	15
1	1	[illegible]	[illegible]	13	14.4	27	30
2	1	QPSK	3/4	19.5	21.7	40.5	45
3	1	16-QAM	1/2	26	28.9	54	60
4	1	16-QAM	3/4	39	43.3	81	90
5	1	64-QAM	2/3	52	57.8	108	120
6	1	64-QAM	3/4	58.5	65	121.5	135
7	1	64-QAM	5/6	65	72.2	135	150

5.8.6 MAC Header Overhead Reduction using Frame Aggregation

Each layer receives a service data unit (SDU) as its input from the upper layer, and then packs it up into a protocol data unit (PDU) as its output as output to communicate with the corresponding layer at the other end. Each MAC PDU has a header and a payload. The header bits are considered overhead, which reduces the net data rate for the payload. This overhead can be large for small payloads. For example, when someone is typing using a remote terminal, each typed character forms a TCP segment, which is transmitted in a single MAC PDU.

Frame aggregation is proposed in 802.11n to amortize the frame header overhead over a large payload by combining multiple short payloads into a single one. This process is shown in Figure 5.6. Obviously, this is possible when many such small payloads are generated for the same destination within short intervals. For example, for someone typing fast, the consecutive characters are generated within milliseconds, which provides an opportunity to exercise the frame aggregation option without delaying the data noticeably.

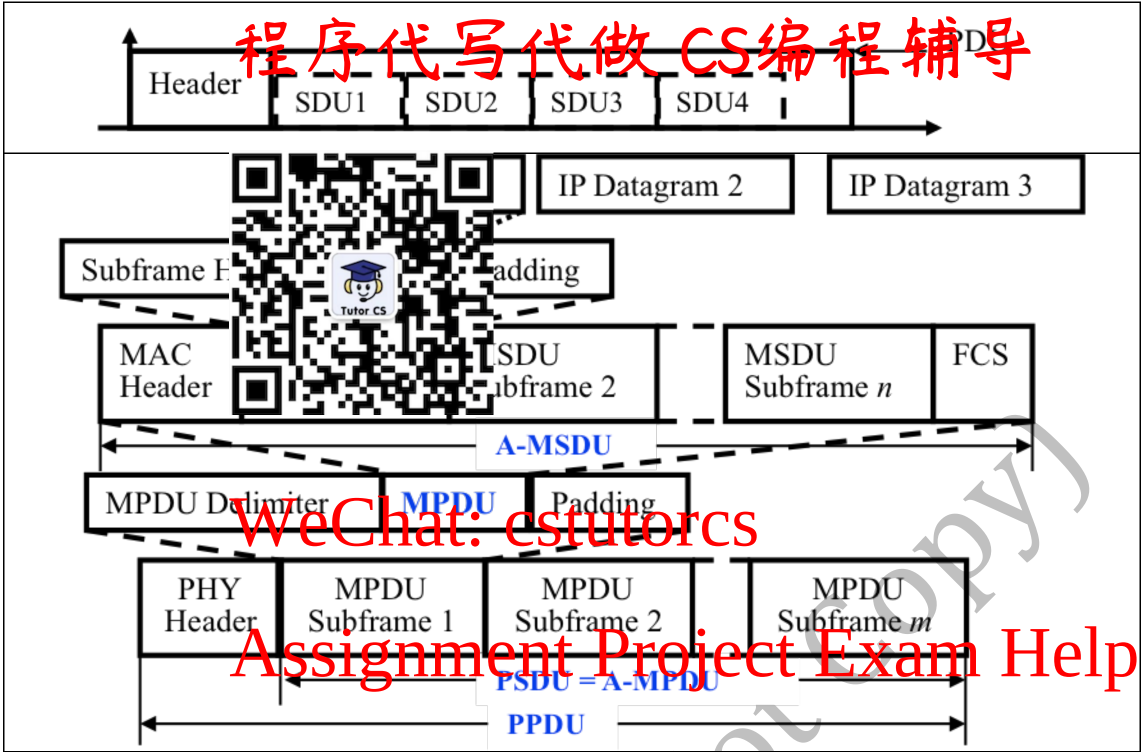

Figure 5.6 Frame aggregation in 802.11n: Multiple SDUs in one PDU, where all SDUs must have the same transmitter and receiver address (top), and illustration from IP layer (bottom)

5.8.7 802.11n Channel State Information

High Throughput Control (HTC) is a new field added to 802.11n frames (see Figure 5.7). A key information carried in this field is the channel state information (CSI). In general, CSI refers to information regarding the channel properties of a communication link between the transmitter antenna and the receiver antenna. This information helps understand how scattering, fading, etc. may affect the channel. CSI can help both ends of the link to take actions which optimize the channel capacity.

For the receiver, it can usually derive the CSI from the pilots embedded in the transmission, but the transmitter cannot learn the CSI directly, unless the receiver communicates this information back to the transmitter. The CSI field can be used by the 802.11n client stations to send this information to the AP, and vice versa.

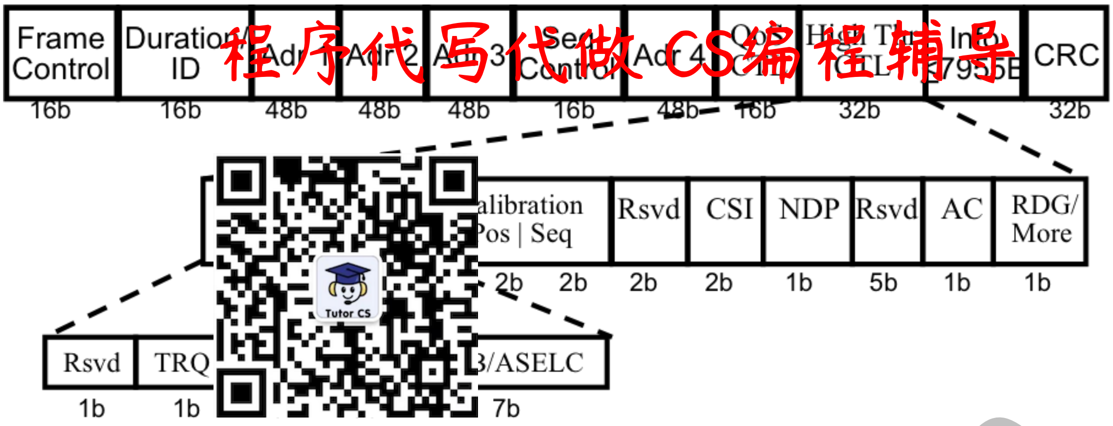

Figure 5.7 802.11n MAC frame and the CSI field

5.9 IEEE 802.11ac

The race for higher data rates continues. While the goal with 802.11n was to break the 100 Mbps mark, 802.11ac aims to hit the Gbps mark. To achieve this incredible rate at the existing 5GHz ISM band, 802.11ac basically continues to tighten the 802.11n parameters to squeeze more bits out of the same spectrum. These include more aggressive channel bonding, modulation, spatial streaming and piloting. A further notable enhancement in 802.11ac [802-11ac] is to enable multi-user MIMO (MU-MIMO), which allows it to benefit from the MIMO technology introduced in 802.11n even when user equipment do not support multiple antennas. We will first examine the parameter updates for data rate increase followed by the discussion on MU-MIMO.

5.9.1 Data Rate Increase

Several parameters have been updated in 802.11ac to boost the data rate significantly. First, 802.11ac supports 80 MHz and 160 MHz channels, which is a significant jump from the 20 MHz and 40 MHz channels used in its predecessor 802.11n. Second, it allows 256-QAM modulation, which yields an 8/6=1.33x throughput increase over the previous maximum of 64-QAM. Third, it supports 8 spatial streams for MIMO, which is a two-fold increase from 802.11n. Finally, it proposes to use a smaller number of pilots to increase the number of data subcarriers and ultimately boost the data rates. Table 5.5 shows the combination of data and pilot subcarriers for different channel bandwidths, while the available data rates for a single stream 802.11ac are summarized in Table 5.6. Note that 802.11ac continues to use the same subcarrier spacing of 312.5 kHz as used in 802.11a/g/n.

Table 5.5 Data and pilot subcarriers for in 802.11ac

Bandwidth	# of Data Subcarriers	# of Pilot Subcarriers
20 MHz	52	4
40 MHz	108	6
80 MHz	234	8

160 MHz	468	16

Table 5.6 Modulation, coding, and data rates for 802.11ac. Single Stream

MCS index[b]	Modulation type	[illegible]	20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			[illegible]	400 ns GI	800 ns GI	400 ns GI	800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	BPSK	[illegible]	[illegible]	7.2	13.5	15	29.3	32.5	58.5	65
1	QPSK	[illegible]	[illegible]	14.4	27	30	58.5	65	117	130
2	QPSK	[illegible]	[illegible]	21.7	40.5	45	87.8	97.5	175.5	195
3	16-QAM	1/2	26	28.9	54	60	117	130	234	260
4	16-QAM	3/4	39	43.3	81	90	175.5	195	351	390
5	64-QAM	2/3	52	57.8	108	120	234	260	468	520
6	64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585
7	64-QAM	5/6	65	72.2	135	150	292.5	325	585	650
8	256-QAM	3/4	78	86.7	162	180	351	390	702	780
9	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7

Example 5.4

Calculate the maximum achievable data rate for an 802.11ac mobile client with a *single antenna*.

Solution:

Single antenna → only 1 stream possible (even if the AP has many antennas)
Minimum guard interval: 400ns (data interval=3200ns) → 3.6µs symbol interval
Maximum modulation: 256 QAM
Maximum coding: 5/6
Maximum # of data carriers: 468 (for 160MHz bonded channels)
Coded bits per symbol = $\log_2 256$ ✗ #-of-data-subcarriers = 8x468 = 3744
Data bits per symbol = coding rate x 3744 = 5/6 x 3744 = 3120
Symbol rate = 1/symbol-interval = 1/3.6Msps
Data rate (single MIMO stream) = symbol rate x data bits per symbol = 1/3.6 x 3120 Mbps = 866.67 Mbps

---

Example 5.5

An 802.11ac mobile client fitted with two antennas is connected to a wireless LAN via an 802.11ac access point equipped with four antennas. Calculate the maximum achievable data rate for the mobile client.

Solution:

Max. # of streams = min(2,4) = 2
Max. data rate with single stream(from previous example) = 866.67 Mbps
Therefore, max. data rate with 2 streams = 2x866.67 Mbps = 1.733 Gbps

---

Example 5.6

What is the max [illegible] a rate in 802.11ac?

Solution:

802.11ac allows a maximum of **8** MIMO streams
Maximum achievable with single stream = **866.67** Mbps
Maximum achievable data rate of 802.11ac = 8x866.67 = **6.9** Gbps

---

5.9.2. MU-MIMO

MU-MIMO extends the concept of MIMO over multiple users. In MU-MIMO, the user equipment does not have to have multiple antennas on it to benefit from MIMO. Antennas at different user equipment can be combined seamlessly and transparently to form a MIMO system as illustrated in Figure 5.8. The users do not even have to know that their antennas are being used in a MIMO system. Figure 5.9 further illustrates the utility of MU-MIMO with flexible sharing of streams among client devices with different antenna capabilities.

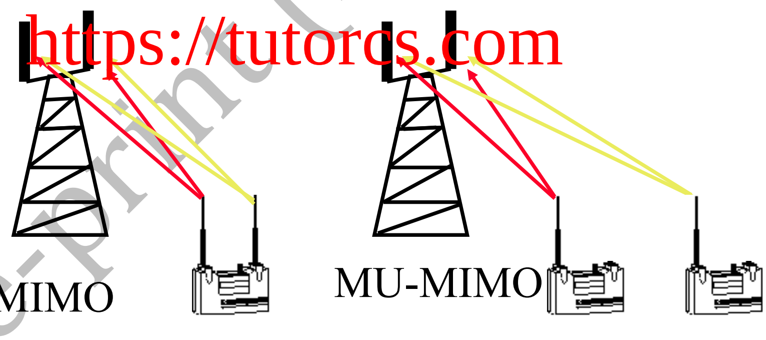

Figure 5.8 MU-MIMO used in 802.11ac

Figure 5.9 The top figure illustrates the conventional case where all MIMO streams are consumed by a single multi-antenna device. The bottom figure shows that with MU MIMO, multiple client devices can share the MIMO streams generated by the transmitter, which enables even single-antenna devices to take part in the MIMO transmission.

5.10 802.11ax-2020

Up until now, 802.11 evolution was purely driven by pushing the data rates and throughput. From the humble 2Mbps in 1997 with 802.11 legacy, we have reached to ~7Gbps in 2013 with 802.1111ac, which is an amazing increase of 3500X in just 16 years!

Unfortunately, WiFi is being deployed so densely, especially in urban areas, that we cannot really use all that speed due to congestion, collisions, and interference from neighbouring installations. A new amendment was in order that could work efficiently in dense deployments and also support the new type of short message communications between IoT machines.

802.11ax [802-11ax, 802-11ax-TUT] is therefore more about efficiency for such new environments than pushing the data rates. As a matter of fact, 802.11ax provides only a modest data rate increase of 37% against its predecessor 802.11ac; whereas 1802.11ac increased data rate by 10X compared to 802.11n. The new developments and the ensuing data rates are explained in this chapter.

5.10.1 Parameters of 802.11ax

While some WiFi parameters remain unchanged, 802.11ax does introduce some changes for the others. These are discussed below.

Band: 802.11ax supports both 2.4GHz and 5GHz bands.

Coding rate: The he coding rate; 5/6 remains the maximum allowed coding r

Channel width: ange for the allowed channel width, i.e. 40MHz and 160MHz rer or 2.4GHz and 5GHz bands, respectively.

MIMO streams: 802.11ax maintains the maximum number of MIMO streams to 8 only.

Modulation: 802.11ax supports an increased modulation rate of up to 1024 QAM.

Symbol interval: 802.11ax uses increased symbol intervals to address longer delay spread in challenging outdoor environments. Symbol data interval is increased to 12.8µs (vs. 3.2µs in 11a/g/n/ac) while the guard interval is also increased to 0.8µs, 1.6µs, or 3.2µs (3 options).

OFDM subcarrier: subcarrier spacing is reduced to 78.125 kHz (vs. 312.5kHz in 11a/g/n/ac), which yields a total number of subcarriers as follows: 256 for 20MHz, 512 for 40MHz, 1024 for 80MHz, and 2048 for 160MHz, which includes two new types of subcarriers, DC and null subcarriers, in addition to the conventional data, pilot, and guard subcarriers used in previous WiFi versions. The number of data carriers available are as follows: 234 for 20MHz, 468 for 40MHz, 980 for 80MHz, and 1960 for 160MHz.

802.11ax OFDM parameters along with the allowed modulation and coding combinations are summarised in Table 5.7 and the data rates are shown in Table 5.8.

Example 5.7

Calculate the maximum achievable data rate for 802.11ax OFDM

Solution:

Minimum guard interval: 0.8µs (data interval=12.8µs) → 13.6µs symbol interval
Maximum modulation: 1024 QAM
Maximum coding: 5/6
Maximum # of MIMO streams: 8
Maximum # of OFDM data subcarriers: 1960 (for 160MHz channels)
Coded bits per symbol = log21024 ✗ #data-subcarriers = 10x1960 = 19600
Data bits per symbol = coding rate x 19600 = 5/6 x 19600 = 16333.33
Symbol rate = 1/symbol-interval = 1/13.6Msps
Data rate (single MIMO stream) = symbol rate x data bits per symbol = 1/13.6 x 5/6 x 19600 Mbps = 1.2 Gbps
Data rate with 8 streams = 8 x 1.2 = 9.6 Gbps

Table 5.7 IEEE 802.11ax OFDM parameters									
Modulation	Codin[illegible]	# of Data Subcarriers				Symbol Data Interval	Guard Interval		
		[illegible]	[illegible]MHz	80MHz	160MHz		Short	Med	Long
BPSK	1/2	234	468	980	1960	12.8µs	0.8µs	1.6µs	3.2µs
QPSK	½,3[illegible]								
16QAM	½,3[illegible]								
64QAM	½,2/3,3/4								
256QAM	2/3,5/6								
1024QAM	¾,5/6								

Table 5.8 IEEE 802.11ax OFDM data rates in Mbps: Single Stream

MCS Index	Spatial Stream	Modulation	Coding	20MHz 0.8µs GI	20MHz 1.6µs GI	20MHz 3.2µs GI	40MHz 0.8µs GI	40MHz 1.6µs GI	40MHz 3.2µs GI	80MHz 0.8µs GI	80MHz 1.6µs GI	80MHz 3.2µs GI	160MHz 0.8µs GI	160MHz 1.6µs GI	160MHz 3.2µs GI
0	1	BPSQ	1/2	8.6	8.1	7.3	17.2	16.3	14.6	36.0	34.0	30.6	72.1	68.1	61.3
1	1	QPSK	1/2	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
2	1	QPSK	3/4	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
3	1	16-QAM	1/2	34.4	32.5	29.3	68.8	65.0	58.5	144.1	136.1	122.5	288.2	272.2	245.0
4	1	16-QAM	3/4	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
5	1	64-QAM	2/3	68.8	65.0	58.5	137.6	130.0	117.0	288.2	272.2	245.0	576.5	544.4	490.0
6	1	64-QAM	3/4	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
7	1	64-QAM	5/6	86.0	81.3	73.1	172.1	162.5	146.3	360.3	340.3	306.3	720.6	680.6	612.5
8	1	256-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
9	1	256-QAM	5/6	114.7	108.3	97.5	229.4	216.7	195.0	480.4	453.7	408.3	960.8	907.4	816.7
10	1	1024-QAM	3/4	129.0	121.9	109.7	258.1	243.8	219.4	540.4	510.4	459.4	1080.9	1020.8	918.8
11	1	1024-QAM	5/6	143.4	135.4	121.9	286.8	270.8	243.8	600.5	567.1	510.4	1201.0	1134.3	1020.8

5.10.2 OFDMA

OFDMA, which stands for Orthogonal Frequency Division Multiple Access, has been used in cellular networks for many years. In WiFi networks, it is introduced for the first time as an option in 802.11ax to centrally allocate channel resources to each competing station using fine-grained time and frequency resource units (RUs) just like cellular networks. In OFDMA, subcarriers are also called *tones*; thus each tone consists of a single subcarrier of 78.125 kHz bandwidth. The tones are then grouped into 6 different sizes of resource units (RUs): 26, 52, 106, 242, 484, or 996 tones. The smallest resource, i.e. 26 tones, allocated to an OFDMA communication is approximately 2MHz (26x78.125kHz = 2031.25kHz), while the largest RU has ~80MHz (996x78.125kHz = 77812.5kHz). A station can have a maximum of two 996 tones allocated, which would occupy ~160MHz of bandwidth.

Table 5.9 IEEE 802.11ax resource units				
RU	20MHz	40MHz	80MHz	160(80+80)MHz
26-tone	9	18	37	74
52-tone	4^{+1}	8^{+2}	16^{+5}	32^{+10}
106-tone	2^{+1}	4^{+2}	8^{+5}	16^{+10}
242-tone	1	2	4^{+1}	8^{+2}
484-tone	NA	1	2^{+1}	4^{+2}

996-tone	NA	NA	1	2

Different RUs can be mixed together to achieve enhanced flexibility required in many practical deploy[illegible], to allocate ~20MHz to a station, the AP can either allocate a [illegible]U (242 subcarriers), or it can allocate 4 52-tone RUs plus a sing[illegible]4 subcarriers) to the station. Table 5.9 shows the RU allocations [illegible]andwidths expected in WiFi networks, where $^{+n}$ means 'plus n [illegible]xample, to allocate ~20MHz, the access point would allocate 4[illegible]26-tone, which results in a total of 4x52+26=234 subcarriers alloc[illegible]

Example 5.8

A single antenna 802.11ax client receives a 26-tone RU allocation from the AP when trying to transmit a 147-byte data frame. What could be the minimum possible time required to transmit the frame?

Solution:

Single antenna means single stream
Maximum data rate for single-stream 26-tone (1024-QAM@5/6, 0.8μs GI) = 14.7Mbps
Data frame length in bits: 147x8 bits
Minimum frame transmission time: (147x8)/14.7μs = 80μs

5.11 The upcoming amendment: 802.11be-2024

While the latest release, 802.11ax, is perfectly capable to meet the data rates and networking needs of current applications, IEEE continues to work on further advancing the technology to ensure that WiFi remains future-proof and scalable. The work for the next amendment therefore has already began at IEEE under the task group called 802.11be [802-11be, 802-11be-LOPEZ] Extremely High Throughput. 802.11be is expected to be released in 2024 supporting data rates in tens of Gbps along with several advanced features to make WiFi even more scalable.

5.11.1 Parameters and Data Rates

Data rates for 802.1be will be increased by enhancing several parameters in parallel. The most significant enhancement will be the doubling of the maximum allowable channel bandwidth from 160MHz to 320MHz. This will be achieved by allowing WiFi to access the unlicensed spectrum in the 6GHz band for the first time. To increase the number of bits per symbol, 802.11be will further use 4096 QAM. Finally, it will take advantage of higher processor powers in future chips to allow for 16 MIMO streams, doubling the number of spatial streams from its predecessor. These planned improvements are summarized in Table 5.10.

Table 5.10 Comparison of 802.11be with previous amendments

Parameter	802.11n	802.11ac	802.11ax	802.11be

Band	2.4/5GHz	5Ghz	2.4/5GHz	2.4/5/6GHz
Max. Channel Bandwidth	40MHz	160MHz	160MHz	320MHz
Max Modulation	64QAM	256QAM	1024QAM	4096QAM
MIMO	[illegible]	4 streams	8 streams	16 streams
Max. Data Rate	[illegible]	6.9Gbps	9.6Gbps	46Gbps

Example 5.9

Calculate the ma[illegible]802.11be.

Solution:

Enhancements against 802.11ax:

Channel bandwidth factor: 320MHz/160MHz = 2
Modulation factor: 12 bits/symbol ($\log_2 1024=10$)/10 bits/symbol ($\log_2 4096=12$) = 1.2
MIMO factor = 16 streams/8 streams = 2

Thereforem 802.11be is expected to achieve a 4.8X (2x1.2x2 = 4.8) improvement against 802.11ax.

Given that 802.11ax has a maximum data rate of 9.6Gbps, 802.11be is expected to achieve a maximum data rate of 4.8x9.6 = 46.08Gbps.

5.11.2 New Features

Besides directly increasing the data rate through enhancements in bandwidth, modulation, and MIMO, 802.11be plans to introduce several new features. Here we examine two interesting new features that have not been used in previous WiFi.

Multiband communication: 802.11be will be standardized to operate over three distinct bands, 2.4GHz, 5GHz, and 6GHz. The multiband communication refers to accessing all three bands simultaneously to increase the throughput or reliability as illustrated in Figure 5.10.

Multi-AP coordination: Two or more APs can coordinate to serve the local clients in a given area to improve the spectral efficiency and quality of experience for the users. Figure 5.11 illustrates one use case for such coordinated communications where AP1 serves the downlink traffic, while the uplink is handled by AP2.

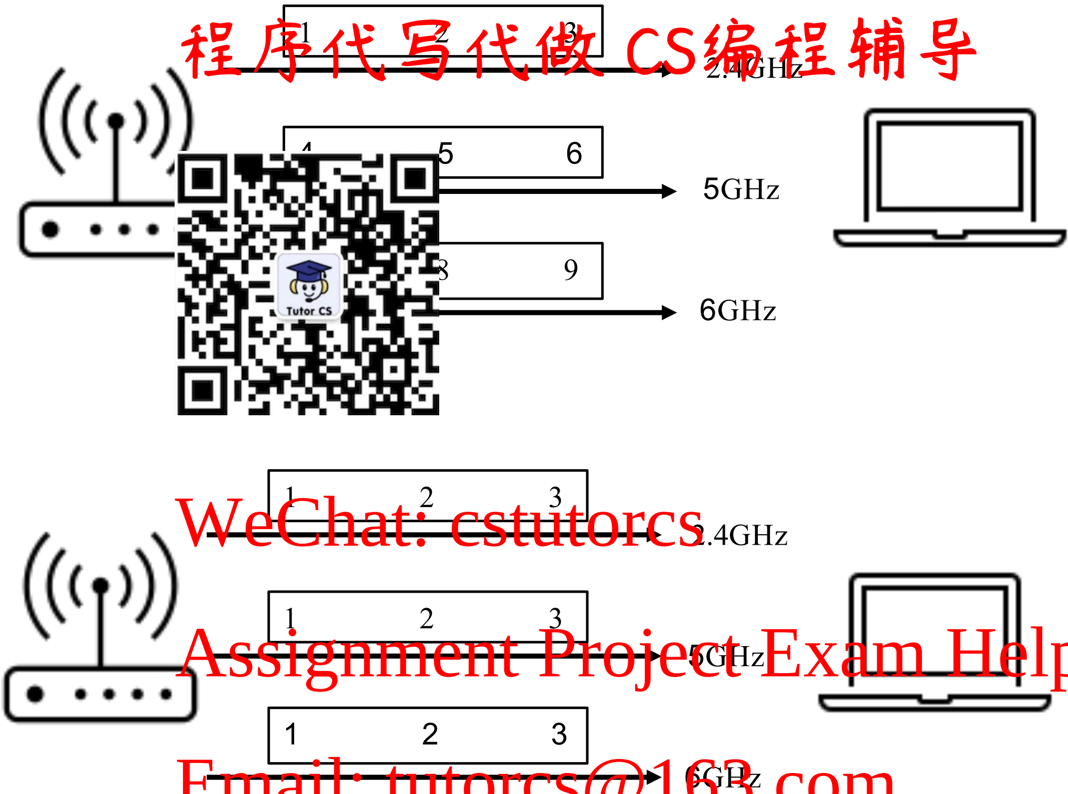

Figure 5.10 Illustration of multiband transmissions: improving **throughput** by allocating data from one traffic stream to multiple bands (top); improving **reliability** by sending duplicate data from one traffic stream over multiple bands (bottom);

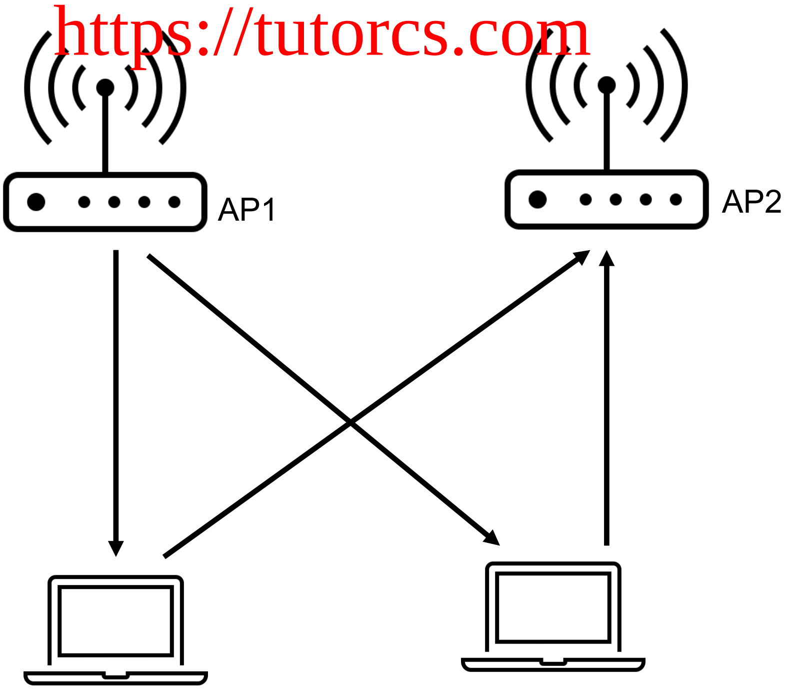

Figure 5.11 Multi-AP coordination. Downlink is handled by AP1, while AP2 handles the uplink.

5.12 Chapter Summary

1. 802.11a/g use OFDM with 64 subcarriers in 20 MHz, which includes 48 Data, 4 Pilot, 1 [illegible]
2. 802.11e i[illegible] with different AIFS and TXOP durations and a QoS fiel[illegible]e enhanced support for QoS.
3. 802.11n [illegible]ation, dual band, and channel bonding.
4. IEEE 80[illegible]i-user MIMO with 80+80 MHz channels with 256-QA[illegible]ive 6.9 Gbps
5. IEEE 80[illegible]QAM, reduces OFDM carrier spacing to 78.125kHz and increases data symbol interval to 12.8μs. It introduced OFDMA.
6. 802.11be expects to increase data rates up to 46Gbps by using 4096 QAM, 320MHz channel bandwidth, and 16 MIMO streams. It uses 6GHz band along with 2.4GHz and 5GHz.

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End of Chap 5 (Wireless and Mobile Networking, M. Hassan, 2022, CRC Press)