The Impact of Wi-Fi 7 on Cable Networks

A Technical Paper prepared for SCTE by

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1. Introduction

Today, Wi-Fi is the predominant way telecommunication customers connect their untethered devices to the Internet, as well as access content like video, virtual reality, and gaming. In the near future, operators will shift compute closer to the end user, expanding the requirements for better Wi-Fi edge compute connectivity. The original Institute of Electronics Engineers (IEEE) 802.11 standard was released in 1997. Since then, the IEEE 802.11 working group has developed and released many amendments to keep up with the growing bandwidth demands of our customers and the industry. During this time, telecommunication operators, CableLabs®, the SCTE®, and vendors developed and deployed DOCSIS and other access network technologies to keep up with the same bandwidth demands.

Today operators are moving towards multi-gigabit offerings and are deploying Wi-Fi solutions using Wi-Fi 6 and Wi-Fi 6E customer premises equipment (CPE) to support these offerings. With the telecommunication industry on the road to 10G and beyond, the wireless industry is working on the next generation Wi-Fi standard, IEEE 802.11be, extremely high throughput (EHT). The IEEE 802.11be task group, or just 802.11be, is leading the development of the EHT amendment to the IEEE 802.11 standard. 802.11be is the amendment on which the Wi-Fi Alliance® Wi-Fi 7 certification will be based.

The 802.11be amendment is currently being developed and is scheduled to be released in May 2024. To help meet the tight development timeline, 802.11be has two sets of release features known as Release 1 and Release 2. The Release 1 features are outlined in Draft 1.0 and Draft 2.0 of the amendment. The Release 2 features will be defined in Draft 3.0 and Draft 4.0. Figure 1 depicts the development timeline, which the 802.11be task group continually evaluates. The Wi-Fi Alliance Wi-Fi 7 certification requirements will be released closer to the end of the 802.11be development cycle, close to the final amendment.

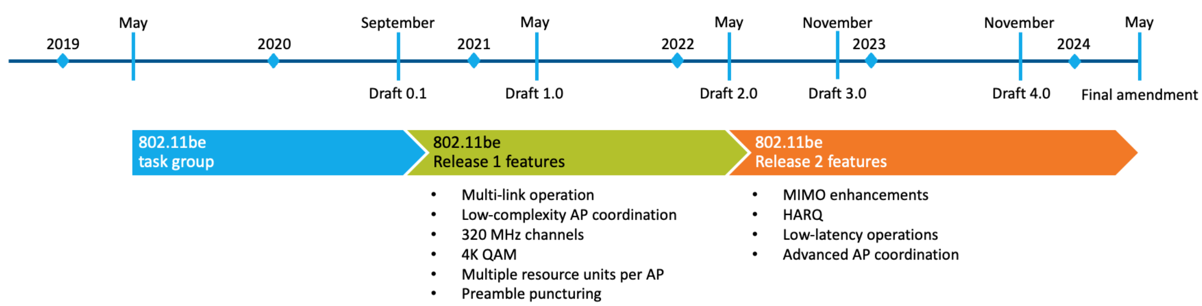


Figure 1 – 802.11be Release Timeline

This paper will explore the 802.11be releases and their features, along with key media access control (MAC) and key physical (PHY) layer techniques. Furthermore, the paper will explore how Wi-Fi 7 will impact the customer quality of experience (QoE) and enable telecommunication operators to support their 10G platform initiatives all the way to the customer premises.

2. The 10G pillars

As connectivity, in particular, Wi-Fi, becomes more crucial to how we live, work, learn, and play, we need a network that will support the hyper-connectivity of our future customers. In 2019, the industry announced the next leap forward in connectivity with the 10G platform, which also encompasses Wi-Fi.

The NCTA–The Internet & Television Association, CableLabs, GIGAEurope, and SCTE have been driving this initiative and the platform forward in the industry.

The 10G platform initiative is a combination of technologies that will deliver multi-gigabit symmetrical Internet services to our consumers in the United States and around the globe. The Wi-Fi 7 certification will dovetail neatly with our intelligent 10G platform initiative in the telecommunication industry. 10G will ensure our customers gain access to the most advanced infrastructure in the marketplace and over Wi-Fi. The pillars of the 10G network span across throughput/speed, low latency, reliability, and scalable security. These pillars will allow our customers to take full advantage of future services over a Wi-Fi network. These customers may be residential, multiple dwelling units (MDU), or business services.

The throughput/speed pillar focuses on consumer bandwidth, enabling Wi-Fi EHT as well as multi-gigabit symmetrical experiences. The low latency pillar delivers on customer QoE, enabling future augmented reality (AR), virtual reality (VR), artificial intelligence (AI), and new digital Wi-Fi experiences like holodecks and lightfield displays. A poor Wi-Fi connection that adds a delay of a few milliseconds (ms) will produce negative user experiences. Lower latency will reduce jitter and delay in a Wi-Fi network, optimizing its performance. While the reliability pillar addresses Wi-Fi network issues proactivity before they inhibit our networks and customers. Wi-Fi network reliability will be required to grow as our consumer devices increase per household or per business. Finally, the security pillar strengthens our more complex Wi-Fi networks' confidentiality, integrity, and availability (CIA) triad, enabling safer symmetrical communications for all.

10G

Figure 2 – 10G

3. Why Wi-Fi 7?

The simple answer to "Why Wi-Fi 7?" is speed. While that is a good answer, especially when considering new features such as wide 320 MHz channels and dense 4K quadrature amplification modulation (QAM). These features enable a potential data rate of 30 to 40 Gbps. However, that does not tell the entire story here.

Many of the features for Wi-Fi 7 are designed to make better use of the available RF bandwidth. With the release of the 6 GHz band, up to 1.2 GHz of new spectrum became available in the USA and other parts of the world. Some areas, such as Europe, only have 500 MHz available initially, but that is still an incredible amount of new bandwidth. However, when designing the 802.11be amendment, the IEEE made some decisions on optimizing the use of all the spectrum. For example, a Release 1 feature called multi-link operation (MLO) allows a device to operate, transmit and receive in more than one band at a time. The AP may access the available links and determine which link will provide the best connection for sending data packets. The AP may even spread the data over multiple links to increase throughput and reduce latency.

Wi-Fi 7 also enables devices to better coordinate their use of the available spectrum. By coordinating resources and adjusting transmit power to reduce interference, nearby devices can share the available bandwidth and spectrum. This can provide significant benefits in high-density deployments, such as MDU and college campuses.

So, to answer the question "Why Wi-Fi 7?". Wi-Fi 7 is designed to enable Wi-Fi networks to work together to maximize the available Wi-Fi airtime resources to provide faster and more reliable connections.

4. Release 1 Features

As mentioned earlier, the Release 1 features are defined in Draft 1.0 and 2.0 of the amendment. Some features improve upon Wi-Fi 6 features; these include 320 MHz channels, 4K QAM, multiple resource units (RU) per station (STA), and orthogonal frequency division multiple access (OFDMA) enhancements. The other features, multi-link operation (MLO) and low-complexity AP coordination, are new features. Let us explore the new features first.

4.1. Multi-Link Operation

Since Wi-Fi 4 (IEEE 802.11n), wireless APs and STAs have had two radios; one operating in the 2.4 GHz band and another operating in the 5 GHz band. With the release of Wi-Fi 6E and the addition of the 6 GHz band, STAs may have three radios, or potentially more with multiple 5 GHz radios. Regardless of how many radios an STA has, it will only use one radio at a time to carry traffic. MLO looks to change this.

The concept is simple: use any available radio to transmit or receive data. A challenge for multi-link is that the upper layers must treat the combination of the radio interfaces as a single interface with a single MAC address. To accomplish this, a new device concept, the multi-link device (MLD), is set in the amendment.

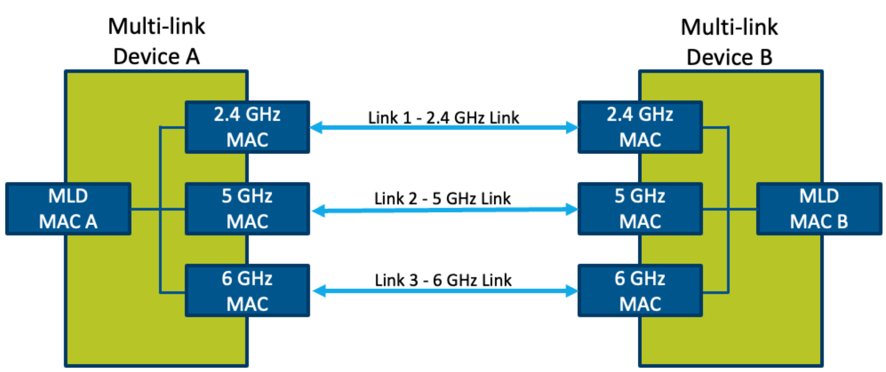


Figure 3 – Multi-link Device

The MLD splits the MAC layer into two parts the upper MAC (U-MAC) and the lower MAC (L-MAC). The L-MAC is the MAC that is tied to the PHY interface, and each wireless radio will have a unique L-MAC address. The U-MAC aggregates the L-MAC to a single MAC and performs link agnostic operations. The figure below shows the L-MAC and U-MAC layout and how they correspond to the upper layers.

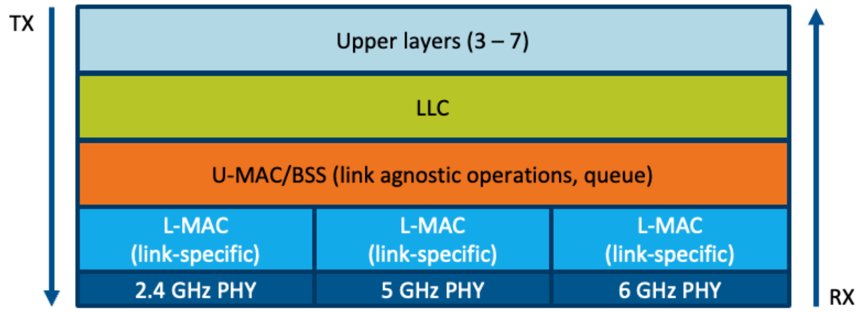


Figure 4 – MLO Architecture

The MLD must determine how to send the traffic. The MLD may be configured in two modes of operation, restricted mode and dynamic link switch mode. The restricted mode uses each link to send different types of frames. One link acts as a data plane and is only used for the data frames and the ACKs. The other link acts as a control plane and is used for the management and the other control frames. In the dynamic link switch mode, each link can send data or control frames, enabling Wi-Fi load balancing.

MLD's channel access can be either asynchronous or synchronous. Asynchronous is the preferred method since it provides more throughput, and when this method is used, it is called the simultaneous transmission reception (STR) mode. When using asynchronous channel access, the MLDs can transmit and receive at the same time using different bands. As noted in the image below, the 2.4 GHz link starts transmitting downstream, and then the 6 GHz link begins receiving data upstream. A little later, the 5 GHz band begins sending data downstream, while the 2.4 GHz sends different data downstream, and the 6 GHz link receives data upstream.

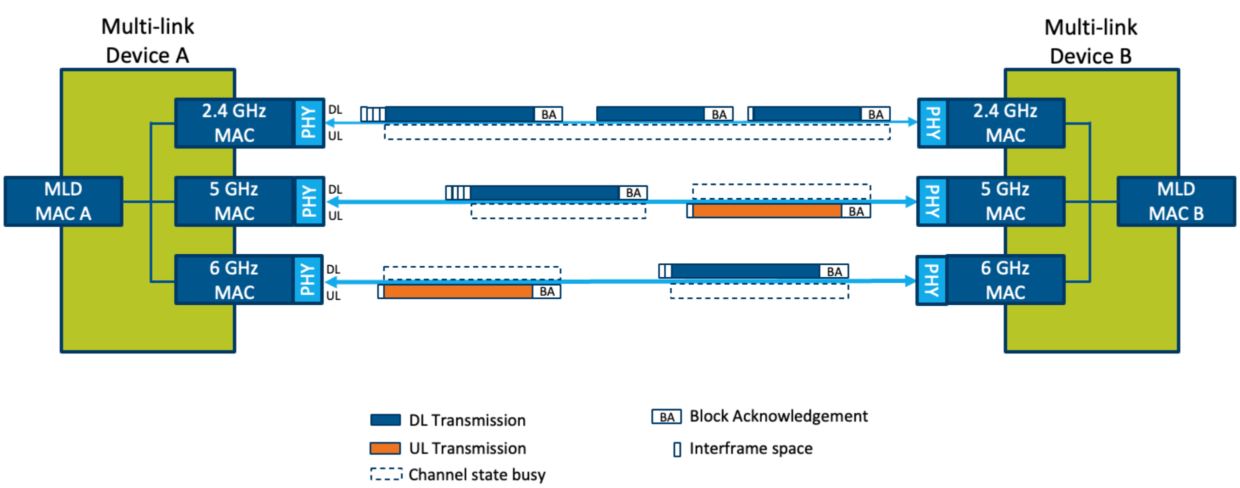


Figure 5 – Asynchronous Multi-Link Channel Access

Synchronous multi-link channel access sends the same data on both links. Synchronous channel access adds redundancy at the cost of reduced throughput. Synchronous channel access is better suited for environments with higher interference. If one link has a high amount of interference, the receiving MLD will examine each packet of the data stream and keep only the good ones. When the MLD uses synchronous channel access, it is in non-simultaneous transmission reception (NSTR) mode. In the image below, the 5 GHz and 6 GHz links are sending the same data, and MLD B will choose the best versions of each packet.

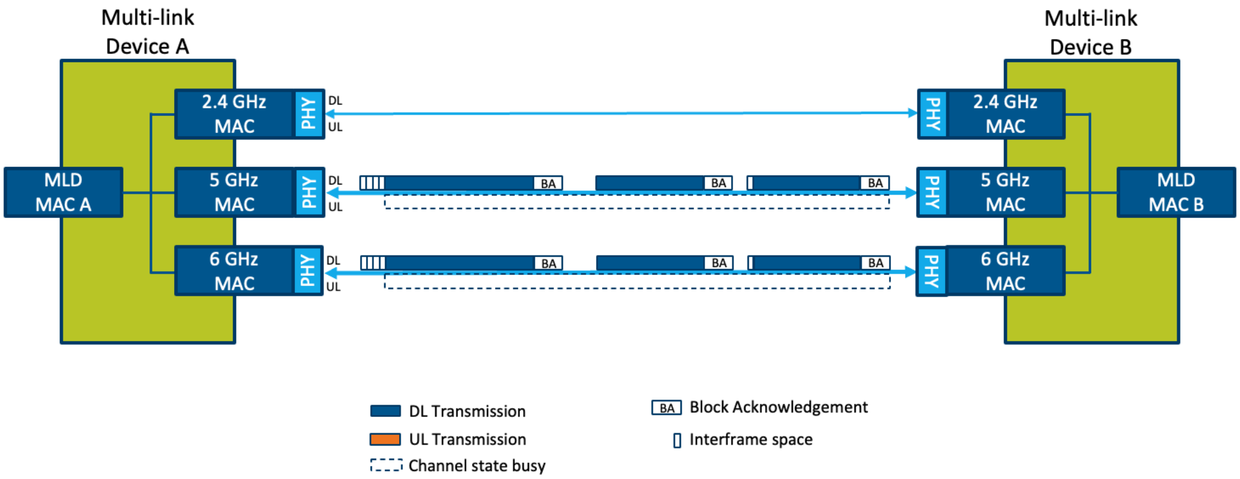


Figure 6 – Synchronous Multi-Link Channel Access

Links do not have to stay in either asynchronous or synchronous mode. They can switch back and forth based on the link conditions. For example, an MLD has two links operating in asynchronous mode. During the transmission, link #1 gets a high number of errors. The MLD responds by switching to a synchronous transmission to ensure all the data is received. Once the conditions improve and the link quality is restored, the MLD can change back to the asynchronous transmission mode.

Multi-link channel access does not require new management frames used to establish links. The 802.11be amendment proposes adding a new multi-link element (MLE) to the existing beacon, probe response, and association response frames. Depending on the frame type, the MLE will use different types of information. Beacon and probe response frames will use a basic MLE, which only has information that is common across all the interfaces. This includes the MLD MAC (aka U-MAC), the set of enabled links, and the STR capabilities. When an MLD STA and AP want to establish the connection, it will use the multi-link request/response type MLE. This more detailed MLE carries all the same information the basic MLE has, and it also includes the information that is different in the other interfaces from the one used to establish the links. Any information not advertised defaults to the settings for the interface establishing the link.

Multi-link channel access can potentially increase the time it takes for an STA to scan and discover an AP and its capabilities since it would have to send information for each link. To reduce the need for the STA to scan each interface, the reduced neighbor report (RNR) is used in the management control frames. Each link will provide information about the other links in the RNR, removing the need for the STA to scan the other interfaces.

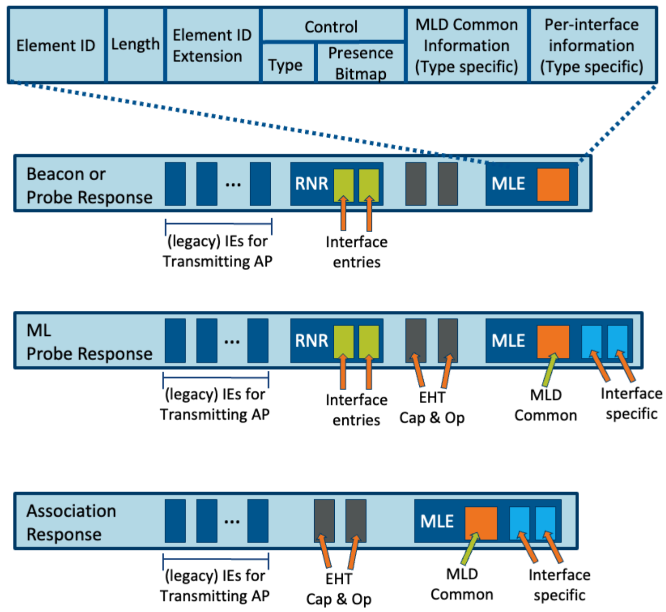


Figure 7 – Multi-Link Frames

Another important aspect of the multi-link channel access operation is the power-saving ability. Having multiple RF radios sending and receiving frames is not an efficient use of power, especially on battery-powered handheld devices. 802.11be will use the traffic indication map (TIM) and the target wake time (TWT) features to address this.

TIM uses beacons to inform the STAs that the AP has information for them. TIM uses an STA ID that is stored in a bitmap. In that bitmap, there is a bit that indicates if there is data for that STA. A binary one indicates there is, and the STA must wake up. A binary zero means there is no data for the STA, and it can stay in snooze mode. For TIM to work with MLDs, a link indication field is added to the bitmap. The link indication informs the STA which link has the data waiting for it.

TWT is based on a TWT schedule that is negotiated between the AP and the client. The TWT schedule includes the wake-up time, the wake interval, and the wake duration for the clients. With multilink, the MLD will negotiate the TWT schedule for each link with the AP. If all links follow the same schedule, then the MLD only needs to negotiate one TWT schedule.

4.2. Low Complexity AP Coordination

Environments such as MDUs where multiple APs are using the same channel and transmitting unique service set identifiers (SSIDs) create the potential for a high amount of Wi-Fi interference. Each AP is a basic service set (BSS), and when they overlap, this creates overlapping BSS (OBSS) interference, which impacts the quality of the wireless signal.

AP coordination can significantly improve Wi-Fi performance in these environments. Due to the complexity of AP coordination, the 802.11be task group split the features into two parts. Release one establishes the technologies used for low-complexity AP coordination, and release two sets the standards for advanced AP coordination. The AP coordination proposed in the 802.11be amendment identifies requirements for primary AP and secondary APs. These APs can be connected via cabling, but they do not need to be connected. However, the secondary APs need to be able to communicate with the primary AP. The secondary APs do not need to hear each other.

The first method for AP coordination in the amendment builds on the spatial reuse (SR) feature introduced in 802.11ax. 802.11ax uses features such as BSS coloring and power management to handle OBSS interference. It controls the interference by managing the power of the secondary device. When the interference is detected, the primary AP will grant the secondary AP an opportunity to transmit simultaneously but using a lower power setting.

The drawback with this solution impacts a device trying to communicate with the secondary AP and can hear the primary AP. As shown in the figure below, STA 2, which is connected to AP 2, may interpret the signal from AP 1 as interference. If the signal is strong enough, it will not be able to communicate with AP 2.

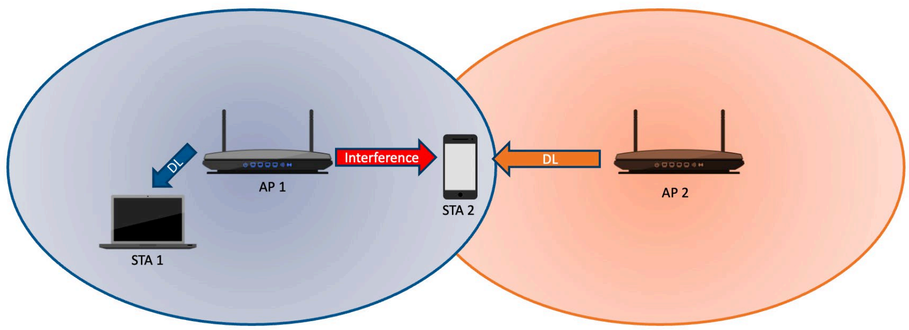


Figure 8 – 802.11ax Spatial Reuse Drawback

802.11be looks to improve the 802.11ax SR with a coordinated spatial reuse (CSR) system. With CSR, when an AP that is part of a coordinated group receives a transmit opportunity (TXOP), it will coordinate with the other APs to share the TXOP. To reduce the impact of OBSS interference, the coordinated APs will adjust their power levels. Using the scenario mentioned above. AP 1 and AP 2 will adjust their transmit power relative to STA 2. AP 1 will reduce its transmit power to reduce the interference for STA 2, so it can communicate with AP 1.

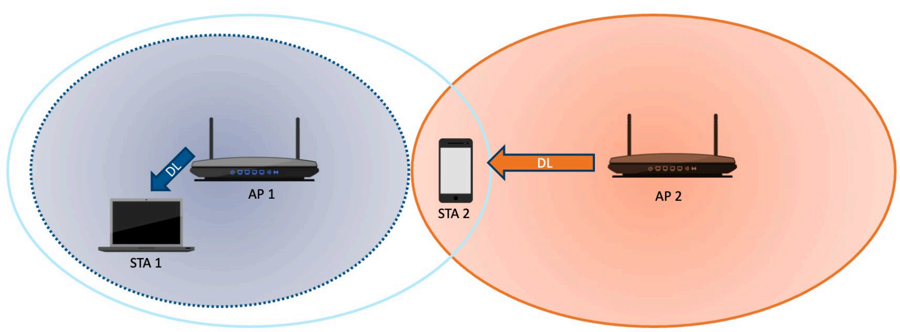


Figure 9 – 802.11be Coordinated Spatial Reuse

The second method proposed for low complexity AP coordination is coordinated orthogonal frequency division multiple access (Co-OFDMA). OFDMA was introduced as part of the 802.11ax amendment, and it enabled APs to schedule time and frequency slots called resource units (RU) for devices to transmit and receive data. Co-OFDMA enables coordinated APs to share those resource units. APs will work together to schedule RUs for devices to use. APs could schedule the same RU slots as long as the signals do not interfere with each other.

CSR and Co-OFDMA are being developed for Release 1 of the 802.11be amendment. We will look at the other AP coordination features proposed for Release 2 later in this paper.

4.3. 320 MHz Channels

Starting with Wi-Fi 4 (IEEE 802.11n), channel bonding was used to increase the potential data rate. Wi-Fi 4 added 40 MHz channels, using two 20 MHz channels. Wi-Fi 5 (802.11ac) added the capabilities for 80 and 160 MHz channels. In contrast, Wi-Fi 6 (802.11ax) did not expand the channel size options. However, it added the 6 GHz band, which made using one or two 160 MHz channels possible.

Wi-Fi 7 looks to expand the channel bandwidth to a massive 320 MHz channel (sixteen 20 MHz channels). The 320 MHz channels will only be possible in the 6 GHz band. The 320 MHz channels can also be non-contiguous, with two 160 MHz channels. If 320 MHz is unavailable, another option is a 240 MHz channel, which is made using one 80 MHz channel and another 160 MHz channel. Having a super wide 320 MHz channel sounds great. However, it will not always be possible, especially in dense AP environments. In these environments, channel reuse is important, and despite the 1.2 GHz of bandwidth in the 6 GHz band, there are only three 320 MHz channels.

4.4. 4K QAM

Another enhancement to previous Wi-Fi generation PHYs is increasing the modulation from 1024 QAM to 4096 QAM (4K QAM). 4096 QAM can potentially increase the data rate by 20%, compared to 1024 QAM. The challenge with 4096 QAM is that the SNR must be extremely high. Specifically, 4096 QAM requires an SNR of 40 dB, which will be difficult for many wireless networks to achieve. It can happen using beamforming in non-crowded environments, but it will be challenging in the best environments.

4.5. OFDMA Enhancements

One of the most significant additions to Wi-Fi 6 was OFDMA. Wi-Fi 7 looks to improve OFDMA to use the bandwidth more efficiently. This next section will look at these enhancements, including multiple RUs per STA, preamble puncturing, and a new physical protocol data unit (PPDU).

4.5.1. Multiple RUs Per STA

OFDMA schedules RUs for devices to use for uplink or downlink communication. The AP will allocate an STA the RU size based on the STA’s bandwidth requirements. A RU is made up of a group of subcarriers called tones, and the size of the RU varies based on the number of tones. For a 20 MHz channel, the smallest RU has 26 tones, and the largest has 242 tones. The 26-tone RU is called an RU26 tone map, allowing 9 RUs in a 20 MHz channel. The table below shows the tone maps.

Table 1 – OFDMA Tone Map

RU Tone	Number of Tones			
	20 MHz Channel	40 MHz Channel	80 MHz Channel	160 MHz Channel
RU26	9	18	37	74
RU52	4	8	16	32
RU106	2	4	8	16
RU242	1	2	4	8
RU484	N/A	1	2	4
RU996	N/A	N/A	1	2
RU2 x 996	N/A	N/A	N/A	1

The image below shows the possible tone maps for an 80 MHz channel. The yellow lines between the tones are direct conversion, guard, and null tones.

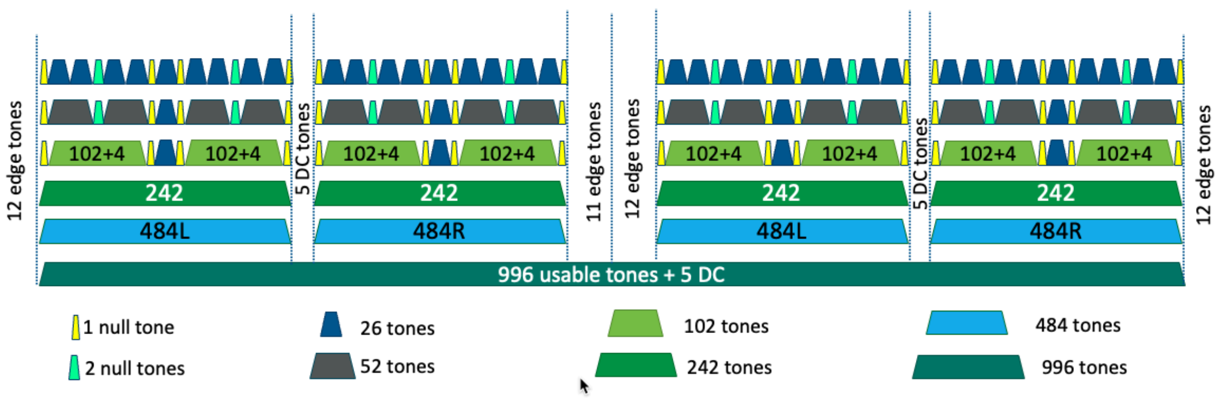


Figure 10 – 80 MHz Tone Map

The 802.11ax standard allowed multiple devices to be allocated a single RUs for each TxOp. An example cited in the *Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7* paper, has two STAs sharing an 80 MHz channel. The AP grants a 242 tone RU to the 1st STA, and the 2nd STA can be granted a maximum of a 484 tone RU. That leaves 25% of the bandwidth unused. If the 2nd STA has more data to transmit, it must wait for its next TXOP.

802.11be looks to improve the spectrum efficiency by enabling APs to assign multiple RUs to a single STA. For the example cited above, the 1st STA would be assigned a 242-tone RU, and then the 2nd STA could be assigned a 484-tone RU and a 242-tone RU. This effectively gives the 2nd STA 726 tones to send data. With the move to larger channels, assigning multiple RUs to a single STA can significantly improve the ability of APs to use the available bandwidth efficiently. The task group is investigating how many RUs will be assigned to a single STA.

802.11be separates the RUs into two groupings based on their size:

- Small-size RUs: RUs less than 242 tones, ex. RU26, RU52, RU106
- Large-size RUs: RUs equal to or greater than 242 tones, ex. RU242, RU484, RU996

The 802.11be draft amendment lists all the possible multi-RU (MRU) possibilities in an MRU index. The only small-size MRUs are RU78 (RU52+RU26) and RU 132 (RU106+RU26). The 802.11be draft standard identifies the large-size MRUs based on the channel size. The following are mandatory RUs specified in the standard.

Table 2 – Multi-Rus for Large-Size RUs

Bandwidth	RU	Mandatory in non-OFDMA for:
80 MHz	484+242	AP, STA
160 MHz	996+484	AP, STA
	996+(484+242)	AP, STA
240 MHz	3×996, 2×996+484, 2×996 (any 2)	AP, STA
320 MHz	4×996, 3×996+484, 3×996 (any 3)	AP, STA

4.5.2. Preamble Puncturing

Wi-Fi 5 introduced dynamic channel bandwidth to go along with the large 80 MHz and 160 MHz channels. When an STA connects to a client, it connects on the primary 20 MHz channel. If the secondary 20 MHz channel is available, the connection expands to be a 40 MHz channel. Next, it will attempt to connect to the secondary 40 MHz. It will first connect to the primary 20 MHz of the secondary channels and then connect to the secondary 20 MHz of the secondary channels. When all four 20 MHz channels are connected, the STA has an 80 MHz channel to use. However, if the initial secondary channel is busy during this process, only the initial 20 MHz primary channel is used. The AP cannot use any of the secondary channel bandwidth, even if it is available.

Wi-Fi 6 introduced preamble puncturing, which enables an STA to avoid using a 20 MHz portion of a large channel (40 MHz, 80 MHz, and 160 MHz) that is busy. Using the 80 MHz channel example again. The STA connects to the AP on the primary 20 MHz channel. The AP will then check if the secondary 20 MHz channel is busy. If the channel is busy, the AP will skip the channel and attempt to connect to the secondary 40 MHz channel. Wi-Fi 6 identified eight bandwidth modes. Modes 0 – 3 are for the standard channel bandwidths with no puncturing, 20 MHz, 40 MHz, 80 MHZ, and 160 MHz. Modes 4 – 7 are the puncturing modes, which are pictured below.

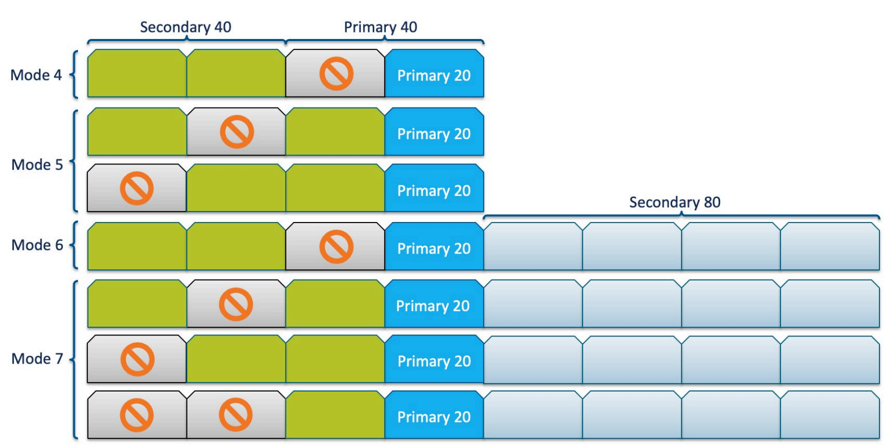


Figure 11 – Wi-Fi 6 Preamble Puncturing

802.11be will build on existing puncturing techniques by expanding the modes to cover the 240 MHz and 320 MHz channels. Also, preamble puncturing is being applied to primary channels. This technology is called preamble puncturing because the preamble is removed from the frame for the channel that is being punctured.

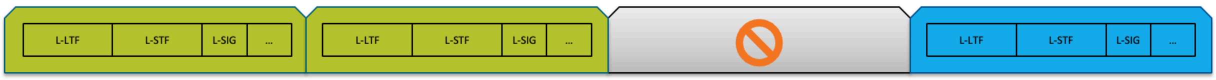


Figure 12 – Preamble Puncturing Frame

4.5.3. PPDU Frame Format

When designing the PPDU, the 802.11be task group aimed to have backward compatibility with previous Wi-Fi standards and provide a framework for future standards. The backward compatibility is maintained by the first four parts of the frame, and the rest of the frame is designed to support future Wi-Fi 7 and future versions.

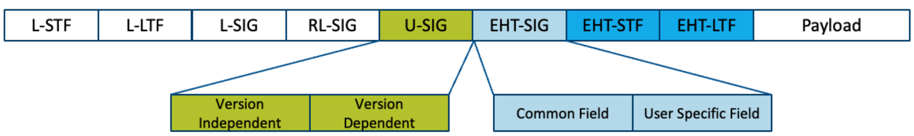


Figure 13 – Wi-Fi 7 PPDU

The 802.11be PPDU begins with using the same legacy preamble training fields as previous Wi-Fi versions. These fields are the legacy short training field (L-STF) and the legacy long training field (L-LTF), and they are used for frame detection and synchronization. The next field is called the legacy signal field (L-SIG), and it is a carry-over from 802.11a to indicate the MCS and frame length. However, since Wi-Fi 4, the values in the field were not related to the MCS. The data in there is fake data as placeholders to maintain compatibility. Wi-Fi 4 and 5 send the MCS and frame length data in the following field. Wi-Fi 6 transmits it after the following field, the repeat legacy signal field (RL-SIG). Wi-Fi 7 will also use the RL-SIG field.

The PPDU frame variation for 802.11be starts with the universal signal (U-SIG) field. The U-SIG field is created with an eye toward compatibility with future Wi-Fi standards. The U-SIG has two parts: the version independent and the version dependent fields. The version independent field includes a PHY version identifier, an uplink (UL)\downlink (DL) flag, the BSS color field, the TXOP duration, and the bandwidth. The 8021.11be task group is still defining the information sent in the version-dependent fields of the U-SIG. Some of the information may include the guard interval duration, EHT-STF, EHT-LTF size, space-time block coding, and information about specific 802.11be features.

The EHT-SIG field will provide information not included in the U-SIG but is needed to implement 802.11 features. The EHT-SIG has two parts: the common field and the user-specific field. The common field has the RU allocation information, the MCS, the guard interval duration, and other signal information. The user-specific field will be present in multi-user (MU) frames and will have information directly related to an STA. The last two fields of the EHT preamble are the EHT-STF and EHT-LTF. These training fields are similar to the training fields at the beginning of the PPDU. They provide synchronization for multiple in multiple out (MIMO) configurations.

5. Release 2 Features

As per the original timeline, the Release 2 features will be added in Draft 3.0 and 4.0. Some of these features build on existing 802.11 standards and the Release 1 features. These features are still being investigated at the time of this writing, and the 802.11be task group has not given final approval. They are reviewing multiple proposals for implementing these features. The features that are part of Release 2 include MIMO enhancements, hybrid automatic repeat requests (HARQ), low latency operation, and advanced AP coordination.

5.1. MIMO Enhancements

Since MIMO was introduced with 802.11n (Wi-Fi 4), MIMO has been enhanced with each release. Wi-Fi 7 continues that trend by doubling the number of spatial streams from 8 to 16. This can potentially double the throughput an AP can handle. However, there are some restrictions on the 16 spatial streams. The first restriction is that the maximum number of STAs using spatial multiplex per AP is eight. The second restriction is that each STA can have a maximum of 4 spatial streams. This will not restrict client capabilities significantly since most mobile devices support a maximum of two spatial streams for power efficiency reasons. As the bandwidth needs of the devices increase, manufacturers can add additional spatial streams up to 4. The other reason for limiting the number of spatial streams is to limit complexity and overhead.

5.1.1. Channel Sounding Optimization

For MU-MIMO to operate effectively, the AP and clients must have accurate information about the channel quality. This is done through channel sounding, and previous 802.11 standards implemented two different versions, implicit and explicit sounding. 802.11ac and 802.11ax use explicit sounding, which replaced the implicit sounding introduced in 802.11n.

The explicit sounding used in 802.11ax works by the AP sending out a null data packet announcement (NDPA). This informs the STA about the null data packet (NDP) that the AP is sending. The STAs use the NDP to assess the channel's status and provide channel state information (CSI) for the channel to the AP. The CSI is sent via a beamforming report (BFR). The BFR provides the SNR for each spatial stream, a comparison of the SNR for the subcarrier compared to the spatial stream, the Givens rotation angles (ϕ and ψ), and other relevant channel quality information. The CSI for a 160 MHz channel with one spatial stream will provide BFR information for every 16th subcarrier, for a total of 128 subcarriers. As the number of spatial streams and channel size increases, the amount of CSI data sent from the clients to the AP will increase. The overhead will increase dramatically, and the information will not be relevant as the channel state constantly changes.

At the time of writing this paper, the 802.11be task group is investigating multiple methods to reduce the overhead. Some of these solutions use implicit sounding. Even though implicit sounding was first introduced in 802.11n, it was never really implemented in APs. The reason was that the APs could not perform the AP-self calibration needed. Self-calibration is needed since the UL and DL signals will vary slightly for each antenna. So, the APs must compensate for these differences. Implicit sounding works by having the STA send NDP sounding information in the UL. The AP will measure the channel using the sounding information. It takes less time to send the NDP than it does to send the BFR, especially when there are many spatial streams and STAs. Reducing the time needed to receive the channel information is more current.

To improve the self-calibration, newer local AP self-calibration techniques can be used where the STAs are not involved in the calibration process. The AP will select a reference antenna and send out a pilot signal from every antenna. It estimates each antenna's baseband to RF gain variations and makes the necessary adjustments. An example of how implicit sounding is used in one of the proposals begins with the AP sending out a trigger frame requesting the STAs to send the UL NDPs. The AP analyzes the NDPs from all the STAs. It then can send beamformed data to each STA. This method is estimated to save approximately 60% of the airtime.

5.2. HARQ

Hybrid automatic repeat requests (HARQ) aims to reduce the amount of traffic on the wireless network by reducing retransmissions. Current Wi-Fi implementations require an entire packet to be retransmitted if the receiving device did not receive a complete packet. This will continue until the receiver gets a complete packet and can lead to a high number of retransmissions and impact the performance of a network. HARQ looks to improve this by combining the failed- transmissions, which will improve the SNR, and the receiver should be able to rebuild the complete packet with the information that it has. In the end, this will reduce the number of retries on the network. Another benefit is that since the SNR is being improved, a higher MCS can be set for the connection.

The task group is evaluating three methods to implement HARQ: chase combining (CC), punctured CC, and incremental redundancy (IR). The lowest complexity solution is CC. With CC, every retry has the same information as the failed packet. Since the information is the same, it makes rebuilding the packet less complex. However, there is the potential for more traffic than other HARQ methods. The second method being examined is punctured CC, which reduces the amount of overhead compared to CC. With punctured CC, the transmitter only repeats the part of the failed transmission. On the receiver side, this version will require more computation than CC. The most complex and bandwidth-efficient method is IR. IR requires the transmitter to use different codewords to represent the same information. The receiver gets more information to rebuild the original packet by using a different set of codewords.

5.3. Low-Latency Operation

Network latency is an essential part of all networking solutions. Residential applications such as virtual reality gaming and commercial applications such as industrial IoT are real-time applications (RTA), and they need networks to have very low latency. The IEEE has done a lot of work looking at time-sensitive networking (TSN) applications. They have established an 802 TSN task group to study these solutions. Most of their work applied to 802.3 Ethernet networks, but now the 802.11 working groups are looking at ways to implement TSN solutions with Wi-Fi.

The solutions being investigated focus on improving the worst-case latency instead of the average latency. Many of the 802.11be features outlined in this paper are a big part of the solutions. Multi-link operation, AP coordination, multi-RU per station, and other techniques are designed to use the spectrum more efficiently, resulting in data packets waiting less to be transmitted.

Two operations scenarios are identified by the 802.11be task group, managed and unmanaged. Examples of unmanaged scenarios are home networks and Wi-Fi hotspots. Managed scenarios are more the corporate and enterprise networks that use controllers to manage the network. The big difference in these scenarios is that the controllers and the APs can better deal with interference and optimize the environment. Unmanaged networks can do things to control latency and jitter, but they have little control of the impact of outside interference.

One way to reduce the latency for RTAs is to use QoS. Wi-Fi uses enhanced distributed channel access (EDCA) to provide QoS in Wi-Fi networks. Currently, EDCA uses four categories of traffic; background, best effort, video, and voice. Voice has the highest priority for getting channel access. The 802.11be task group is investigating adding additional categories. While voice traffic will continue to have higher priority, some applications need to have higher priority than video. A typical example used is gaming. Gaming does not require as much bandwidth as high-resolution video, but the latency must be much less. Adding a category for gaming that is a higher priority than video can reduce the worst-case latency for gaming applications.

The challenge is getting access to the medium. In Ethernet networks, collisions can clear the medium so that the higher priority traffic can get access. Wi-Fi does not have collision detection. The device using the medium cannot do any sensing on the channel while transmitting. The solution for this is different on managed and unmanaged networks. With managed networks, the controllers can coordinate the channel access. They can give access to the channel to the device that has the higher priority traffic. This can be done via scheduling using hybrid coordinated function-controlled channel access. This function is not used in WLANs today. Another option is using a trigger frame. The controller can allocate medium access to high-priority applications using short trigger frames.

On unmanaged networks getting access to the medium can be more difficult. 802.11be enhancements like multi-link operation will help with this since there are multiple mediums to carry traffic. One solution is a busy tone. A busy tone can let a device that is transmitting lower priority traffic know there is higher priority traffic waiting to be sent. When the busy tone is detected, the device stops transmitting, so the higher priority traffic can be sent. Multi-link devices can use another link to send the busy tone. Another way multi-link is being used to reduce latency is by implementing asynchronous communication, also known as joint mode. The AP will use multiple links to send different data in joint mode.

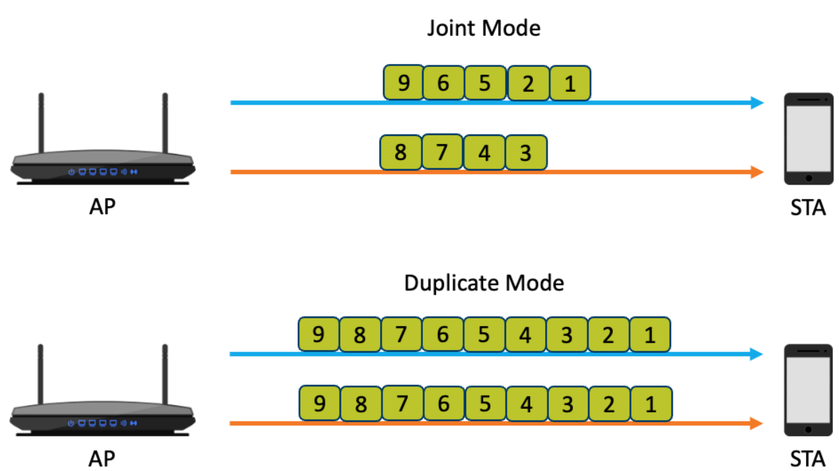


Figure 14 – Multi-Link Joint Mode

5.4. Advanced AP Coordination

Release 2 looks to add more advanced ways of doing AP coordination. The two methods being investigated for Release 2 are coordinated beamforming (CBF) and multi-AP joint transmission and reception.

5.4.1. Multi-AP Joint Transmission and Reception

Multi-AP joint transmission and reception creates a way for multiple APs to serve a single STA. This is a similar concept to multi-link operation, but in the reverse scenario, where there is one STA being served by multiple APs. However, the challenge for this system is the synchronization of the APs. This challenge is extremely difficult in the DL as it requires a high-speed, low latency backhaul to create synchronization among the APs. The backhaul is needed because it must provide the data to all the APs to transmit. The APs need to be in synchronization so they know which parts of the data were transmitted and received. For the UL, multi-AP systems distributed successive interference coordination (SIC) can be used to improve the data reception at the APs. With SIC, each AP receives the data from their STAs. The data is then sent to the other APs for interference subtraction. The APs remove the interfering signal from the received signal to get their data. The other method being investigated for the uplink is joint frame reception. With this method, the APs process the data from all the STAs. The high-bandwidth backhaul is needed to synchronize the APs for handling the STA traffic. The APs share signal time stamps to stay in synchronization.

5.4.2. Coordinated Beamforming

CBF is also called null steering. It is called null steering because the AP sending the traffic will attempt to cancel or null the interference from neighboring STAs. The nulling of the interference happens while the AP is creating the beamforming signal to the STA. To know what interference there is, the AP must collect CSI information for all nearby STA, including the ones it is not serving.

For UL transmissions, each AP must collect interference information for neighboring STAs. During the UL reception, the AP configures its receiver so it can receive data from its STAs while ignoring interference from other STAs.

6. Security

The Wi-Fi Alliance sets security standards for Wi-Fi networks as part of its certification process. The standards identify which Wi-Fi protected access (WPA) version and modes that a device must support. The Wi-Fi Alliance has not announced any new security requirements around Wi-Fi 7. At the time, it is expected that the Wi-Fi 7 device certification will have similar security requirements as Wi-Fi 6 and Wi-Fi 6E. Those certifications brought significant updates to Wi-Fi network security. Wi-Fi 6 added the following security updates:

- WPA3-Personal
  - Simultaneous authentication of equals (SAE) for authentication and association
  - Management frame protection (MFP) used to combat deauthentication attacks
- WPA3-Enterprise
  - 802.1X/EAP
  - Management frame protection (MFP)
  - 192-bit security key optional
- Enhanced Open
  - Provides encryption on open networks

To obtain Wi-Fi 6 certification, the Wi-Fi Alliance requires that devices support these new and legacy security standards such as WPA and WPA2. To enhance the security of devices operating in the 6 GHz band, the Wi-Fi 6E certification requires that devices only support the new security standards. Wi-Fi 6E devices do not support legacy standards.

Some of the questions around Wi-Fi 7 security are:

- Will the same security requirements from Wi-Fi 6 and 6E be carried over as they are for Wi-Fi 7?
- Will there be a separate Wi-Fi 7E certification, similar to 6E?
- Will multi-link devices support legacy security standards on non-6GHz channels?

The Wi-Fi Alliance has not established a time frame for Wi-Fi 7 certification and security requirements. It is expected to be ready in early 2024 to align with the release of the 802.11be standard.

7. Benefits to Customers

As noted in previous sections of the paper, Wi-Fi 7 increases the potential maximum data rate. Wi-Fi 7 takes advantage of the extended available spectrum and increases its efficiency for spectrum using wider channels, preamble puncturing, and 4K QAM. Besides the throughput/speed benefits, Wi-Fi 7 offers lower latency and better reliability in high interference environments using Co-OFDMA, RUs, and tones. The benefits in reliability extend beyond residential and into MDU and business environments. Wi-Fi 7 builds on the security benefits of Wi-Fi 6/6E, making it a viable choice for untethered connectivity. The increased throughput/speed, lower latency, reliability, and solid security in WPA3 makes it easier for operators to achieve their 10G platform pillars.

7.1. MDUs

In MDU environments, where there are many APs operating close to one another, it is important to identify areas of interference, like co-channel interference (CCI) or adjacent channel interference (ACI). One thing that is not changing with Wi-Fi 7 is, as with previous Wi-Fi versions, performing a Wi-Fi site survey at the MDU is important to understand the operating environment. Most Wi-Fi site survey tools offer a Wi-Fi heatmap to represent the coverage and RF signal strength visually. These heatmaps are often overlaid with MDU floor plans, increasing their effectiveness as a deployment and troubleshooting tool. This overlay also provides operators a visual map of the location of trouble zones, the location of APs and other relevant survey data.

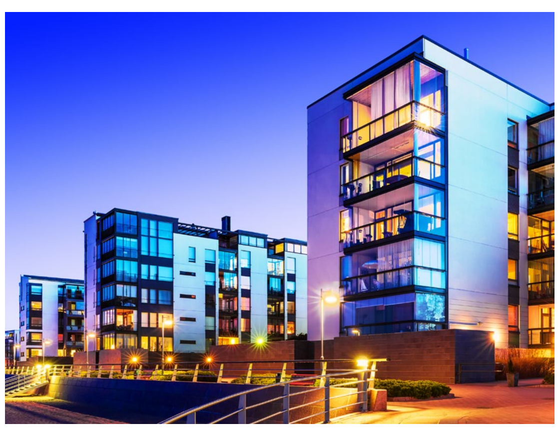


Figure 15 – MDU

Besides the high areas of interference, the MDU is a dense environment. Wi-Fi 7 has access to an increased amount of RF spectrum and tools to use this RF spectrum better. Preamble puncturing is one of those features mentioned, along with Co-OFDMA. These features greatly benefit those using Wi-Fi to communicate in MDU environments. Wi-Fi 7, like Wi-Fi 6E, takes advantage of the 6 GHz spectrum and may leverage MLO to increase throughput/speed and reliability in MDUs.

As mentioned, adjusting AP transmit power can provide big benefits in high-density deployments, reducing OBSS interference. Environments such as MDUs where multiple APs are using the same RF channel and transmitting unique SSIDs create the potential for a high amount of Wi-Fi interference. Furthermore, MDUs will benefit from the low complexity AP and advanced AP coordination features of Wi-Fi 7.

7.2. Business Services

Business services are transforming their enterprise networks with a host of digital elements that require higher data rates than residential. Wi-Fi 7 has a roadmap of throughput/speed options that extend the certification out to 40 Gbps. Today, service offerings like private/public/hybrid cloud, software-defined networking (SDN), and virtualization will benefit from the added Wi-Fi 7 throughput/speed options. Technologies like the 3rd Generation Partnership Project's (3GPP) 5G, citizens broadband radio service (CBRS), along with Wi-Fi 7, will be used to transform the access network edge for enterprise services using SCTE's generic access platform (GAP) enclosure (ANSI/SCTE 273-1 2021) and module (ANSI/SCTE 273-2 2021) specification standards. Further transformation of the edge will occur with the reality of 3GPP's 6G and Wi-Fi 7 Release 2.

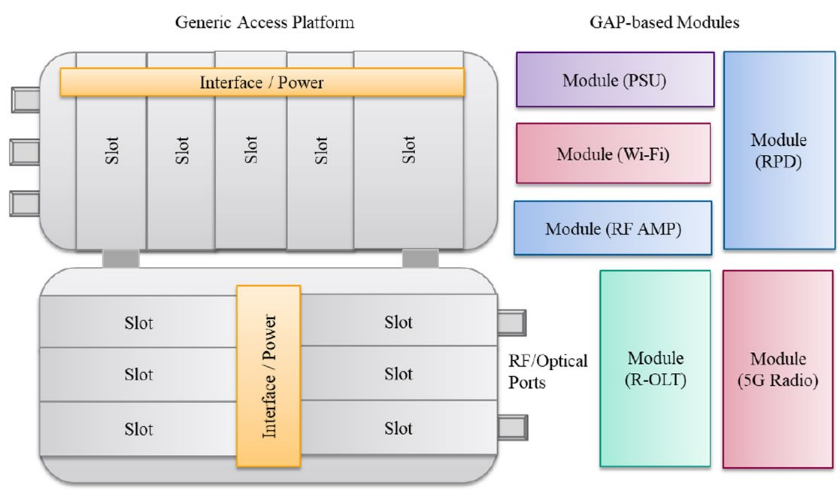


Figure 16 – SCTE GAP

For improving reliability in the enterprise, Wi-Fi 7 offers a toolkit here as well. Business enterprise time-sensitive applications require latency that is deterministic, offering high reliability and quality of service (QoS). Deterministic latency offers predictable jitter and network delays for enterprise networks. Operator enterprise Wi-Fi 7 networks must be designed to cope with the compromise between throughput/speed and deterministic latency. Wi-Fi 7's latency features and Co-OFDMA will benefit the explosion of IoT and industrial (IIoT) smart devices making their way into the enterprise.

The enterprise features mentioned will improve reliability, a key performance indicator (KPI) on the health of a Wi-Fi network.

8. Wi-Fi Performance Management

Subscribers want a consistent wireless/Wi-Fi experience, making performance management an important topic for Wi-Fi 7. A few of the top issues for operators with in-home or business service Wi-Fi are throughput/speed, range, interference, congestion, and compatibility.

In any Wi-Fi network, a high number of users or STAs may overload an AP, reducing the available RF energy in a BSS. In addition, as the STA distance from an AP's radios increases, the receive signal strength indicator (RSSI) value decreases towards the noise floor of -90 dBm. This is because extending the range from the STA to the AP reduces the power due to free space path loss (FSPL). Each 3 dB of signal loss in the RSSI equates to a reduction in milliwatt (mW) power by one-half (1/2). A reduction in RSSI also reduces the data throughput/speed of the AP, like how cellular devices operate with a base station. Leveraging the benefits of Wi-Fi 7 MU-MIMO, preamble puncturing, MLO, and AP coordination will increase performance in these scenarios. An additional consideration that might benefit performance here would be load balancing STAs, additional APs, and decreasing STA to radio distance.

In high multi-path environments, interference and signal fading are always top of mind and an operator's priority. Multi-path environments, or indirect line of sight (LoS) communication, occur from reflected, scattered, and other RF extrinsic factors in a Wi-Fi environment. Wi-Fi 7 offers 16x16 MU-MIMO and spatial diversity to reduce interference and signal fading in high multi-path environments. Spatial diversity allows an AP to select from multiple input signals for the best reception. Furthermore, to identify interference, always perform a Wi-Fi site survey to understand the operating environment and talk with the subscriber about the Wi-Fi coverage in the BSS. A site survey is a great step to providing a good Wi-Fi service in residential, MDU, and business service enterprise environments. A survey identifies items that may reduce RF coverage, range, or performance in the Wi-Fi network. The survey tool offers data to discuss options with subscribers.

Not all Wi-Fi site survey tools are the same. Most survey tools offer a heat map characterization, as well as a Wi-Fi extender and mesh characterization. The heat map produces images utilizing a color map to show the AP's RSSI and RF throughput levels. With most Wi-Fi networks deploying extenders to create mesh networks for range and coverage improvements, we must characterize their range and throughput/speed. Heatmaps will show ways to improve range, coverage, and throughput/speed for larger dwellings. Heatmaps also look for CCI and ACI, as well as an elevated noise floor.

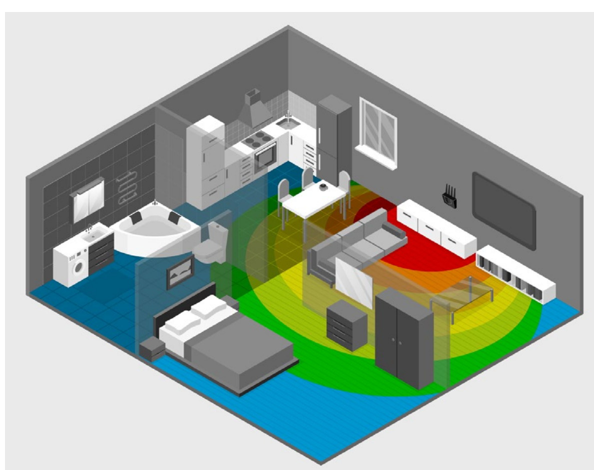


Figure 17 – Heatmap

WI-FI networks operate between -30 dBm and -90 dBm, where -90 dBm is the noise floor. The higher the RSSI, the better the performance of the Wi-Fi network. For example, a -80 dBm is considered poor, while a -60 dBm may be considered acceptable. A dB is a decibel or relative power measurement used to compare two dBm values like the SNR metric. SNR refers to the Wi-Fi signal level of the received signal versus the ambient noise on the RF channel, meaning measurable RF energy without a signal, referred to as noise. For example, Figure 18 below shows a plot of a Wi-Fi signal and the noise floor. The noise floor is a little higher than normal at -79 dBm, and the signal is around -41 dBm, which makes the SNR for this connection 38 dB. Depending on the Wi-Fi design, operators may want an S/N of 35 dB or greater.

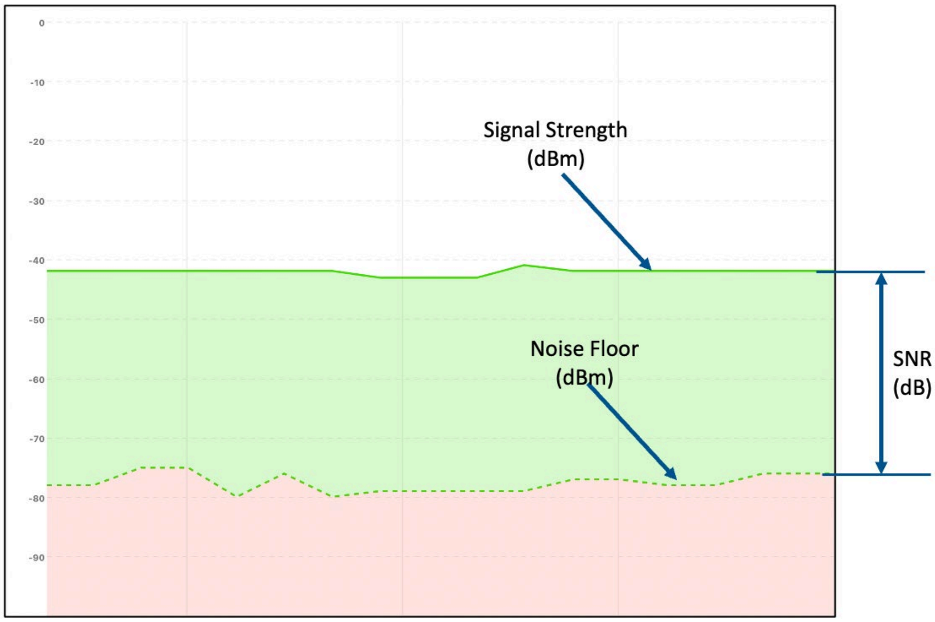
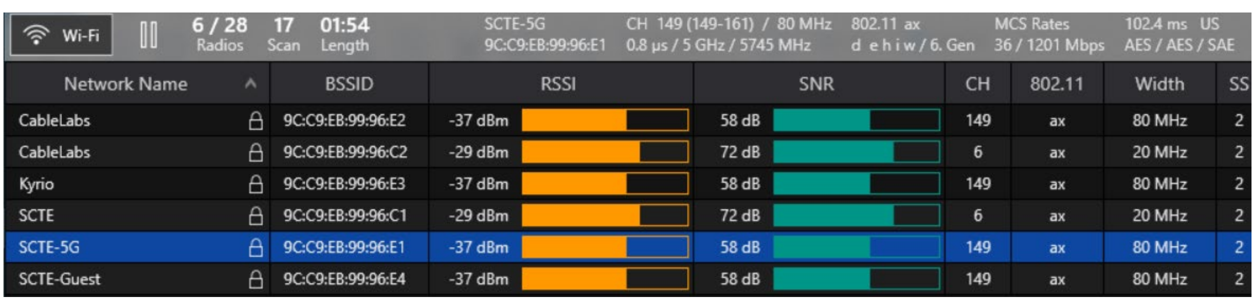


Figure 18 – Signal to Noise Ratio

The dBm is a decibel relative to a milliwatt (mW), where 0 dBm equates to 1 mW of RF power.   The mW is an absolute power measurement often used in combination with dBm in Wi-Fi networks. RSSI and S/N will still apply to Wi-Fi 7 networks and will vary based on the radios used, 2.4 GHz, 5 GHz, and 6 GHz.



Network Name	BSSID	RSSI	SNR	CH	802.11	Width	SS
CableLabs	9C:C9:EB:99:96:E2	-37 dBm	58 dB	149	ax	80 MHz	2
CableLabs	9C:C9:EB:99:96:C2	-29 dBm	72 dB	6	ax	20 MHz	2
Kyrio	9C:C9:EB:99:96:E3	-37 dBm	58 dB	149	ax	80 MHz	2
SCTE	9C:C9:EB:99:96:C1	-29 dBm	72 dB	6	ax	20 MHz	2
SCTE-5G	9C:C9:EB:99:96:E1	-37 dBm	58 dB	149	ax	80 MHz	2
SCTE-Guest	9C:C9:EB:99:96:E4	-37 dBm	58 dB	149	ax	80 MHz	2

Figure 19 – RSSI

As with Wi-Fi 5/6, it is operating in the 5 GHz as opposed to 2.4 GHz reduces the range of a Wi-Fi network. Then we have newer STAs that will take advantage of 6 GHz from Wi-Fi 6E and Wi-Fi 7, further reducing the range of the RF signal and the RSSI value. This is because the wavelength of 6 GHz is much shorter than 2.4 GHz. Mesh networking will be an important component of the deployment of these Wi-Fi 7 networks.

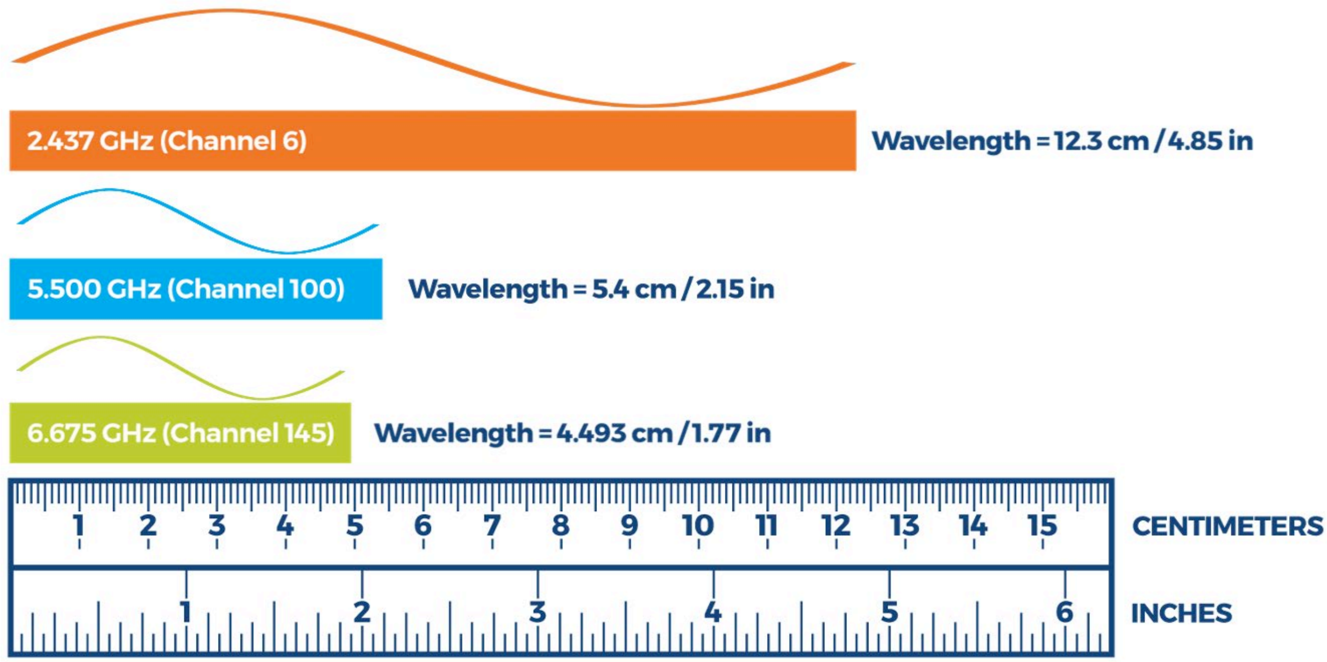


Figure 20 – Wavelength of 2.4, 5, and 6 GHz

Other tests may be conducted to determine airtime fairness implementation in the AP. These tests look into the throughput/speed of the AP and how it allocates bandwidth to each of the STAs. These types of tests help operators understand scenarios where a good QoE or QoS may not be delivered. A different kind of test that is useful is determining the band steering capabilities of an AP. Band steering will become more important as Wi-Fi 6E/Wi-Fi 7 utilize multiple radios, especially when multi-link capacity is available. Having the AP and STA choose the best bands to operate in will be crucial for providing the best possible QoS.

9. Conclusion

Residential, MDU, and business service wireless communications will support the mission of the 10G platform, extending the benefits of throughout/speed, low latency, reliability, and security. In addition, Wi-Fi 7 will offer a more carrier-grade version of wireless while driving a more positive customer QoE. In all the access network technologies an operator deploys, it is the premises' Wi-Fi experience that will determine the image of an operator. The Release 1 features like PHY enhancements, OFDMA, MLO, and preamble puncturing will be critical to the next generation of connectivity. Release 2 features will solidify the experience with MIMO enhancements, channel sounding, HARQ, low latency, and AP coordination.

Managing the impact of Wi-Fi 7 will require benchmarking devices with partners like Kyrio and truly understanding the metrics that lead to a healthy Wi-Fi ecosystem. With any new Wi-Fi certification, workforce education and credentialing will be the tools to manage our talent teams, further pushing positive interactions and experiences with Wi-Fi 7. Any such educational program (e.g., SCTE BWS and SCTE CWNP) must measure the return on investment (ROI) to quantify the reduction of call volumes, truck rolls, etc. related to wireless technology in our industry. Stay tuned as advancements in Wi-Fi 7 take place, and look to the trusted applied science leader in telecommunication to keep you ahead of the curve on this exciting technology.

Abbreviations

3GPP	3rd Generation Partnership Project
ACI	adjacent channel interference
AI	artificial intelligence
AP	access point
AR	augmented reality
bps	bits per second
BFR	beamforming report
BSS	basic service set
CBF	coordinated beamforming
CBRS	citizens broadband radio service
CC	chase combining
CCI	co-channel interference
CIA	confidentiality, integrity, and availability
CPE	customer premises equipment
CSI	channel state information
CSR	coordinated spatial reuse
dB	decibel
dBm	decibel relative to one milliwatt
DL	downlink
EDCA	enhanced distributed channel access
EHT	extremely high throughput
FSPL	free space path loss
GAP	generic access platform
HARQ	hybrid automatic repeat requests
IEEE	Institute of Electronics Engineers
IIoT	Industrial Internet of things
IoT	Internet of things
IR	incremental redundancy
KPI	key performance indicator
L-LTF	legacy long training field
L-SIG	legacy signal field
L-STF	legacy short training field
L-MAC	lower MAC
LoS	line of sight
MAC	media access control
MCS	modulation code scheme
MDU	multiple dwelling unit
MFP	management frame protection
MIMO	multiple in multiple out
MLD	multi-link device

MLE	multi-link element
MLO	multi-link operation
MRU	multi-resource unit
ms	milliseconds
MU	multi-user
mW	milliwatts
NDP	null data packet
NDPA	null data packet announcement
NSTR	non-simultaneous transmission reception
OBSS	overlapping basic service set
OFDMA	orthogonal frequency division multiple access
PHY	physical
PPDU	physical protocol data unit
QAM	quadrature amplitude modulation
QoE	quality of experience
QoS	quality of service
RL-SIG	repeat legacy signal field
RNR	reduced neighbor report
ROI	return on investment
RSSI	receive signal strength indicator
RTA	real-time applications
RU	resource unit
SAE	simultaneous authentication of equals
SCTE	Society of Cable Telecommunications Engineers
SDN	software-defined networking
SIC	successive interference coordination
SNR	signal to noise ratio
SR	spatial reuse
SSID	service set identifier
STA	station
STR	simultaneous transmission reception
TIM	traffic indication map
TSN	time-sensitive networking
TWT	target wake time
TXOP	transmit opportunity
U-MAC	upper MAC
UL	uplink
U-SIG	universal signal
VR	virtual reality
WLAN	wireless local area network
WPA	Wi-Fi protected access

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