DOCSIS 4.0 and Wi-Fi 7

Perfect Together for Multiple Gigabits per Second Speed

A Technical Paper prepared for SCTE by

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1. Introduction

It is a thing of beauty when two interdependent technologies arrive at the same time wherein each needs the other to deliver service to customers. Such is the case with the newest cable modem standard for Data-over-Cable Service Interface Specification DOCSIS 4.0 and Institute for Electrical and Electronic Engineers (IEEE) 802.11be standard Wi-Fi 7. Two technologies under development for many years coming out of the lab and into customer homes. Wi-Fi 6 and 6E wireless adapters in many phones, computers and tablets have a maximum physical symbol, PHY rate of 2400 Mbps, (million bits per second). With a 2400 Mbps PHY rate throughput of file downloads, speed tests can reach 1.2 gigabits per second (Gbps). Wi-Fi 7 increases the modulation to 4096-QAM, quadrature amplitude modulation, and the channel width to 320 MHz, million cycles per second, resulting in a 2x2 client wireless adapter with a maximum PHY rate of 5764 Mbps, enough PHY rate for a throughput of 4.6 Gbps. About one and a half years ago, the first laboratory trials of DOCSIS 4.0 demonstrated speeds faster than 4 Gbps upload and download. This paper will describe the underlining technology propelling Wi-Fi 7 based on the IEEE 802.11be standard that will allow the speeds delivered by the DOCSIS 4.0 cable modem and the DOCSIS 4.0 infrastructure sending the signal to the cable modem to be delivered all the way to customer phones, tablets, and computers. In addition to higher order modulation and wider channel width, Wi-Fi 7 adds key technology to improve the range in the 6 GHz, billion cycles per second, band. Improving the range in the 6 GHz band is just as important as improving the speed. After all, high speed in the 6 GHz band is not much good to customers if they need to use another band to maintain coverage. Dual carrier modulation, duplication of dual carrier modulation, increased transmit power at 320 MHz channel width, and improved receiver sensitivity are key aspects of Wi-Fi 7 to improve the 6 GHz band range. This paper explains how modulating two carriers within a 20 MHz block of spectrum and duplicating these 20 MHz blocks results in improved dynamic range and better coverage. The paper provides measured results in both the lab and customer homes showing DOCSIS 4.0 and Wi-Fi 7 are perfect together.

2. DOCSIS 4.0

Cable operators are building next generation networks to provide multigigabit upload and download speeds at scale. Increased reliability, performance, and lower latency are benefits to customers provided by the next generation 10G network. The 10G network is a natural evolution of the original hybrid fiber coaxial cable (HFC) concept.

In an HFC architecture radio frequency (RF) signals in the 5-42 MHz upstream band and the 54-750/860/1002 MHz downstream band are created at the head end and carried over long distance with a low loss fiber optic cable using modulated transmitter and receiver laser to a fiber node. The extent of the downstream frequency varies. The fiber node converts the RF signal from optical to electrical, to distribute to cable modems and set top boxes in customer homes over coaxial cable, amplifiers, directional couplers, taps, and cable drops to homes. The signals to the cable modem (CM) are created at the head end by the cable modem termination system (CMTS). The CMTS converts 10 Gbps Ethernet signals for high-speed data to RF signals in the 5-42 MHz upstream and 108-750/860/1002 MHz downstream spectrum to feed optical receivers and transmitters that feed the HFC network. Over the years the downstream spectrum has been steadily expanded to 750, 860, and 1002 MHz as needed on a per fiber node basis and even the upstream in some cases has been expanded to 40 to 42 to 85 MHz upper end upstream spectrum. The ability of HFC to incrementally add capacity as needed with advanced technology with small changes to filters, amplifiers, and spacing has been key to the success of HFC to deliver voice, video, and phone to customer homes, continually meeting demand in a cost-effective way.

The 10G network replaces the CMTS with a virtual cable modem termination system (vCMTS). The vCMTS is located in the head end or even deeper in the operator's core network of routers linked with

100 Gbps connections distributed nationwide. The vCMTS provides the functionality of the CMTS without the RF converters that create the upstream signals in the 5-85 MHz band and downstream signals in the 108-1200 MHz band. The RF converters are moved to a remote physical interface node (RPHY) node. The RPHY node converts a 10 Gbps Ethernet interface carried over optical fiber to upstream RF signals in the 5-85 MHz band and downstream signals in the 108-1200 MHz band. The RF signals from the RPHY node are delivered to cable modems and set top boxes in customer homes over coaxial cable with trunk feeds, directional couplers, splitter taps, and drop coaxial cables. For a frequency division duplex system (FDD), the boundaries of the upstream and downstream allocated spectrum can be adjusted as upload and download demand from customers changes over time. For a full duplex DOCSIS system (FDX) the spectrum from 108 to 684 MHz within the downstream band of 108-1200 MHz can be used for upstream as well as downstream signals. This network architecture is still a hybrid of fiber optical cable and coaxial cable, thus an HFC network. To distinguish the new HFC from the old, the new 10G network is called a distributed access architecture (DAA) in order to highlight the virtualization of the CMTS.

10G and DAA deliver greater reliability by providing visibility into Internet performance from the core to the gateway and every element in between. Download speeds of 8 Gbps and upload speeds of 5 Gbps have been demonstrated over an HFC cable network to a DOCSIS 4.0 cable modem. (Comcast Demonstrates Fastest-Yet Speeds Over a Complete 10G Connection on a Live Network, 2022) Lab tests of FDX CM have delivered upload and download speeds faster than 4 Gbps using 10G network technology. (Comcast Announces World-First Test of 10G Modem Technology Capable of Delivering Multigigabit Speeds to Homes, 2022) A key component of the 10G network is low latency DOCSIS (LLD) based upon Internet Engineering Task Force's (IETF) open standards to mark latency sensitive traffic for interactive applications (Comcast Kicks Off Industry's First Low Latency DOCSIS Field Trials, 2023). All the advances in the 10G wide area network (WAN) require a next generation wireless local area network (WLAN) to match. Wi-Fi 6 will not suffice; Wi-Fi 7 comes to the rescue.

The focus of this paper is how Wi-Fi 7 can deliver the speeds of DOCSIS 4.0 to customer phones, tablets, computers, watches, and televisions. This section will provide a summary of the speeds of DOCSIS 4.0 as a WAN connection to a home router with WLAN (wireless local area network) radio to customer devices.

To get a rough idea of the speed capability of DOCSIS 4.0, over 1,000 MHz of spectrum is utilized from 5 MHz up to 1,200 MHz and perhaps beyond. 1,000 MHz of bandwidth with 10 bits/sec/Hz spectral efficiency yields a data rate of 10 Gbps. 4096-QAM modulates each OFDM (orthogonal frequency division multiple access) subcarrier with 12 bits, allowing for error correction and overhead to still get to a spectral efficiency of around 10 bits/s/Hz. Coaxial cable is bi-directional, meaning signals carried by the coaxial cable in both forward and reverse directions at the same time using the same frequency spectrum can be separated for demodulation in the receivers without filtering using a directional coupler. Thus, in theory a 1,000 MHz coaxial distribution system can support 10 Gbps in the upstream and downstream direction at the same time.

Directional couplers effectively separate the upstream and the downstream of a coaxial cable without the need for filtering of distinct upstream and downstream spectrum. The transmitted signal reflects back into the receiver due to impedance mismatches in the HFC plant. The reflected forward signal propagates in the coaxial cable in the same direction as the reverse signal. The directional coupler cannot separate the reverse signal from an echo of the forward signal since these two signals travel inside the coaxial cable in the same direction. An echo canceller is needed to feed samples of the transmitted signal back into the receiver with just the right time delays, amplitude, and phase to cancel the unwanted echoes of the transmitted signal inside the receiver.

The details of DOCSIS 4.0 are described in reference (Robert Howald, 2022) as well as many other excellent references. The key takeaway from reference (Robert Howald, 2022), for the purposes of this paper, is that 4 Gbps upload and download speeds become practical with DOCSIS 4.0 cable modems. 4 Gbps is not a speed that a Wi-Fi 6 or Wi-Fi 6e phone, tablet, or computer today can deliver. Wi-Fi 7 is needed to match the speed of DOCSIS 4.0 with customer devices.

3. Wi-Fi 7

Wi-Fi 7 is based on the IEEE 802.11be standard (IEEE 802.11be D3.0, 2023) for extremely high throughput. The increase in data rate is primarily accomplished with a doubling of the channel width in the 6 GHz band to 320 MHz and a quadrupling of the number of points in the constellation of the highest modulation from 1024 to 4096.

The IEEE 802.11be standard introduces a new physical layer interface (PHY) called extremely high throughput (EHT). EHT defines many new parameters, some borrowed from older standards and some novel. A definition of the timing-related parameters new to EHT PHY is needed to calculate the speeds of Wi-Fi 7 and determine if Wi-Fi 7 can carry the speeds of DOCSIS 4.0 to customer devices.

Subcarrier frequency spacing for the pre-EHT modulated fields is defined in equation (1).

$$\Delta_{F,Pre-EHT} = 312.5kHz \tag{1}$$

All transmissions are not EHT, even for EHT access points (AP) and stations (STA). Management and control signals as well as preambles of EHT signals mostly use 802.11a signals with data rates of 6, 12, and 24 Mbps. For EHT signals these are called pre-EHT. When OFDM was first introduced to WLAN with IEEE 802.11a, the subcarrier spacing was called, well, the subcarrier spacing, since there was only one. With the introduction of 802.11n, the subcarrier spacing did not change but the number of subcarriers increased for better spectral efficiency and a 40 MHz channel width option and 256-QAM modulation was added. The coexistence of the two PHY types necessitated the need to designate 802.11a as non-HT fields. And that technique and terminology is still with us today.

Subcarrier frequency spacing for the EHT modulated fields is defined in equation (2). This is the subcarrier spacing for EHT data symbols.

$$\Delta_{F,EHT} = \frac{\Delta_{F,Pre-EHT}}{4} = 78.125kHz \tag{2}$$

An OFDM transmitter applies modulation to frequency domain subcarriers and then performs an inverse discrete Fourier transform (IDFT) to create a time domain signal that provides input to an analog-to-digital converter (ADC). IDFT/DFT (discrete Fourier transform) period for the pre-EHT modulated field is defined in equation (3). It takes 3.2 μs time duration to create an 802.11a symbol DFT. An OFDM receiver accepts the time domain samples created in the transmitter and performs a DFT that converts the time domain samples into the frequency domain modulated symbols.

$$T_{DFT,Pre-EHT} = \frac{1}{\Delta_{F,Pre-EHT}} = 3.2\mu s \tag{3}$$

IDFT/DFT period for the EHT Data field is defined in equation (4). In calculating the PHY data rate in Mbps of EHT symbols, the denominator will be 12.8 μs plus the guard interval (GI). Using μs units for the symbol time conveniently results in data rate units of Mbps.

$$T_{DFT,EHT} = \frac{1}{\Delta_{F,EHT}} = 4 \cdot T_{DFT,Pre-EHT} = 12.8\mu s \quad (4)$$

$$T_{GI,Pre-EHT} = 0.8\mu s \quad (5)$$

Guard interval duration for the pre-EHT modulated fields excluding the legacy long training field (L-LTF) is defined in equation (5).

$$T_{GI,L-LTF} = 1.6\mu s \quad (6)$$

The guard interval of the L-LTF field is defined in equation (6).

The base guard interval duration for the Data field is defined in equation (7). For indoor residential environments, the base guard interval is plenty long enough to protect against inter-symbol interference due to multipath reflections.

$$T_{GI1,Data} = 0.8\mu s \quad (7)$$

The double guard interval duration for the Data field is defined in equation (8).

$$T_{GI2,Data} = 1.6\mu s \quad (8)$$

The double guard interval duration for the Data field used to protect against reflections from objects 800 feet from the AP is defined in equation (8). The double guard interval duration is useful for the long echoes of outdoor applications with an elevated AP.

The quadruple guard interval duration for the Data field is defined in equation (9). The quadruple guard interval is also useful to protect against long echoes for outdoor access points mounted high above the ground to increase coverage.

$$T_{GI4,Data} = 3.2\mu s \quad (9)$$

The quadruple guard interval duration for the Data field used to protect against reflection from objects 1600 feet away from the AP is defined in equation (9).

$$T_{GI,Data} = T_{GI1,Data} \ or \ T_{GI2,Data} \ or \ T_{GI4,Data} \quad (10)$$

The guard interval of the Data field defined in equation (10) is either the base, double, or quadruple guard interval duration. For indoor applications in residential homes and apartments, the base guard interval provides sufficient protection from multipath reflections. The longer guard intervals provide additional redundant information so that rate adaptation algorithms will sometimes resort to the double and quadruple guard intervals in special cases that need help with demodulation.

$$T_{GI,EHT-LTF} = T_{GI,Data} \quad (11)$$

The guard interval duration for the EHT-LTF is the same as the guard interval duration of the Data field as shown in equation (11).

The OFDM symbol duration with base guard interval is defined in equation (12).

$$T_{SYM1} = T_{DFT,EHT} + T_{GI1,Data} = 1.0625 \cdot T_{DFT,EHT} = 13.6\mu s \quad (12)$$

The OFDM symbol duration for the base interval is the sum of the EHT DFT duration defined in equation (4) and the base guard interval defined in equation (7).

The subcarrier frequency spacing for pre-EHT modulated fields is 312.5 kHz, making the DFT period 3.2 µs as shown in equation (13). The subcarrier frequency spacing for EHT modulated fields is 78.125 kHz, one fourth that of pre-EHT signals, making the DFT period 12.8 µs, four times longer than the pre-EHT period. EHT subcarrier spacing and DFT period is the same as high efficiency mode (HE) introduced in IEEE 802.11ax. The reasons for the longer DFT period and the closer subcarrier spacing used for EHT and HE are explained in reference (Urban, The Importance Of Wi-Fi 6 Technology For Delivery Of GBPS Internet Service, 2019).

$$\Delta_F = \frac{1}{T_{DFT}} \quad (13)$$

The signal that a Wi-Fi 7 receiver demodulates is called a physical layer protocol data unit (PPDU). The physical layer (PHY) preamble of the PPDU is processed by the receiver to aid in detection and demodulation of the PPDU.

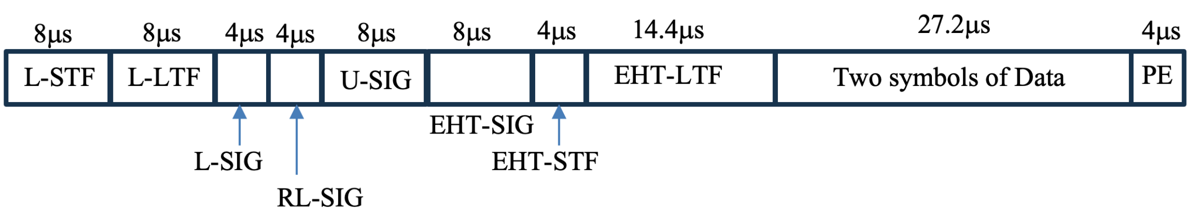


Figure 1 – EHT MU PPDU fields and typical durations

The maximum PHY rate of a 2x2 320 MHz Wi-Fi 7 wireless adapter is 5764 Mbps. The PHY rate is the number of data bits carried in one OFDM data symbol divided by the symbol period. Data symbols are only part of a PPDU field. A preamble is needed in order to detect the signal, lock onto the frequency, estimate the channel, determine the signal parameters, and adjust for amplitude and phase in order to demodulate the data symbol.

The EHT PPDU fields are listed in Table 1 along with a description and duration in μs.

Table 1 – EHT PPDU fields with typical durations

Field	Description	Duration μs
L-STF	Non-HT short training field	8
L-LTF	Non-HT long training field	8
L-SIG	Non-HT SIGNAL field	4
RL-SIG	Repeated Non-HT SIGNAL field	4
U-SIG	Universal SIGNAL field	8
EHT-SIG	EHT SIGNAL field	4
EHT-STF	EHT short training field	8

Field	Description	Duration μs
EHT-LTF	EHT long training field	14.4
Data	The data carrying the PSDU(s)	13.6 per symbol
PE	Packet Extension field	0

An EHT transmission begins with a legacy short training field (L-STF). A legacy symbol is also referred to as a non-HT symbol. HT mode stands for high throughput mode, which was introduced with 802.11n, thus a non-HT symbol uses the PHY mode of 802.11a. 802.11a was the first Wi-Fi standard to use OFDM with a 312.5 kHz subcarrier spacing and a 6 Mbps data rate symbol using binary phase shift keying (BPSK) and ½ binary convolutional coding (BCC) code rate in a 20 MHz channel width. The L-STF is followed by a legacy long training field (L-LTF) the legacy signal field (L-SIG). After the 20 μs legacy part of the preamble, a repeated L-SIG (RL-SIG) and universal SIG (U-SIG), precedes the EHT preamble fields. EHT-SIG, EHT-STF, EHT-LTF precede the Data symbols followed by a packet extension (PE) field.

4. Channel Width: EHT ups the ante to 320 MHz

Wi-Fi 7, based upon the IEEE 802.11be standard, increases the maximum channel width from 160 MHz to 320 MHz of spectrum. A fast Fourier transform (FFT) is a mathematically efficient algorithm to calculate a discrete Fourier transform (DFT). The DFT of a time domain signal sampled every 3.125 ns will demodulate tones covering a 320 MHz channel width as shown in equation (14).

$$B = \frac{1}{T_{sampling}} = \frac{1.0}{3.125E-9} = 320E6 \tag{14}$$

The guard interval protecting two symbols from interfering with each other due to multipath reflections for EHT symbols can be one of three selections 0.8, 1.6, or 3.2 μs. The 800 ns guard interval protects against reflections that are 400 feet from the access point, AP, since light travels one foot in one ns. The 800 ns guard interval is sufficient for indoor applications while the 1.6 and 3.2 μs guard intervals are mostly applicable for outdoor applications with a km or greater coverage range.

The DFT period and the guard interval form a symbol period. The DFT period is selected to be 16 times the guard interval of 800 ns to increase efficiency, putting the DFT period at 12.8 μs as shown in equation (15). The 12.8 μs DFT period was introduced in 802.11ax and continued in 802.11be, this is what puts the efficiency in high efficiency (HE) mode.

$$T_g = 800 \cdot 10^{-9} \qquad T_{DFT} = 16 \ \cdot Tg = 12.8 \cdot 10^{-6} \tag{15}$$

The DFT size is the number of time domain samples and the number of frequency domain tones that make up the useful part of an OFDM symbol. The DFT size can be determined by dividing the DFT period by the time domain sampling rate or equivalently dividing the channel width by the subcarrier spacing as shown in equation (16).

$$N_{DFT} = \frac{T_{DFT}}{T_{sampling}} = \frac{12.8 \cdot 10^{-6}}{3.125 \cdot 10^{-9}} = 4096 = \frac{\mathrm{B}}{\Delta_{\mathrm{F}}} = \frac{320\mathrm{MHz}}{78.125\mathrm{kHz}} \tag{16}$$

The DFT size of an EHT 320 MHz channel width OFDM symbol is 4096. A transmitter creating a 320 MHz OFDM EHT symbol will perform an IDFT on 4096 frequency domain tones to produce the 4096 time domain samples of the DFT period portion of an OFDM symbol. An OFDM symbol is created by appending a cyclic prefix to the DFT period to provide a guard time between OFDM symbols to prevent inter-symbol interference due to multipath reflections. The OFDM EHT symbol period is 13.6 µs as calculated in equation (17).

$$T_{SYM} = T_{GI} + T_{DFT} = 0.8 + 12.8 = 13.6\mu s \tag{17}$$

For the purposes of understanding data rates and throughput of Wi-Fi 7 signals as it relates to customer experience, coverage, range, device, and application requirements, the key takeaway of an understanding of the DFT used in forming an OFDM symbol is the number of data subcarriers in a symbol and the symbol duration. These are used in the calculation of PHY rate, which is one of the important parameters impacting throughput.

Table 2 – Subcarrier allocation of 320 MHz EHT modulated fields

parameter	CBW320 tones	Description
N_{DFT}	4096	DFT subcarriers or tones
$N_{SD,total}$	3920	Total number of data subcarriers
N_{SP}	64	Number of pilot subcarriers
N_{SR}	2036	Highest data subcarrier index
N_{DC}	23	Direct current null subcarriers (DC)
$N_{Guard,Left}$	12	Number of low frequency guard subcarriers
$N_{Guard,Right}$	11	Number of high frequency guard subcarriers

The 4096 subcarriers that make up an EHT 320 MHz OFDM symbol consist of three types: null, pilot, and data subcarriers. An EHT OFDM 320 MHz symbol has 3,920 data subcarriers as shown in Table 2.

An EHT signal with 320 MHz channel bandwidth is composed of four identical blocks of 80 MHz of spectrum. An 80 MHz block of spectrum contains 16 pilot subcarriers. The receiver needs pilot subcarriers to demodulate the signal. The frequency response of the received signal can be estimated and corrected by comparing the pilot subcarriers at different frequencies within a symbol time. The center frequency of the received signal can be locked by determining the phase change between two pilot subcarriers at different symbol times. The symbol time is known so the frequency offset can be calculated as the change in phase divided by the change in time.

Null subcarriers have zero energy and are used to protect the receiver from transmit center frequency leakage, receiver DC offset, and interference from neighboring adjacent signals. Null subcarriers are added to the left and right guard band and baseband DC. Baseband DC corresponds to the center frequency of a radiated signal on a particular 6 GHz band channel. The left guard band of an 80 MHz channel is protected by 12 null subcarriers while the right guard band is protected by 11 null subcarriers, and the baseband DC offset is protected by 5 null subcarriers.

Range is improved with increased channel width. A common misperception is that narrower channel width provides better range for WLAN systems. As with many myths, a truth taken out of context is the root of the misunderstanding. It is certainly true that in the 5 GHz band WLAN, as one walks further and further from the access point, the rate adaptation algorithm will adjust the channel width from 160 to 80 to 40 and finally to 20 MHz as the receive level decreases. However, the coverage range is only improved at reduced channel width when the only factor considered is connectivity without considering throughput. Wi-Fi is a high-speed data transfer system, so high speed must be an important requirement. When one looks at the range of coverage for a given required amount of throughput, the picture looks quite different.

The plot in Figure 2 illustrates the range advantage of increased channel width. The total conducted transmit level is the same at each channel width of 20, 40, 80, 160, and 320 MHz of spectrum. This is often the case in the 2.4 and 5 GHz Wi-Fi bands due to convention and regulatory limits. The Federal Communications Commission (FCC) allows 1 watt of conducted power into the antenna in the 2.4 GHz industrial, scientific, medical (ISM)band, and unlicensed national information infrastructure (U-NII) 1 and 3 bands with some restrictions in power spectral density, bandwidth, and out-of-band emissions.

Since the transmit level is the same for a 20, 40, 80, 160, and 320 MHz channel width, the signal to noise ratio improves by 3 dB when the channel width is cut in half since the receive level remains the same, while the noise level decreases by 3 dB with the halving of the equivalent noise bandwidth. This improves coverage and is reflected in the plot at the very low PHY rates.

However, as the PHY rate is increased, the range advantage of wider channel widths becomes more apparent. The range advantage of wider channel width increases as the PHY rate increases, seen as the widening gap for different channel widths moving to the right in the plot as PHY rate increases. The 3 dB advantage in the lower noise floor due to halving the channel width becomes small compared to the stronger signal level needed for higher modulation level to double the spectral efficiency. Increased modulation rate is needed for small channel width to make up for the greater number of data carrying subcarriers of wider channel width signals.

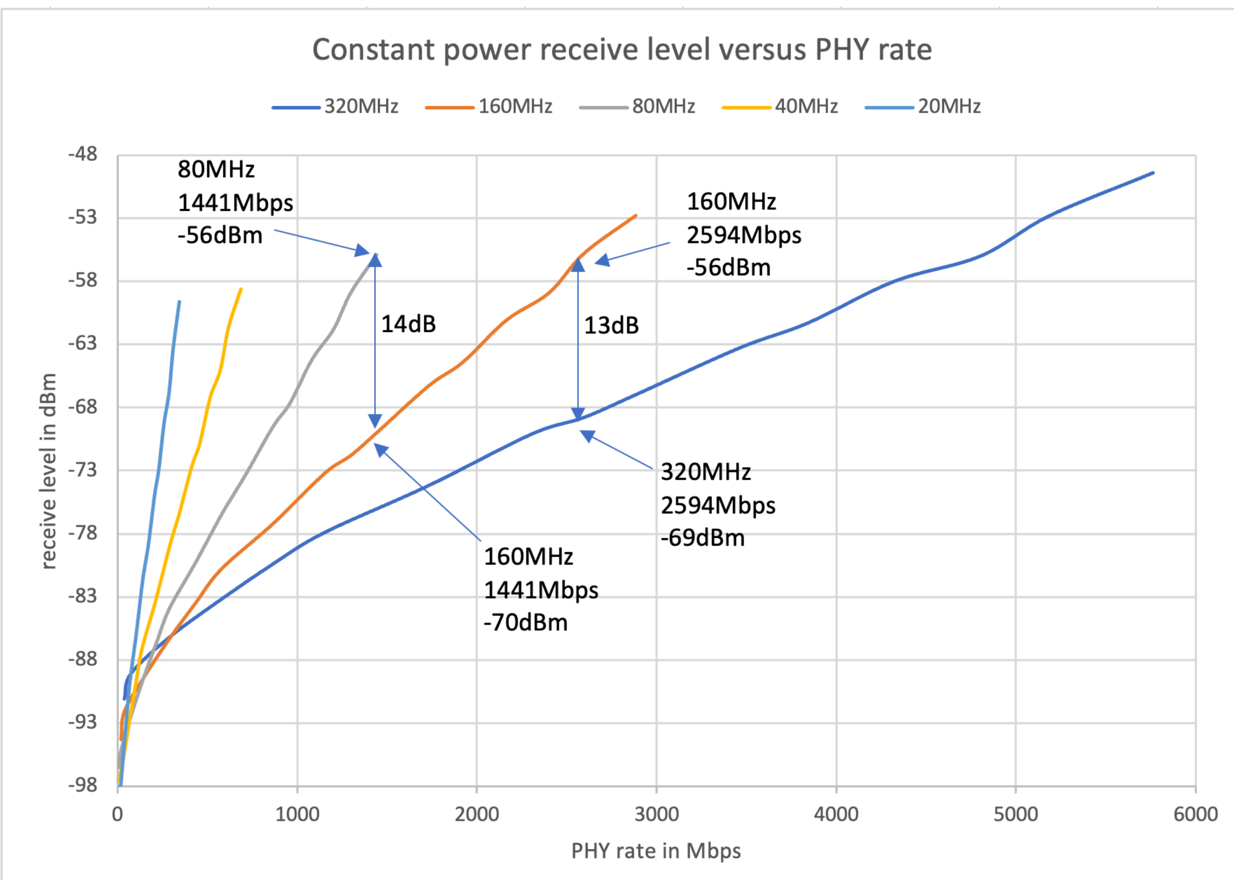


Figure 2 – Range is improved with increased channel width for a required throughput

When power spectral density is restricted, as is the case with the 6 GHz band for indoor operation, the advantage of wider channel width for range improvement becomes more acute as shown in Figure 3. A plot of PHY rate versus distance, comparing 320 MHz and 160 MHz using the 802.11 path loss model for indoor residential, is shown. The cell edge is neither improved nor degraded by 320 MHz channel width compared to 160 MHz as seen in the converged lines beyond 35 meters. At any given PHY rate above about 200 Mbps, the distance is greater for the 320 MHz channel width than the 160 MHz channel width. This is the range advantage of 320 MHz versus 160 MHz or lower channel width. As a result, the rate adaptation algorithm will always use the highest available channel width when range is the limiting factor. There can still be reasons for using narrower resource units, such as channel availability and OFDMA, but the link budget will never be a reason to reduce the channel width. The higher the required PHY rate, the greater the distance advantage of 320 MHz channel width over 160 MHz channel width.

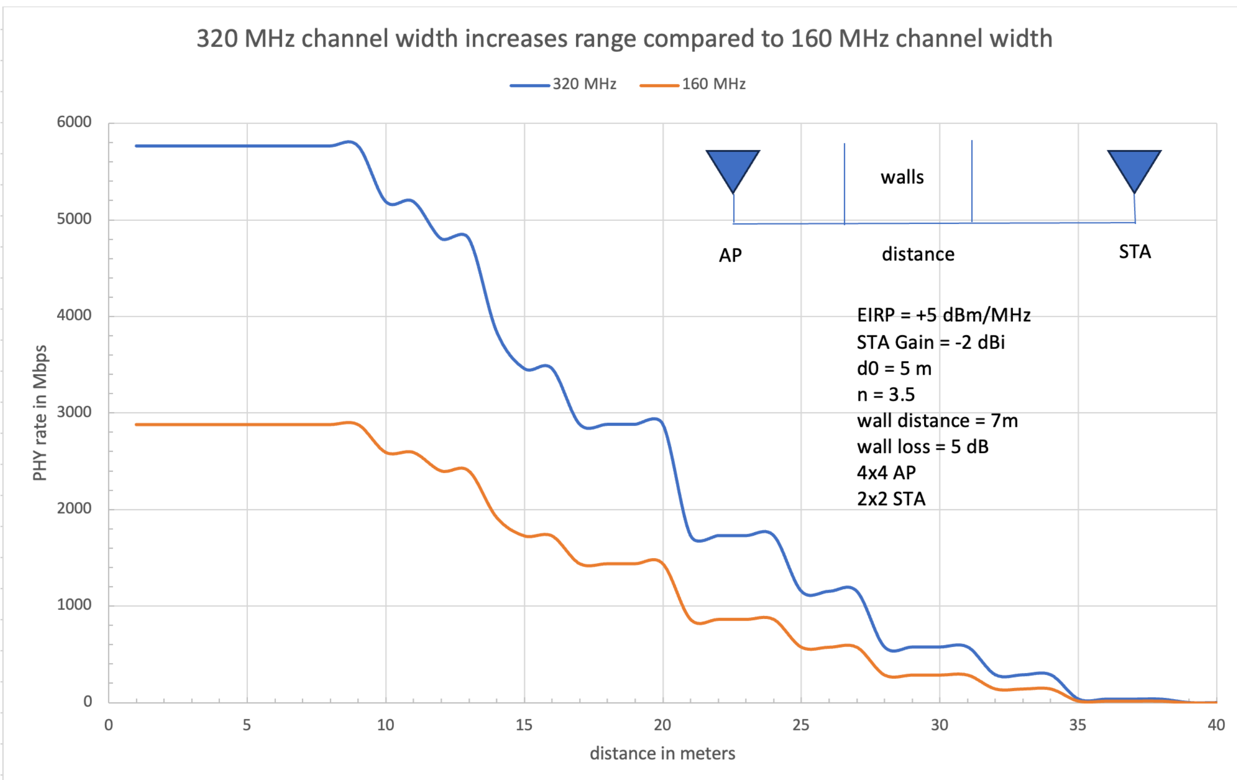


Figure 3 – Improvement in range for 320 MHz with constant power spectral density

5. EHT Preamble

Before an OFDM data symbol can be transmitted or received, a preamble must precede the OFDM data symbol for the receiver to detect the presence of the signal, lock into the frequency of the signal, estimate the channel, determine the characteristics of the signal, and use automatic gain control to adjust for signal level.

5.1. L-STF to detect the signal

An EHT transmission begins with a legacy short training field, L-STF. A legacy symbol is also referred to as a non-HT symbol. HT mode stands for high throughput mode, which was introduced with 802.11n, thus a non-HT symbol uses the PHY mode of 802.11a. 802.11a was the first Wi-Fi standard to use OFDM with a 312.5 kHz subcarrier spacing and a 6 Mbps data rate symbol using BPSK and ½ BCC code rate in a 20 MHz channel width.

A DFT with a time domain input sampling rate of 3.125 ns and 4096-time samples will output 4096 frequency domain tones, having a channel width of 320 MHz. The DFT period is 12.8 μs. The L-STF consists of 172 tones over 320 MHz channel width. The tones can be created with a 256-point IDFT using a 3.125 ns sampling interval since 172 subcarriers are greater than 128 but less than 256. The L-STF symbol time is 256 times 3.125 ns, which equals 800 ns or 0.8 μs. The 0.8 μs duration of the L-STF field consists of 10 repeated symbols without any guard interval. The repetition of ten symbols in the L-STF is important since it allows a self-correlation function to detect the reception of an 802.11 signal. Wi-Fi is an asynchronous time division duplex (TDD) system so a receiver never knows a priori when a signal will arrive that needs to be demodulated. A self-correlation function that detects the repeated 10 symbols of the L-STF is critical in detecting the presence of an incoming signal.

5.2. L-LTF

Following the L-STF in the EHT preamble is the L-LTF.

5.3. L-SIG

Following the L-LTF in the EHT preamble is the L-SIG.

5.4. RL-SIG

Following the L-SIG in the EHT preamble is the RL-SIG.

5.5. U-SIG Introducing version independent fields

Following the RL-SIG in the EHT preamble is the U-SIG. The U-SIG is composed of two 4 μs symbols. The duration of the U-SIG is 8 μs. U-SIG introduces version independent fields designed to improve compatibility with future versions of Wi-Fi beyond Wi-Fi 7. Wi-Fi 8 is already in the works.

5.6. EHT-SIG

Following the U-SIG in the EHT preamble is the EHT-SIG.

5.7. EHT-STF

Following the EHT-SIG in the EHT preamble is the EHT-STF.

5.8. EHT-LTF for receiver MIMO channel estimation

The EHT-LTF helps the receiver with multiple input multiple output (MIMO) antennas channel estimation. The duration of the EHT-LTF is not always the same, $N_{EHT-LTF}$ is the number of EHT-LTF symbols in the EHT preamble. Most client wireless adapters are 2x2 so that most often two spatial streams are used, $N_{SS} = 2$. When $N_{SS} = 2$ the initial number of EHT-LTF symbols is two, $N_{EHT-LTF} = 2$.

The EHT-LTF duration of each OFDM symbol without a guard interval can be set to 3.2, 6.4, or 12.8 μs.

Table 3 – EHT-LTF symbol duration options

Parameter	Value	Description
$T_{EHT-LTF-1X}$	3.2 μs	Duration of each 1xEHT-LTF OFDM symbol without GI
$T_{EHT-LTF-2X}$	6.4 μs	Duration of each 2xEHT-LTF OFDM symbol without GI
$T_{EHT-LTF-4X}$	12.8 μs	Duration of each 4xEHT-LTF OFDM symbol without GI

2xEHT-LTF is the most common setting, so this will be used in calculations for this paper. Using a T_{GI} of 0.8 μs and two EHT-LTF symbols of 6.4 μs each yields an EHT-LTF symbol duration of 7.2 μs as shown in equation (18) .

$$T_{EHT-LTF-SYM} = T_{EHT-LTF} + T_{GI,EHT-LTF} = 0.8 + 6.4 = 7.2\mu s \quad (18)$$

For two spatial streams, a most common situation, the duration of the EHT-LTF field will be 14.4 μs for a setting of EHT-LTFx2.

5.9. PE packet extension field

Following the EHT preamble and the Data field in the EHT PPDU is the packet extension field (PE). The duration of the packet extension field denoted T_{PE} in the IEEE 802.11be standard (IEEE 802.11be D3.0, 2023) can be 0, 4, 8, 12, 16, or 20 μs depending on the actual packet extension duration used.

6. Let's talk about spectrum.

The rules and regulations for Unlicensed National Information Infrastructure (U-NII) in the United States are defined in part 15.407 (FCC). Table 4 – USA FCC Unlicensed National Information Infrastructure Frequency in MHz lists the number of the band, the start and stop frequency in MHz and the bandwidth in MHz of each band. U-NII 2B is listed in the table but usage is not allowed for WLAN application.

Table 4 – USA FCC Unlicensed National Information Infrastructure Frequency in MHz

Band	Start	Stop	Bandwidth
U-NII 1	5150	5250	100
U-NII 2A	5250	5350	100
U-NII 2B	5350	5470	120
U-NII 2C	5470	5725	255
U-NII 3	5725	5850	125
U-NII 4	5850	5925	75
U-NII 5	5925	6425	500
U-NII 6	6425	6525	100
U-NII 7	6525	6875	350
U-NII 8	6875	7125	250

In the United States the FCC has allocated 1,200 MHz of spectrum for unlicensed use in U-NII bands 5,6,7,8. While one can always look up the channels and frequencies, it is sometimes handy to have a mnemonic trick that can aid in developing a better appreciation of the capacity of the allocation. The spectrum from 6 GHz to 7 GHz spans 1,000 MHz so that 200 MHz of addition spectrum is required outside of the 6 GHz band. 75 MHz is allocated below 6 GHz and 125 MHz is allocated above 7 GHz. That puts the range of spectrum from 5925-7125 MHz.

Thus, 6 GHz band spectrum in the United States for WLAN begins at 5925 MHz and ends at 7125 MHz, covering 1200 MHz total bandwidth. U-NII 5 spans 500 MHz of spectrum beginning 75 MHz below 6 GHz. The lowest frequency is 5925 MHz, and the highest frequency is 6425 MHz. The first 20 MHz is not used, being too close to U-NII 4. The first 20 MHz channel thus begins at 5945 MHz and ends at 5965 MHz with a center frequency of 5955 MHz. This 20 MHz channel is designated as channel 1, leading to the formula to calculate the center frequency given the channel number as shown in equation (19).

$$f_c = 5950 + 5 \cdot n_{ch} \tag{19}$$

The lowest frequency 20 MHz block of spectrum is centered at 5955 MHz, designated as channel 1. The highest frequency 20 MHz block of spectrum is centered at 7115 MHz, designated as channel 233. With 233 possible primary channels of 20 MHz channel width to choose from, preferred scanning channels are defined to reduce the time and resources it takes to find a signal to connect. If the process of sending a probe request leading to the connection on a primary channel takes 20 ms and there are 233 primary channels to scan, then it will take 4.66 seconds to scan all the channels. 15 primary channels are defined as preferred scanning channels (PSC) spaced by 16 channels. The list of PSC in the 6 GHz band is 5,21,37,53,69,85,101,117,133,149,165,181,197,213,229.

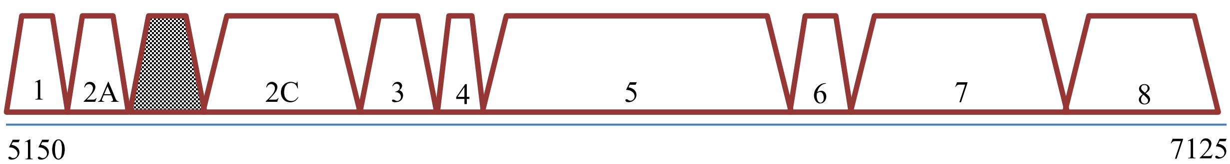


Figure 4 – U-NII band

The U-NII band begins, and 5150 MHz ends at 7125 MHz. The 2.4 GHz band has three 20 MHz channels, the 5 GHz band has three 160 MHz channels, and the 6 GHz band has three 320 MHz channels.

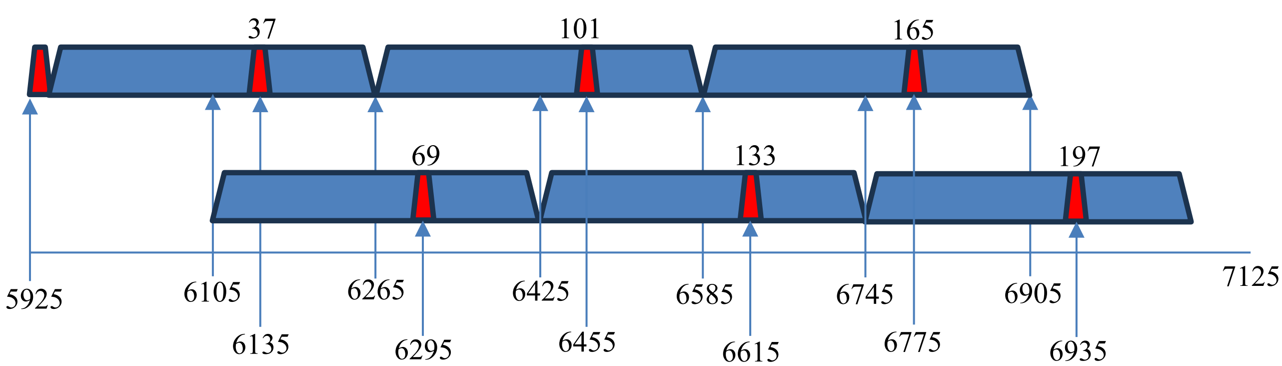


Figure 5 – 6 GHz band preferred scanning channels and center frequencies in MHz

The 6 GHz band has three 320 MHz channel width signals that can be placed beginning at the lowest frequency or ending at the highest frequency as shown in Figure 5 and listed in Table 5 – 6 GHz band 320 MHz channels.

Table 5 – 6 GHz band 320 MHz channels

Channel	f_c MHz	Center channel	PSC Channel	PSC f_c MHz
6g37/320-1	6105	31	37	6135
6g101/320-1	6425	95	101	6455
6g165/320-1	6745	159	165	6775
6g69/320-2	6265	63	69	6295
6g133/320-2	6585	127	133	6615
6g197/320-2	6905	191	197	6935

The list of 320 MHz channels shown in Table 5 – 6 GHz band 320 MHz channels details the channel naming scheme, the center frequency in MHz of the 320 MHz wide channel width, the number of the primary scanning channel, and the center frequency in MHz of the 20 MHz wide primary scanning channel. Since channel 37 is also a 5 GHz band channel number, 6g37 is used to indicate that this refers to channel 37 in the 6 GHz band and not the 5 GHz band. The 6g37/320 notation indicates the primary scanning channel is 37 in the 6 GHz band with a channel width of 320 MHz where the three 320 MHz channels begin at the lower end of the 6 GHz band.

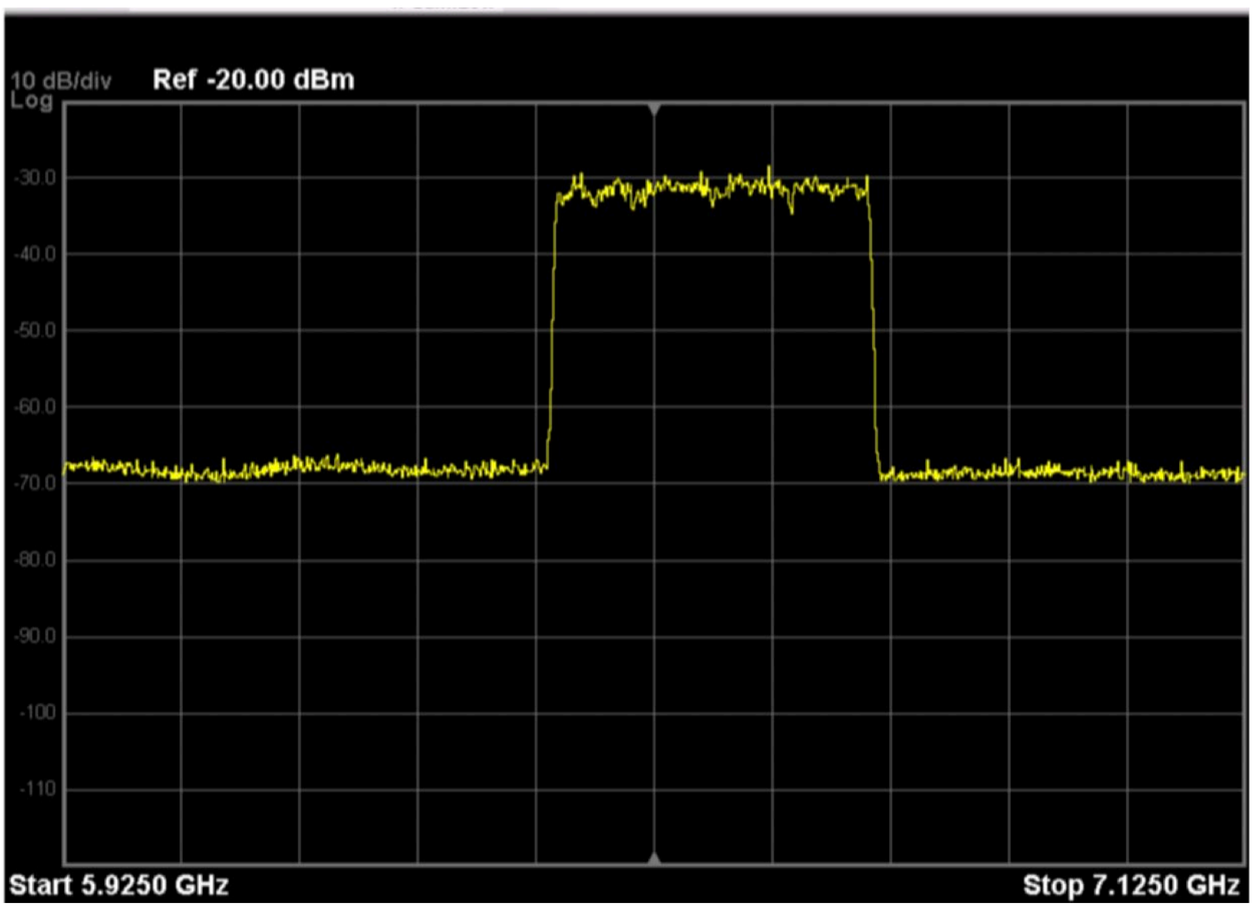


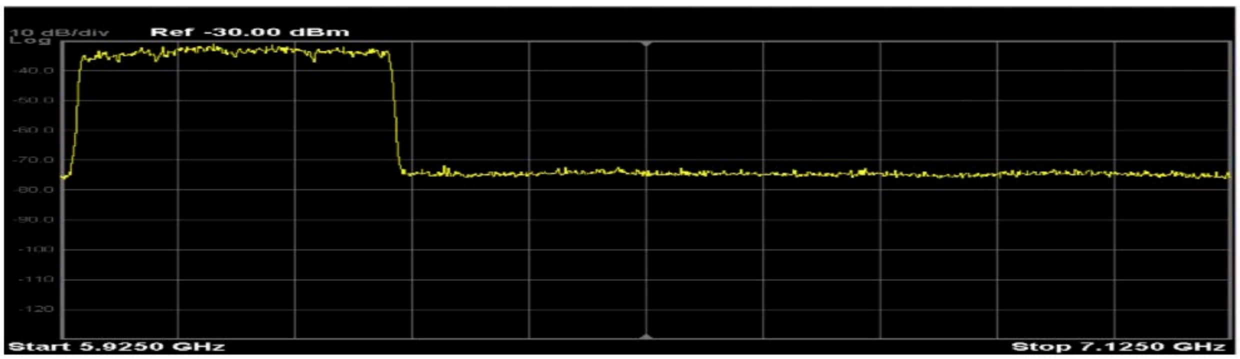
Figure 6 – Spectrum analyzer plot of 6g133/320-2 over 6 GHz band

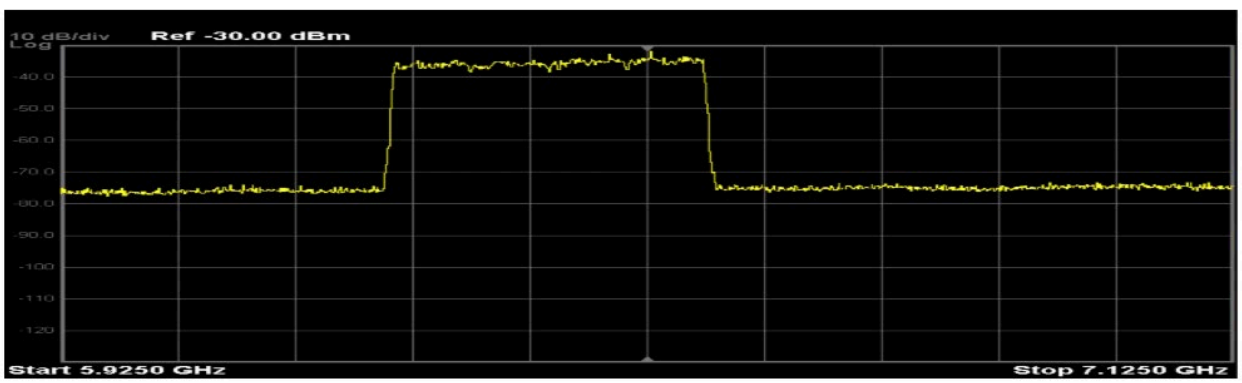
A spectrum analyzer sweep is shown in Figure 6 with peak hold to reveal the full 320 MHz channel width of 6g133/320-2 swept from the 5925 MHz lowest part of the 6 GHz band to the 7125 MHz highest part of the 6 GHz band. The frequency sweep over the whole 6 GHz band spectrum shows the relative position of 6g133/320-2 within the full 6 GHz band.

Figure 7 – Spectrum analyzer plot of 6g37/320-1, 6g101/320-1, 6g165/320-1 shows a sweep of all three of the 320 MHz channel width signals set towards the lower end of the 6 GHz band.

Figure 8 – Spectrum analyzer plot of 6g69/320-2, 6g133/320-2, 6g197/320-2 shows a sweep of all three of the 320 MHz channel width signals set at the upper end of the 6 GHz band.

The peak hold spectrum analyzer measurements of all six 320 MHz channel width signals in the 6 GHz band helps illustrate the channel selections that overlap in spectrum and those that do not. When trying to keep channels from overlapping within a cluster of access points stick with either the “-1” scheme or the “-2” scheme. Don’t mix the dashes.





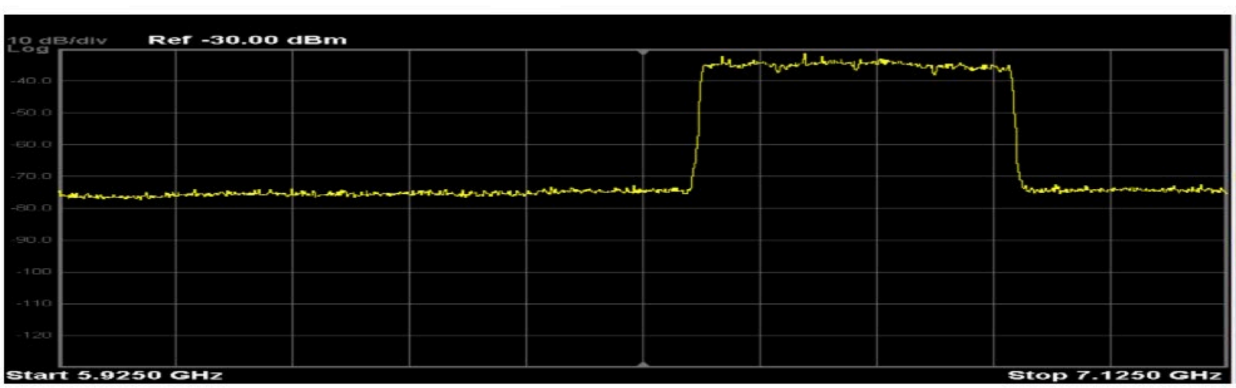


Figure 7 – Spectrum analyzer plot of 6g37/320-1, 6g101/320-1, 6g165/320-1

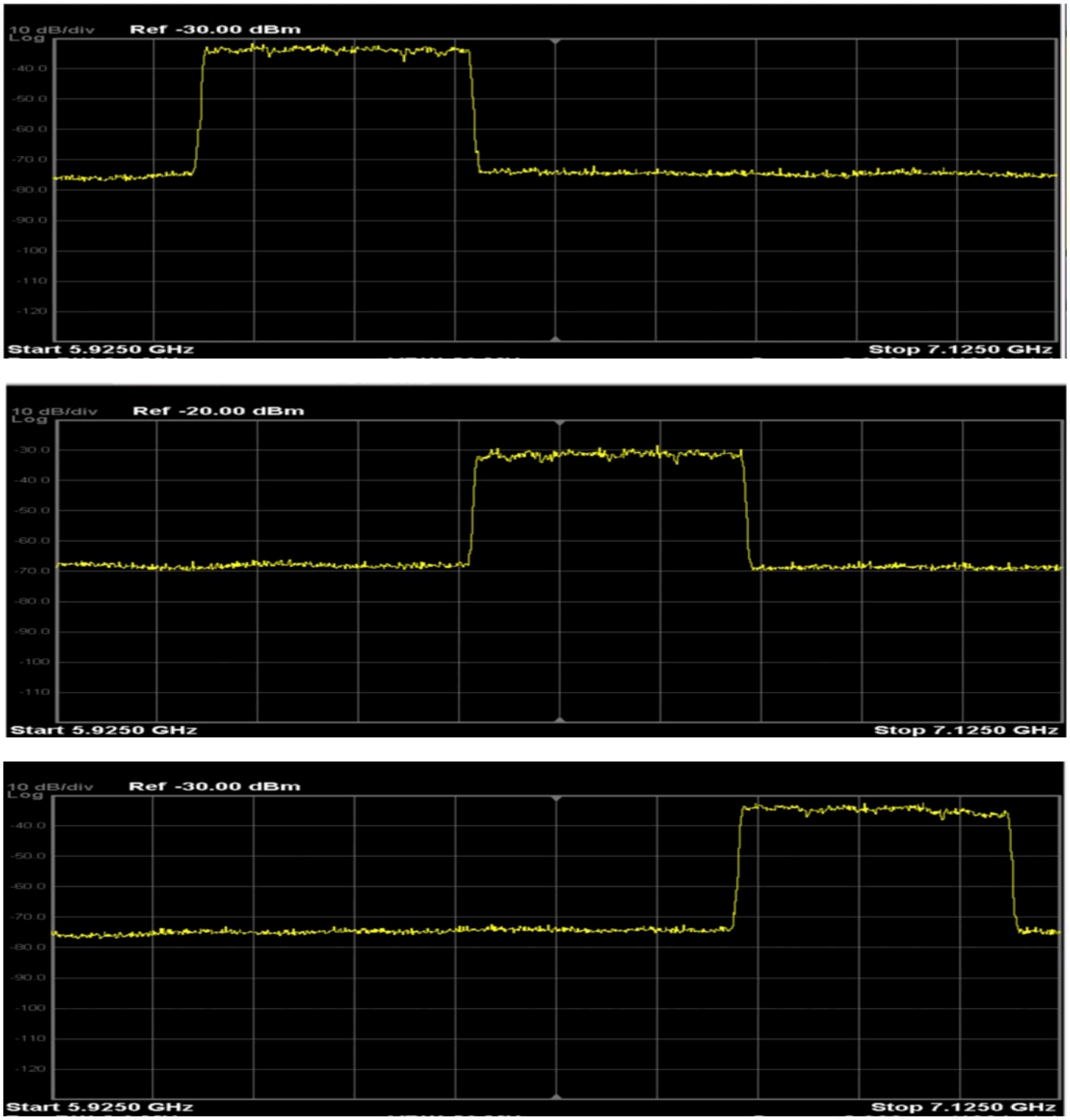


Figure 8 – Spectrum analyzer plot of 6g69/320-2, 6g133/320-2, 6g197/320-2

Figure 9 – Spectrum analyzer plot to 8 GHz with EHT 6g37/320-1 max download shows a spectrum analyzer sweep with a span of 8.39 GHz and a center frequency of 4.205 GHz while a TCP download is run on channel 6g37/320-1. It is always important to widen the sweep outside of the channel width and even the U-NII band to make sure that no unwanted emission falls outside of the desired frequency spectrum.

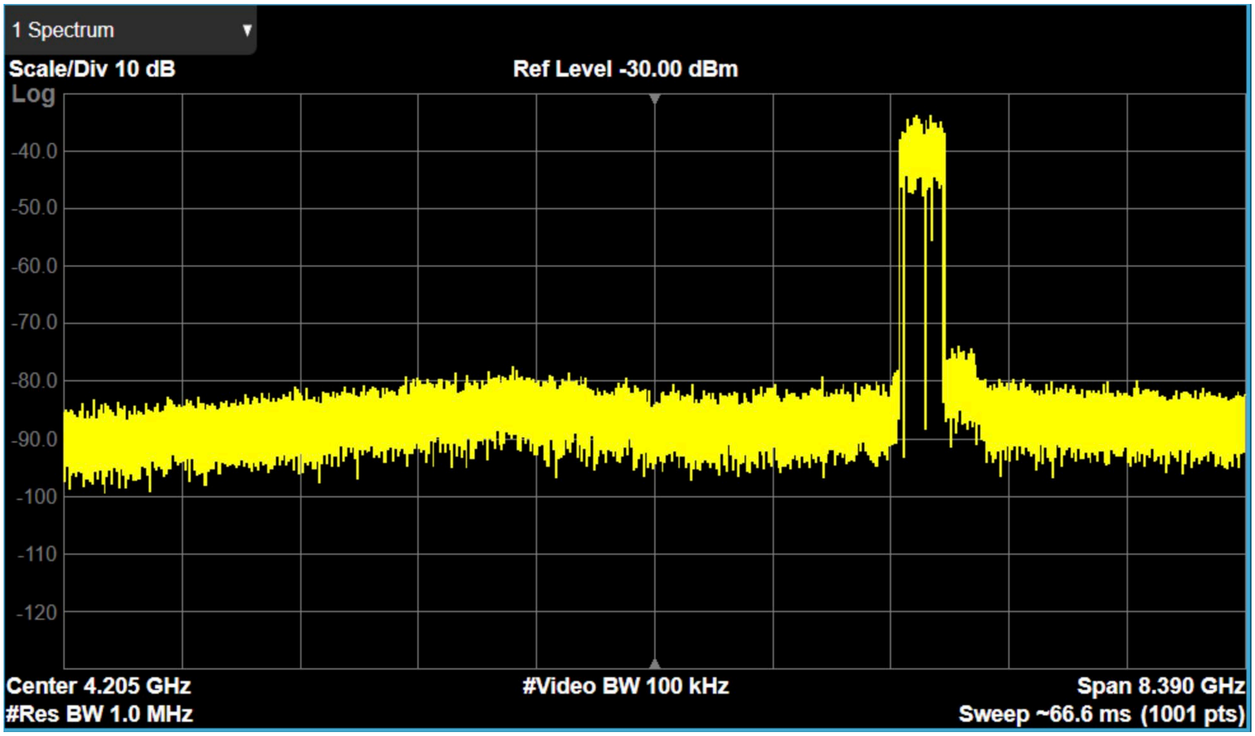


Figure 9 – Spectrum analyzer plot to 8 GHz with EHT 6g37/320-1 max download

7. Modulation and Coding; Introducing 4k-QAM to Wi-Fi

Wi-Fi 7, based upon the IEEE 802.11be standard, adds two modulation and coding (MCS) levels with higher spectral efficiency. MCS12 employs 4096-QAM with ¾ low density parity check coding (LDPC) coding. MCS13 employs 4096-QAM with 5/6 LDPC coding. 4096-QAM has a constellation size of 4096 points, where each point represents 12 bits as calculated in equation (20).

$$2^{12} = 4096 \tag{20}$$

Claude Shannon published a mathematical theory of communications in the Bell System Technical Journal in 1948. A key insight in this seminal paper was that methods of modulation exchange bandwidth for signal to noise ratio (Shannon, 1948). The capacity of a channel of band W perturbed by white thermal noise power N when the average power is limited to P is given by equation (21).

$$C = B \cdot log_2\left(1 + \frac{P+N}{N}\right) \tag{21}$$

Solving for signal to noise ratio (SNR) in dB as a function of bits is shown in equation (22).

$$SNR = 10 \cdot log_{10}\left(\frac{P+N}{N}\right) = 10 \cdot log_{10}\left(2^{\left(\frac{C}{B}\right)} - 1\right) \tag{22}$$

Applying a C/B of 10 bits per second per Hz for 1024-QAM modulation in (22) calculates 30 dB SNR. Applying a C/B of 12 bits per second per Hz for 4096-QAM modulation in (22) calculates 36 dB SNR. These are reasonably close to the measured SNR threshold for MCS11 and MCS13, and the difference of 6 dB higher SNR requirement between 1024-QAM and 4096-QAM is quite close to the IEEE 802.11be receiver sensitivity requirement differences between 1024-QAM and 4096-QAM for the same LDPC code rate and the measured sensitivity level differences. Applying the actual data rate and channel width to Shannon's capacity formula seems to indicate that there is still some room for improvement. Shannon's capacity formula is good to keep in mind in order to appreciate the relationship between adding capacity to channel width compared to adding capacity with modulation in relation to the impact of SNR requirement and receive level requirement.

The PHY data rate, R_d can be calculated using the number of spatial streams, N_{SS}, the number of data subcarriers, N_{SD}, the number of coded bits per OFDM symbol per subcarrier, N_{CBPSS} , the code rate, R, and the symbol period, $T_{SYM} = T_{DFT} + T_{GI}$. The formula is shown in equation (23) and calculated for the maximum PHY rate of a 4x4 320 MHz EHT AP.

$$R_d = \frac{N_{SS} \cdot N_{SD} \cdot N_{CBPSS} \cdot R}{T_{DFT} + T_{GI}} = \frac{4 \cdot 3920 \cdot 12 \cdot 5/6}{12.8 + 0.8} = 11{,}529\ Mbps \tag{23}$$

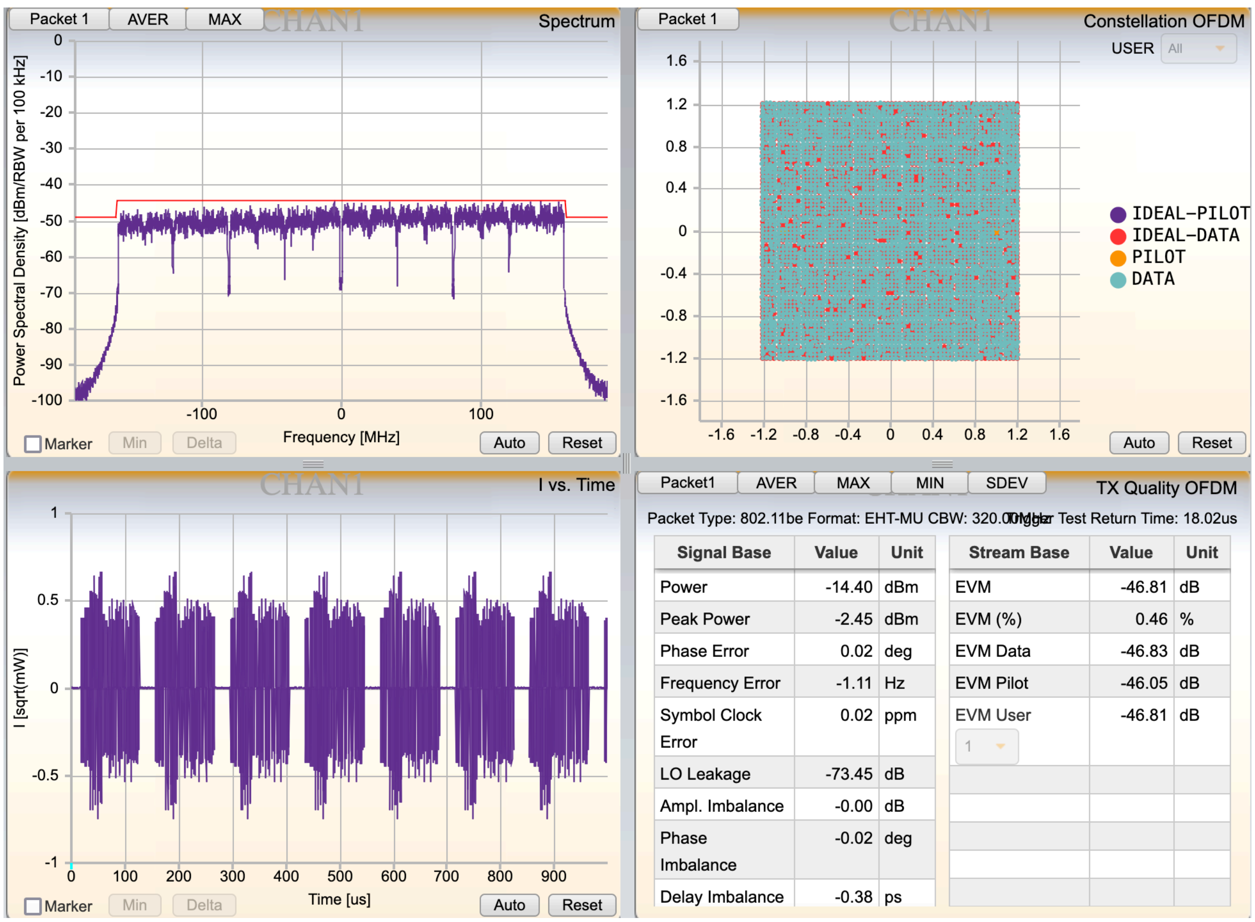


Figure 10 – MCS13 QAM-4096 LDPC 5/6 320 MHz 802.11be Wi-Fi 7 signal

Figure 10 – MCS13 QAM-4096 LDPC 5/6 320 MHz 802.11be Wi-Fi 7 signal show the 320 MHz spectrum of the signal, the 4096 point constellation diagram of MCS16, the power versus time waveform of the signal, and the error vector magnitude (EVM) of -46 dB.

BPSK modulation assigns 1 bit to each subcarrier with two points in the constellation diagram. The measured BPSK constellation is shown in Figure 11 along with the time waveform power, spectrum, and EVM per subcarrier.

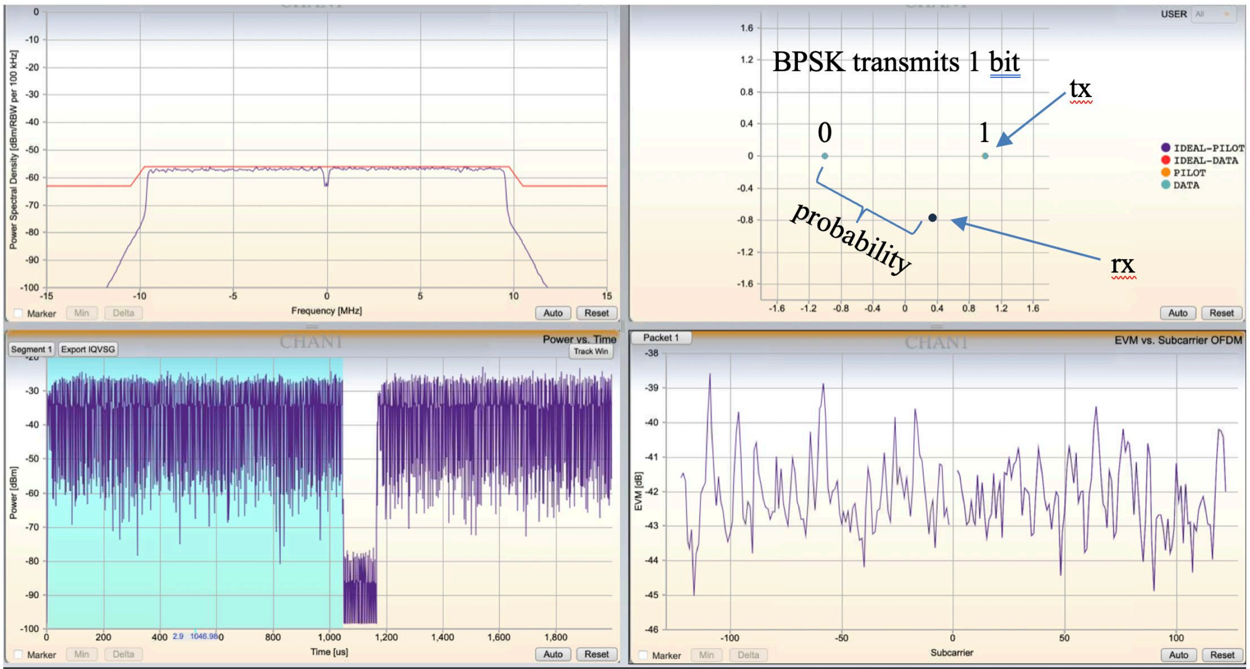


Figure 11 – BPSK signal showing spectrum, constellation, time domain signal, EVM.

The markup in the BPSK constellation diagram illustrates that BPSK carries 1 bit of information, one dot represents a 0 and the other a 1. The point labeled “tx” is the transmitted signal and the added point labelled “rx” represents an example receive point that deviates from the transmitted signal due to noise, interference, and distortion. The BPSK demodulator will send two probabilities to the LDPC decoder for the message passing algorithm. A probability that the transmitted bit was a 1 given the received vector. and a probability that the transmitted bit was a 0 given the received vector is sent to the message passing algorithm of the LDPC decoder based upon the distance from the two possible transmitter vectors and the received vector using a probability distribution model.

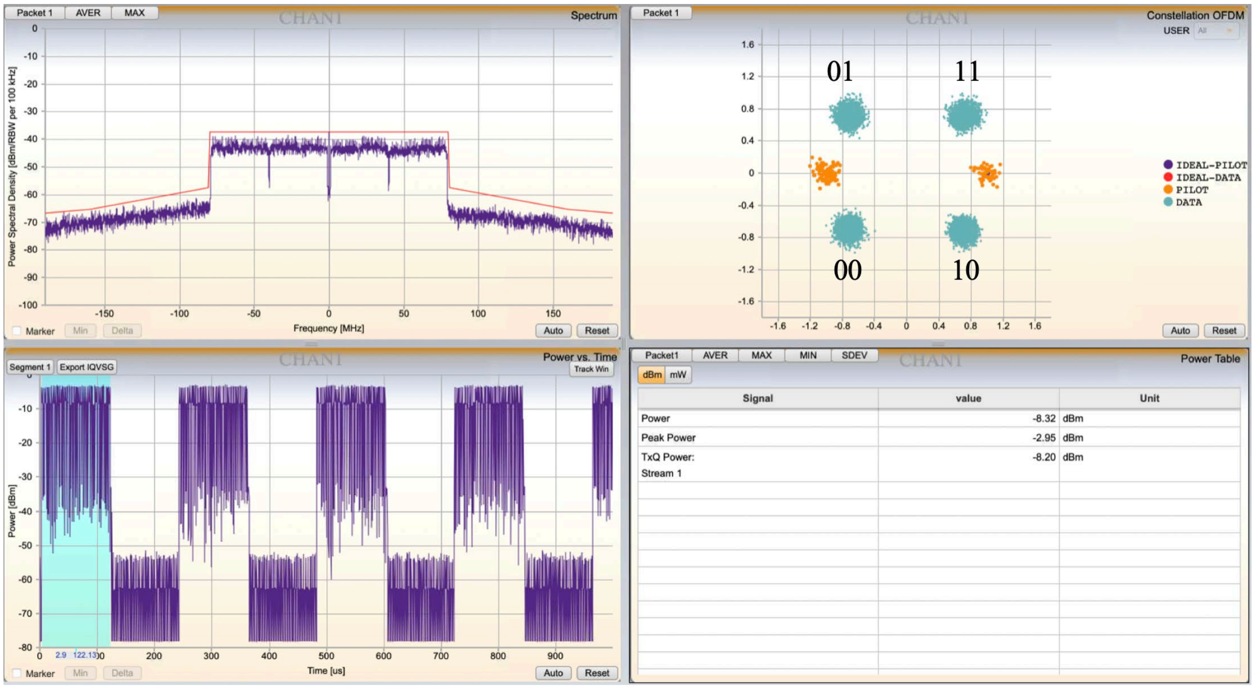


Figure 12 – QPSK modulation maps 2 bits to each subcarrier.

QPSK modulation maps two bits to each subcarrier. QPSK has four constellation points. This is illustrated in Figure 12 – QPSK modulation maps 2 bits to each subcarrier.

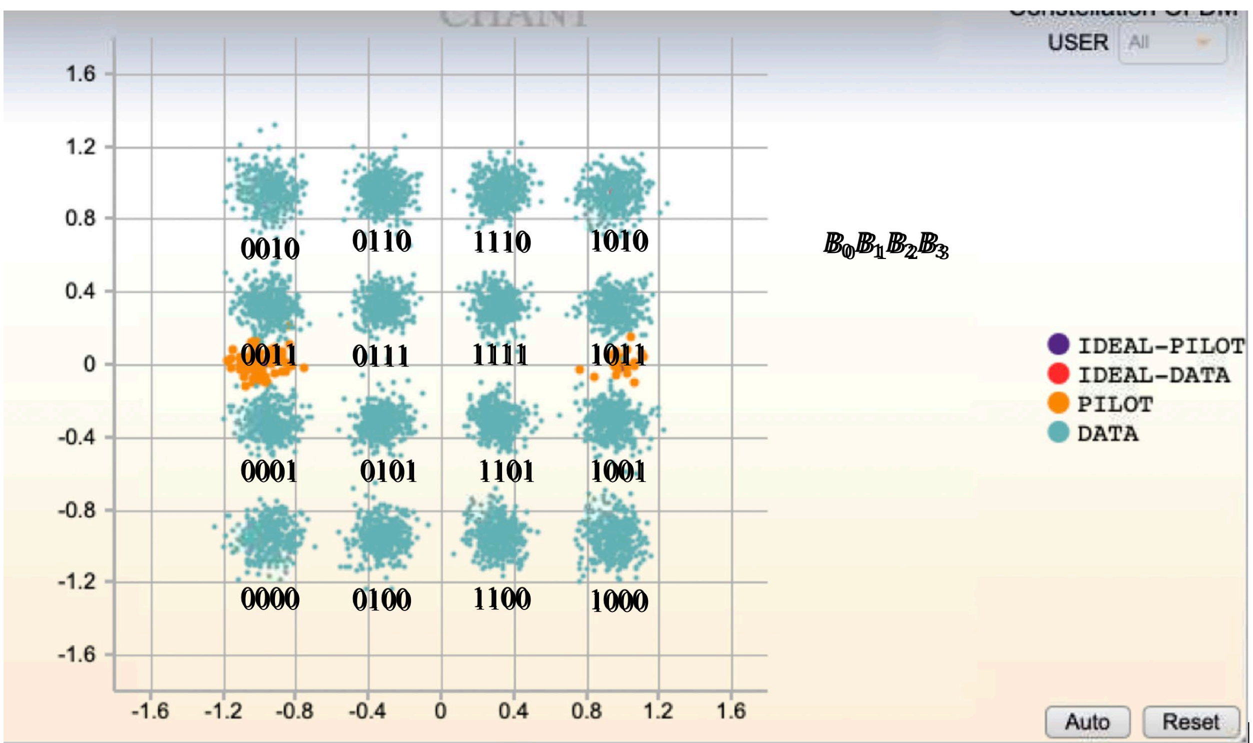


Figure 13 – 16-QAM modulation maps 4 bits to each subcarrier.

Figure 13 – 16-QAM modulation maps 4 bits to each subcarrier. The markup shows how 4 bits are mapped to each constellation according to the IEEE 802.11 standard.

Table 6 – Modulation 2x2 320 MHz Wi-Fi 7 station

MCS Index	Modulation	Code rate	Subcarriers	PHY Mbps
14	BPSK	1/2	980	36
15	BPSK	1/2	1960	72
0	BPSK	1/2	3920	288
1	QPSK	1/2	3920	576
2	QPSK	3/4	3920	864
3	16-QAM	1/2	3920	1152
4	16-QAM	3/4	3920	1729
5	64-QAM	2/3	3920	2305
6	64-QAM	3/4	3920	2594
7	64-QAM	5/6	3920	2882
8	256-QAM	3/4	3920	3458
9	256-QAM	5/6	3920	3843
10	1024-QAM	3/4	3920	4323
11	1024-QAM	5/6	3920	4803
12	4096-QAM	3/4	3920	5188
13	4096-QAM	5/6	3920	5764

The PHY rate in Mbps is shown in Table 6 for all MCS indices from 0 to 15 for a 2x2 320 MHz EHT STA. The modulation and code rate for each MCS index is also shown. MCS 14 and MCS 15 only use one spatial stream since these rates are intended to trade off throughput to get the best range at cell edge. As a result, the PHY rate for MCS 15 is 72 Mbps while MCS 14 is 36 Mbps. All the other MCS indices calculate the PHY rate for two spatial streams since the EHT STA is 2x2 and the EHT AP is 4x4. Two spatial streams require sufficient multipath reflections for the required MIMO channel capacity. Indoor Wi-Fi channels have proven to easily support two spatial streams with 4x4 AP and 2x2 STA.

Table 7 – PHY rate in Mbps and SNR for 20, 40, 80, 160, 320 MHz channel width shows the PHY rate of each MCS from lowest PHY to highest PHY for all channel widths. The SNR requirement is the same for all the channel widths. The noise floor will change for each channel width but not the required SNR. Since the noise floor changes with channel width, the input level required for each MCS rate increases along with the channel width. For a noise figure of 3 dB, the noise floor in a 320 MHz channel width will be -86 decibel above a milliwatt (dBm). A 39 dB SNR will require an input level of -47 dBm. MCS13 for a 320 MHz channel width signal has a PHY rate of 5764 Mbps and needs an input level of -47 dBm. The SNR requirement, the number of spatial streams, the receiver noise figure, the maximum ratio combining effectiveness, and the quality of both the AP and STA radios will vary. Still these estimates are helpful in determining requirements and understanding how Wi-Fi 7 will work in customer homes. An SNR of about 1 dB is required for MCS14, indicating that an input level of -85 dBm will be required for a PHY rate of 36 dBm. Measurements of MCS14 show a throughput of about 30 Mbps with input level of about -85 dBm.

Table 7 – PHY rate in Mbps and SNR for 20, 40, 80, 160, 320 MHz channel width

STA	2x2		AP	4x4		
Channel Width in MHz		20	40	80	160	320
MCS	SNR in dB	PHY Mbps	PHY Mbps	PHY Mbps	PHY Mbps	PHY Mbps
14	1	N/A	N/A	9.0	18.0	36.0
15	3	4.3	8.6	18.0	36.0	72.1
0	3	17.2	34.4	72.1	144.1	288.2
1	6	34.4	68.8	144.1	288.2	576.5
2	8	51.6	103.2	216.2	432.4	864.7
3	11	68.8	137.6	288.2	576.5	1152.9
4	15	103.2	206.5	432.4	864.7	1729.4
5	19	137.6	275.3	576.5	1152.9	2305.9
6	20	154.9	309.7	648.5	1297.1	2594.1
7	21	172.1	344.1	720.6	1441.2	2882.4
8	26	206.5	412.9	864.7	1729.4	3458.8
9	28	229.4	458.8	960.8	1921.6	3843.1
10	31	258.1	516.2	1080.9	2161.8	4323.5
11	33	286.8	573.5	1201.0	2402.0	4803.9
12	36	309.7	619.4	1297.1	2594.1	5188.2
13	39	344.1	688.2	1441.2	2882.4	5764.7

Figure 14 – 2x2 320 MHz EHT device data rate including impact of preamble shows that the duration of the PPDU needs to be about 1 ms in duration to get close to the symbol data rate of 5.7 Gbps when factoring in the preamble. This is why the preamble field was detailed with particular attention to the duration of each field. The PHY rate only translates into high throughput when many data symbols are packed into a single PPDU. This tells us two things. First, aggregation will be just as important of a factor when measuring throughput as PHY rate. Second, the traffic demand must be very high to feed the high PHY rates so that PHY rate results in high throughput.

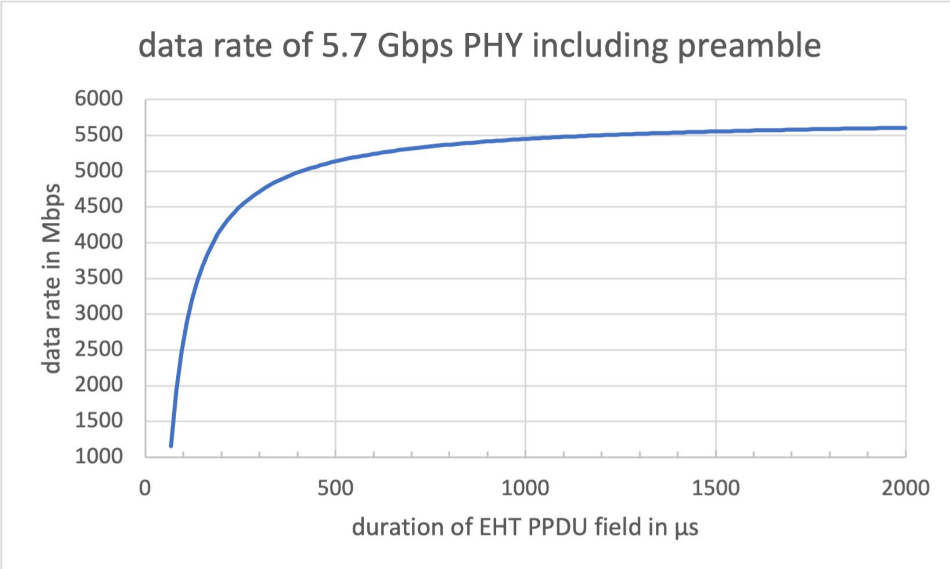


Figure 14 – 2x2 320 MHz EHT device data rate including impact of preamble

8. The hidden node problem

AP and STA check for channel busy before transmitting. This works as long as all radios here all signals. The hidden node problem is common and occurs when a radio checks for channel busy and finds all clear only because the interference at the receiver is blocked from the transmitter. Request to send (RTS), clear to send (CTS), and block acknowledgment (block Ack), prevent the hidden node problem by first asking the receiver to check for channel busy rather than just relying on the transmitters assessment.

The RTS from an AP to STA has a length of 76 bytes. The RTS data rate is 24 Mbps. The RTS duration is 28 μs with preamble of 20 μs and interframe space (IFS) of 83 μs. The CTS response from the STA to the AP has a length of 70 bytes. The CTS data rate is 24 Mbps. The CTS duration is 28 μs with 20 μs preamble and 14 μs IFS. The RTS and CTS packets are followed by a series of quality of service (QoS) Data packets and then a Block Ack packet. The Block Ack from the STA to the AP after a download of packets has a length of 88 bytes. The Block Ack data rate is 24 Mbps. The Block Ack duration is 32 μs with a preamble of 20 μs.

Figure 15 – 2x2 320 MHz EHT device data rate including impact of preamble and RTS CTS Block Ack plots the data rate as a function of duration from RTS to block Ack. At least two ms is required to get the effective data rate to 5 Gbps.

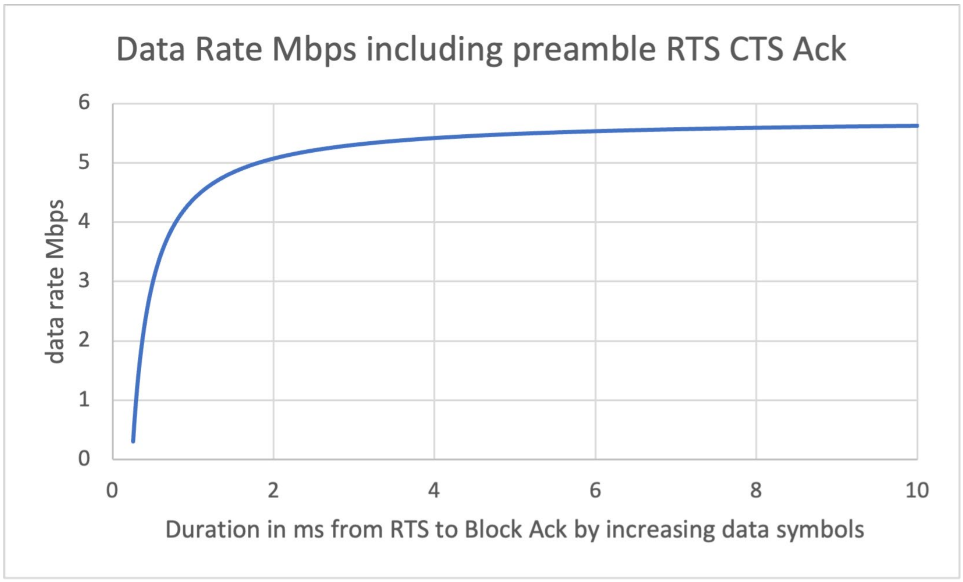


Figure 15 – 2x2 320 MHz EHT device data rate including impact of preamble and RTS CTS Block Ack

9. A quick word on beacons and probes

Often the most impactful variable in Wi-Fi performance in customer homes is beacon pollution, that is, too many beacons making it hard for clients to find the service set identifier (SSID) they are searching for and competing for airtime when trying to transmit and receive data packets.

The measured beacon duration of 0.6 ms is shown in Figure 16. Beacons are repeated every 102.5 μs so that a single beacon occupies only 0.59% of the airtime. Inverting the beacon duty cycle reveals that 171 beacons within earshot would try to fill all of the airtime. Access points often transmit multiple beacons for different services provided. If each AP transmits three beacons, then only 57 access points with overlapping coverage beacons attempt to transmit 100% of the time. Beacons must check for channel busy like any other transmission before transmitting so that beacons will not actually fill all the airtime. However, beacon pollution will still impact the data capacity of the spectrum and impact clients trying to connect to a desired SSID. Excessive beacons and probes, particularly with overlapping yet offset primary channel, trick the self-correlator into detecting signals that cannot be demodulated. This is called false detection and will result in automatic gain control to respond by increasing the effective receiver noise floor.

The 20 MHz 802.11a beacon signal is repeated 16 times to cover the full 320 MHz channel width as shown in Figure 16 – The measured beacon duration of a 320 MHz 6GHz band EHT signal.

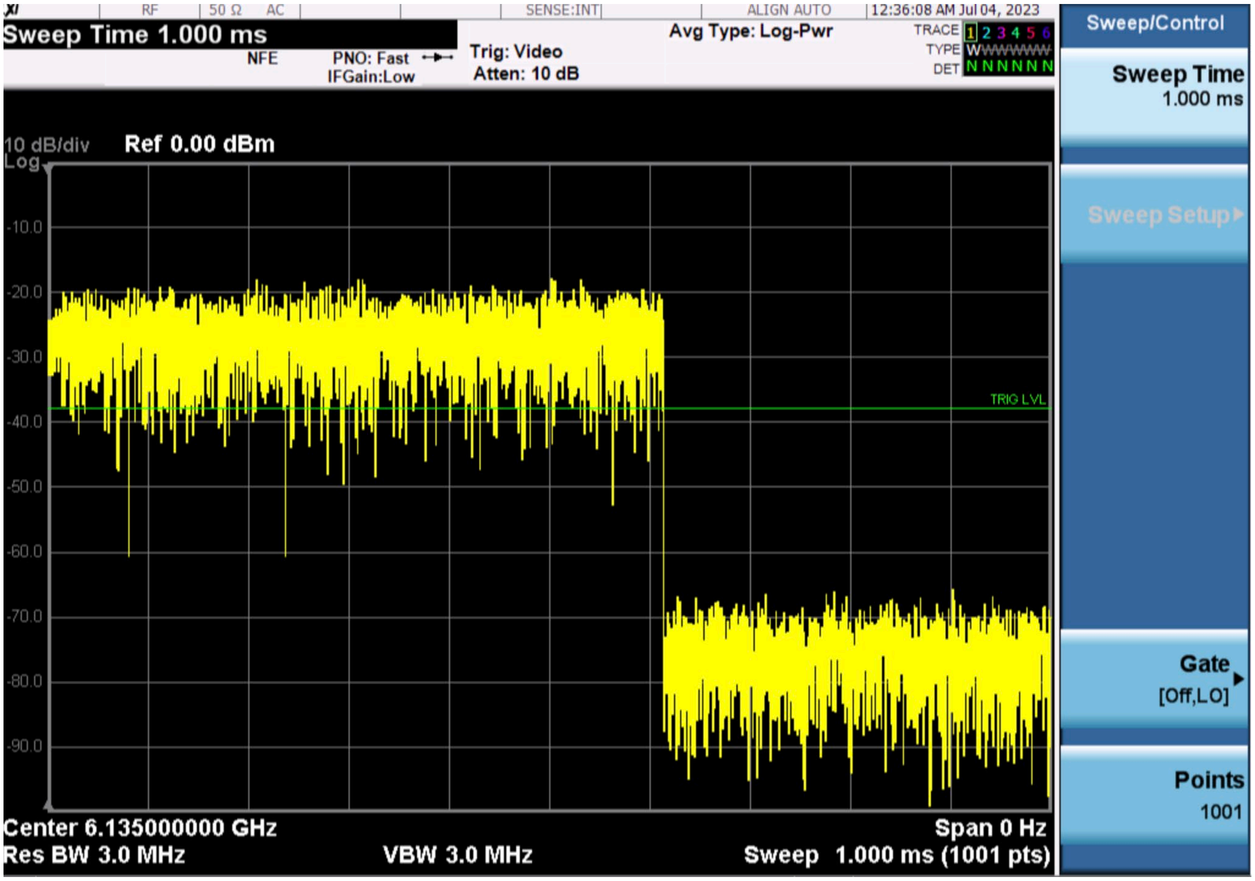


Figure 16 – The measured beacon duration of a 320 MHz 6GHz band EHT signal.

The peak power of the signal is only about 6 dB higher than the average power in this example, peak to average power ratio (PAPR) reduction is working. The modulation of the signal is BPSK as indicated by the constellation of two points separated by 180 degrees of phase shift.

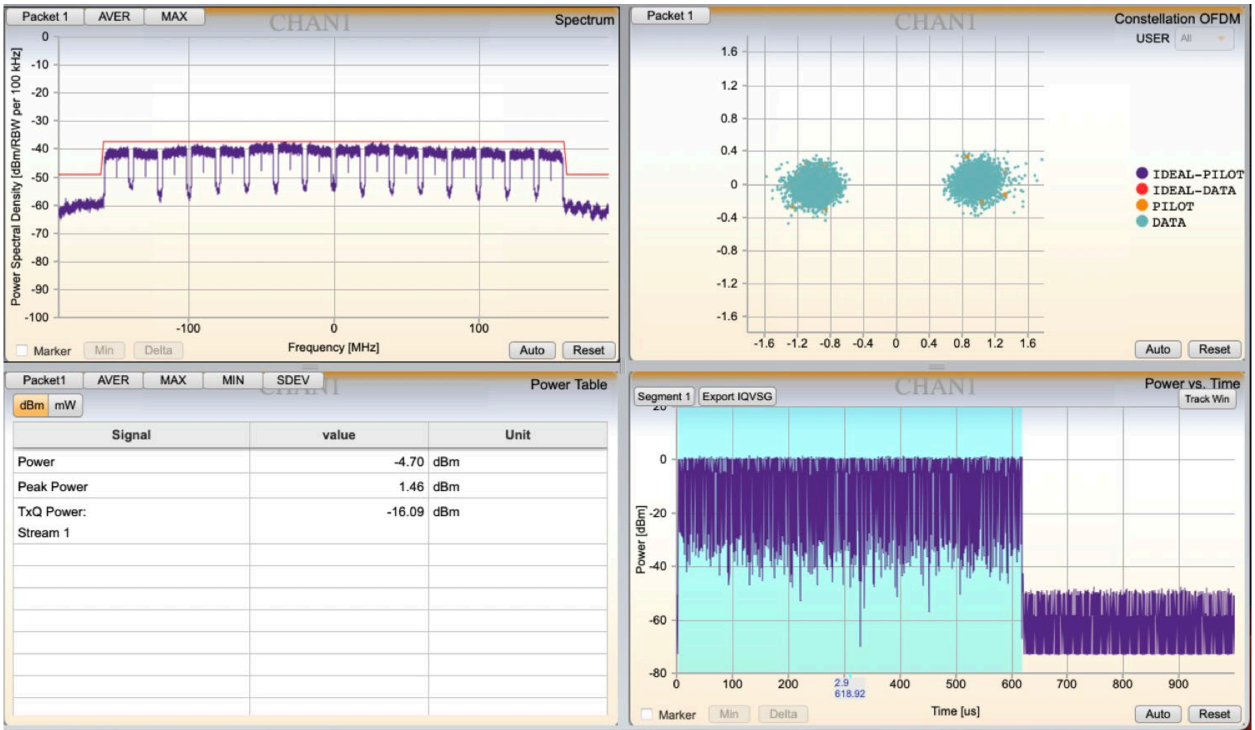


Figure 17 – The beacon is repeated over the full 320 MHz channel width

10. DCM+DUP: How to use 320 MHz channel width to improve range

The increase to 320 MHz channel width can be used to double the throughput with only a 3 dB penalty in input signal level. Since the 6 GHz band for indoor operation rules limit effective isotropic radiated power (EIRP) per MHz, doubling the channel width allows 3 dB increase in transmit power level which counteracts the 3 dB increase in noise with a doubling of the equivalent noise bandwidth. In general, wider channel width is the closest thing to a free lunch in wireless communications with a doubling of the channel width doubling the throughput with a small price of 3 dB increase in receive level. With EIRP per MHz as the regulatory limit, increasing the channel width is truly a free lunch, doubling the channel width doubles the throughput without reducing the link budget. The receive level needs to be 3 dB higher but the allowed transmit level is 3 dB greater.

Doubling the throughput by increasing the channel width from 160 MHz to 320 MHz is great and all for extremely high throughput, but how does this help with coverage range? Spread spectrum techniques have been utilized often to make a tradeoff between spectrum use, data rate, and range. The first cellular systems used wideband frequency modulation (FM) to improve the link budget by 10 dB by FM modulating a 3 kHz analog voice signal with 30 kHz FM.

Dual carrier modulation (DCM) and duplicate (DUP) combine to improve range for MCS14 in IEEE 802.11be. How does repeating modulation on two subcarriers within a 20 MHz channel width and then repeating the 20 MHz DCM subcarriers twice within the 320 MHz channel width improve range? To help us understand, let's begin with the old approach to enhancing range with narrow channel widths at higher power spectral density.

In the 2.4 and 5 GHz WLAN bands, the main regulatory restriction on transmit level is the total conducted power. There are also restrictions on out-of-band emissions, antenna gain, and power spectral density as well as practical limits to DC power consumption and thermal constraints. However, in many cases, the conducted transmit level can get very close to the regulatory limit, without being impacted by the channel width.

Consider a 160 MHz channel width in the 5 GHz band transmitting at +24 dBm total conducted power. The noise level with a 3 dB noise figure receiver is -89 dBm for a 160 MHz channel width signal as calculated in Table 7 in reference (Urban, How Broadband Customers Can Benefit from Newfangled Wi-Fi Multiple User Features, 2022). As the receiver level gets close to -89 dBm the MCS rate will go to zero and spatial streams will go to one. As the level approaches -89 dBm at 160 MHz channel width, the rate adaptation algorithm can reduce the channel width from 160 MHz to 80 MHz to 40 MHz to 20 MHz. The conducted power into the antenna can remain at close to +24 dBm as the noise level goes to -92 dBm for 80 MHz channel width, and -95 dBm for 40 MHz channel width, and -98 dBm for 20 MHz channel width. At the very cell edge the MCS level will be zero with one spatial stream and the channel width will be 20 MHz.

In the 6 GHz band for indoor operation with a restriction of peak EIRP per MHz when the channel width is halved, the conducted transmit level must be reduced by 3 dB. Reducing the channel width from 320 MHz to 160 MHz will reduce the noise level from -86 dBm to -89 dBm. However, the transmit level must be reduced by 3 dB so that the signal to noise ratio of the receiver will not change. This is, in fact, one of the advantages of indoor limits on peak EIRP per MHz, as wider channel width is encouraged resulting in less concentrated interference levels to other users of the spectrum.

So, if going from 320 MHz channel width to 160 MHz channel width provides no advantage in SNR then what can be done when the receive levels approach the noise level of -86 dBm?

Consider packet detection, using self-correlation to detect the repeated symbols in the L-STF field of the preamble. A single L-STF has 16 samples to perform a cross correlation while the cross correlation of 256 samples can be used for signal detection when the L-STF is repeated 16 times over the full 320 MHz channel width. Detecting a signal with 256 samples is much easier than trying to detect a signal with only 16 samples.

Maximum ratio combining (MRC) can be employed on the L-SIG, RL-SIG, and U-SIG and EHT-SIG to provide a 12 dB range improvement compared to a 20 MHz PPDU since these signals are repeated 16 times over the 320 MHz channel width.

10.1. EHT DUP transmission

EHT duplicate (EHT-DUP) transmission repeats the payload portion of a PPDU in frequency. EHT-DUP is only for the 6 GHz band with 80, 160, and 320 MHz channel width and $N_{SS} = 1$ spatial streams.

MCS14 uses both DCM+DUP to get a 36 Mbps PHY rate with a 320 MHz channel width. The measured throughput using MCS14 and 320 MHz channel width is around 30 Mbps. The improved sensitivity between MCS0 and MCS14 for a 320 MHz channel width EHT signal measured between 2 and 6 dB.

While it proved hard to pinpoint the sensitivity difference between MCS0 and MCS14 due to the hysteresis and variability in establishing and maintaining connectivity at cell edge, it was certainly the case that when connectivity was lost at MCS0, connectivity and 30 Mbps of steady throughput could be restored by enabling MCS14.

30 Mbps throughput is not much in a multiple Gbps world. Yet it is important to understand the variability and fading that results in connectivity loss or a move to a band or extender not able to deliver

many Gbps speed. The advantage of the MCS14 PHY rate is to maintain connectivity in the 6 GHz band during temporary and transient fades.

11. Dual Lane PCIe3: The interface between DOCSIS 4.0 and Wi-Fi 7

Both DOCSIS 4.0 and Wi-Fi 7 are capable of throughput greater than 10 Gbps. Importantly, the maximum PHY rate of a 4x4 AP using 320 MHz channel width is over 11 Gbps. Experience has shown that bottlenecks feeding the Wi-Fi radio less than the PHY rate wreak havoc on Wi-Fi rate adaptation resulting in erratic behavior and excessive re-transmission.

The transactions per second of peripheral component interconnect express (PCIe) 3 have been increased to 8 Gbps compared to PCIe 2 transactions per second of 5 Gbps. Both standards use two bits of parity for error correction. However, the older standard uses eight information bits while the newer standard uses 128 information bits. The older PCIe 2 standard has a raw information rate of 4.0 Gbps, while PCIe 3 has a raw information rate of 7.8 Gbps. The raw information rate of dual lane PCIe 3 is 15.7 Gbps.

Feeding a Wi-Fi 6 radio with a maximum PHY rate of 4800 Mbps using a single lane PCIe 2 measured TCP throughput of close to 2.5 Gbps with a window size of 4 Mbytes and 8 TCP streams. Assuming equal efficiency between PHY rate and throughput indicates that the throughput will be about 9.8 Gbps with a 15.7 Gbps dual lane PCIe 3 raw information rate and an 11.4 Gbps PHY rate. Indeed, this matches measured results on early Wi-Fi 7 radios.

12. Conclusion

DOCSIS 4.0 and Wi-Fi 7 are indeed perfect together.

Abbreviations

Ack	acknowledgment
ADC	Analog-to-digital converter
AP	access point
bps	bits per second
BPSK	binary phase shift keying
BCC	binary convolutional coding
CM	cable modem
CMTS	cable modem termination system
CTS	clear to send
DAA	distributed access architecture
dBm	decibels above a milliwatt
DC	direct current, baseband representation of center frequency
DCM	dual carrier modulation
DFT	discrete Fourier transform
DOCSIS	data over cable service interface specification
DUP	duplicate DCM
EHT	extremely high throughput
EHT-DUP	extremely high throughput duplicate transmission
EHT-LTF	EHT Long Training field
EHT MU PPDU	EHT multi-user PPDU
EHT-SIG	EHT SIGNAL field
EHT-STF	EHT Short Training field
EHT TB PPDU	EHT trigger based PPDU
EIRP	effective isotropic radiated power
EVM	error vector magnitude
FCC	Federal Communications Commission (USA)
FDD	frequency division duplex
FDX	full duplex DOCSIS
FEC	forward error correction
FFT	fast Fourier transform
FM	frequency modulation
Gbps	gigabits per second
GI	guard interval
HE	high efficiency
HFC	hybrid fiber coaxial cable
HT	high throughput
Hz	hertz
IDFT	inverse discrete Fourier transform
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IFS	interframe space
ISM	Industrial scientific medical band
K	kelvin
LDPC	low density parity check coding
LLD	low latency DOCSIS

L-LTF	Non-HT Long Training field
L-SIG	Non-HT SIGNAL field
L-STF	Non-HT Short Training field
LTF	long training field
Mbps	Megabits per second
MIMO	multiple input multiple output
MRC	maximum ratio combining
OFDMA	orthogonal frequency division multiple access
PAPR	peak to average power reduction
PCIe	peripheral component interconnect express
PSC	preferred scanning channel
PE	Packet Extension field
PHY	physical layer interface
PPDU	physical layer protocol data unit
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RF	radio frequency
RPHY	remote physical interface
RL-SIG	Repeated Non-HT SIGNAL field
RTS	request to send
SCTE	Society of Cable Telecommunications Engineers
SNR	signal to noise ratio
SSID	service set identifier
STA	station
STF	short training field
TDD	time division duplex
U-NII	Unlicensed National Information Infrastructure
U-SIG	Universal SIGNAL field
vCMTS	virtual cable modem termination system
WAN	wide area network
WLAN	wireless local area network

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