# The Importance Of Wi-Fi 6 Technology For Delivery Of gbps Internet Service

A Technical Paper prepared for SCTE•ISBE by

**David John Urban**
Distinguished Engineer
Comcast
One Comcast Center
Philadelphia PA 19103
610-476-2596
david_urban@cable.comcast.com

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# Introduction

Wi-Fi 6 based upon 802.11ax standard changes the OFDM carrier spacing and the multiple access method for the first time in 16 years.

The subcarrier spacing is narrowed by one fourth resulting in symbol times four times longer allowing the spectrum to be divided into many resource units to be shared by multiple users at the same time.

A home may have several video set top boxes and security cameras and each member of the family may actively be using a phone and notebook computer with messaging and video streaming applications.

Thus, twenty active stations consuming less than 5 Mbps each is an important use case.

The devices can be served efficiently with OFDMA.

Each device transmits and receives a narrow portion of the 160 MHz channel width.

This is more robust for each station while still efficient since many stations are served at the same time.

In addition to many devices in the home consuming small average data rates, the cable operator is expected to deliver the Gbps service tier that the customer pays for.

Serving many stations simultaneously with OFDMA frees up air time for devices that occasionally demand much higher peak data rates.

Wi-Fi 6 PHY rates for 2x2 80 MHz phones and tablets will be 1200 Mbps, for 2x2 160 MHz notebooks will be 2400 Mbps, for 4x4 160 MHz desktop computers with media bridge adapters 4800 Mbps.

These PHY rates are critical for the stable, reliable, consistent delivery of Gbps service in the presence of spectrum sharing both within the home and with neighbors.

The phone with 1200 Mbps maximum PHY rate can be expected to deliver speeds of 700-900 Mbps in the same room and adjacent rooms as well as directly above and below.

The notebook with 2400 Mbps maximum PHY rate can be expected to deliver equivalent speeds of a 1 Gbps Ethernet NIC with whole home coverage.

This paper describes the technical details of Wi-Fi 6 802.11ax high efficiency and why the technology is critical for cable operators to deliver consistent, stable, reliable Gbps service.

# Traffic Demand

Like Ethernet before it, Wi-Fi has been successful in part by using simple low cost technology with raw data rate an order of magnitude greater than traffic demand. 10Base-T for LAN was faster and simpler than 1.544 Mbps T1 lines. Wi-Fi works in shared spectrum governed with CSMA-CA and other distributed coordination methods such as RTS/CTS with very low cost stations so that Wi-Fi connectivity is ubiquitous in phones, tablets, video streaming boxes, televisions and notebook and desktop computers.

 

The speeds of Wi-Fi have been able to stay ahead of traffic demand over the years, from 11 Mbps, to 54 Mbps, to 300 Mbps, to 1300 Mbps, and with Wi-Fi 6 to 2400 Mbps. Having an understanding of the traffic demand from customers is essential for the service provider to size up the speeds needed in a cable modem wireless router.

As an illustrative example, the data rate was measured for a popular UHD video streaming app. The video was displayed on a UHD television set with the app running on an HDMI dongle with external power supply. The STA connected to the AP in the 2.4 GHz band. The STA had a maximum PHY rate of 130 Mbps, 2x2, 802.11n mode, 20 MHz channel width. The AP and STA were separated by one floor and located in opposite corners of the house. The data rate in Mbps was measured by the AP every second. The mean data rate measured was 3.928 Mbps with a peak data rate of 29.5 Mbps. The minimum and median value of the data rate was 0. The first quantile was 0 and the third quantile was 7.9 Mbps.

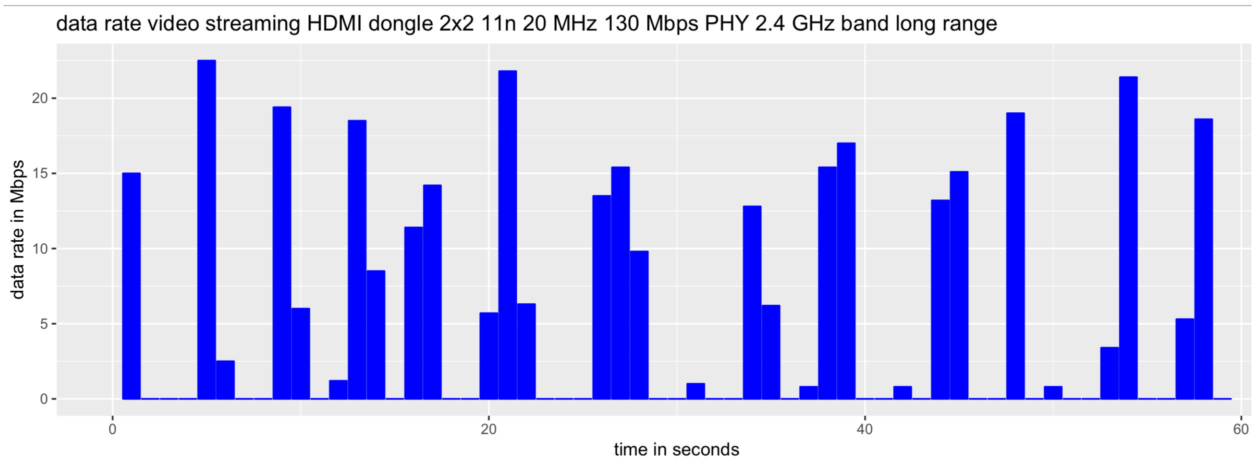


**Figure 1 – Data rate measured for video device UHD streaming**

Figure 1 shows a plot of the download rate measured in 1 second intervals during video streaming. With 12 bursts in 60 seconds, the traffic demand is satisfied with 20 Mbps one second data bursts followed by four seconds without any download demand. Figure 2 plots the measured downloaded data rate over a 37 minute time interval. While the traffic is constant over the full video viewing period, the traffic demand overall is less than 5 Mbps consisting of bursts lasting 1 second followed by no traffic demand for four seconds. Bursty traffic demand such as measured in this example is typical of video streaming and can serve as a traffic model for one of the most common and popular Internet consumer applications.

 

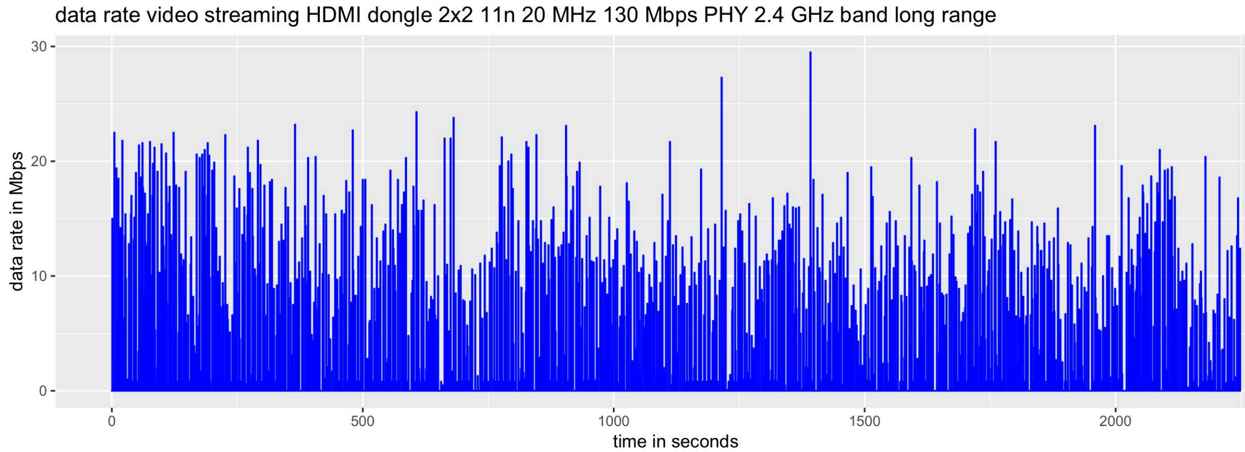


**Figure 2 – Data rate measured of UHD video streaming device over full show**

Downloading large files, including video downloads of many Gbytes, is an important application for high speed data service. Files can be very large and when a customer wants to download a video for offline viewing before running out the door appreciates the fastest speeds possible. As an illustrative example, a 4.4 GB file was downloaded from a popular website with a Wi-Fi 6 2400 Mbps STA over the Internet with a Gbps high speed data service. Even when downloading a large file, it still takes time to navigate the websites to set up the download. The peak download speed measured during the download of the 4.4 GB file was 1.2 Gbps and the average transfer rate was 235 Mbps. Once the download started, it took about 30 seconds before the download was finished as shown in Figure 3.


**Figure 3 – Download 4.4 GB file in 30 seconds with Wi-Fi 6 2400 Mbps PHY**

Traffic demand must be much lower than the delivered capacity by the service provider in order to ensure a satisfactory customer experience. It is important for the customer to know that the service promised is being delivered. A speed test is one method for customers to determine how their Internet service is working. Many factors impact speed test results, interpreting speed test results is as much an art as a science. Still, when understood correctly speed tests available to customers are a useful tool for the service provider and the customer.  Figure 4 show a speed test measured with a Wi-Fi 6 2400 Mbps PHY station with a CMTS max-tr-rate of 1250 Mbps with the STA one floor above the AP.

 

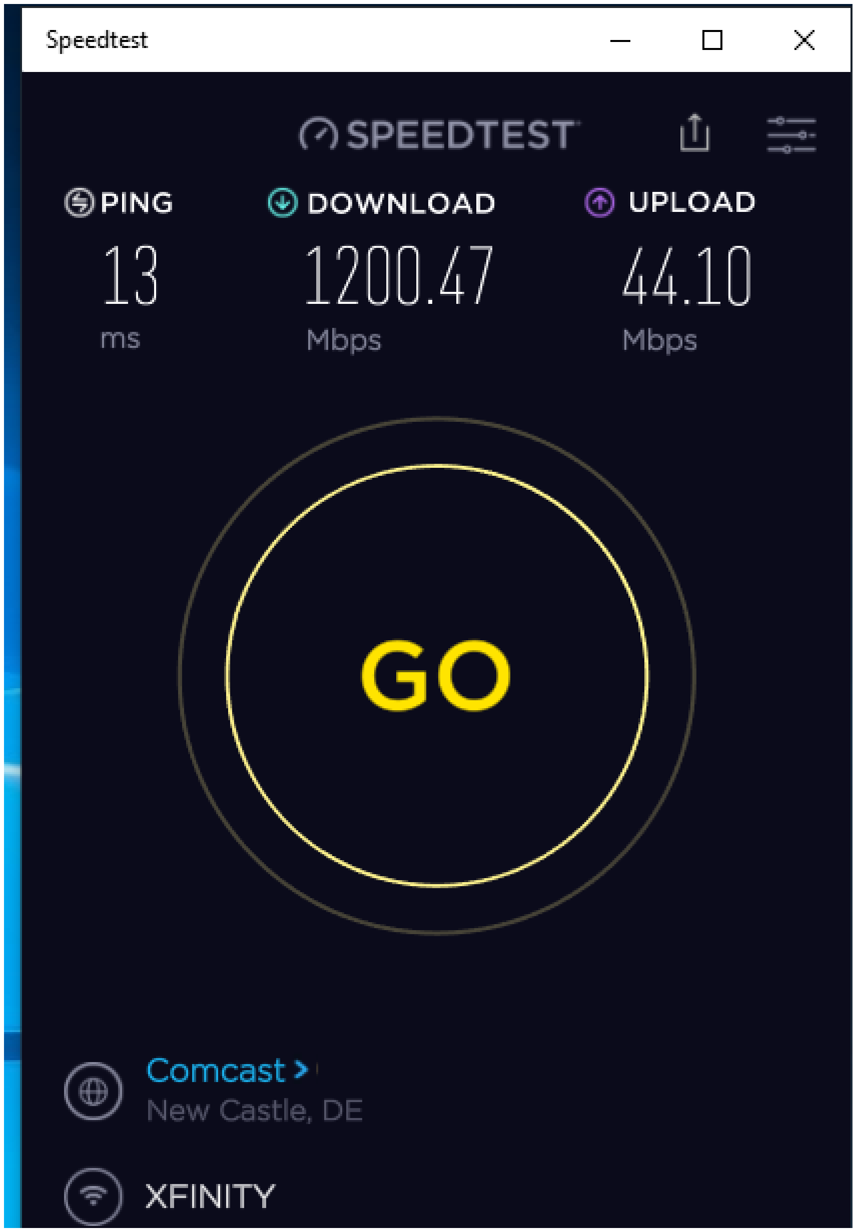


**Figure 4 – Wi-Fi 6 2400 Mbps PHY speed test with 1 Gbps Internet service in room above**

Figure 5 shows the progression of the download rate during the speed test. Not all speed test download progressions look like this, which accounts for variations is speed test results from run to run. Getting the best speed test results from DOCSIS to Wi-Fi requires a steady increase in download rate from 0 to 1250 Mbps within the first 10 seconds of the download portion of the speed test followed by 5 seconds of steady 1250 Mbps download rate. When speed tests go wrong and report less than the provisioned speed of the cable modem and the throughput capability of the Wi-Fi, it is typically due to the download rate taking too long to ramp up to 1250 Mbps or hitting the 1250 Mbps but dropping to lower rates, failing to maintain the peak rate for the full 5 seconds.

 

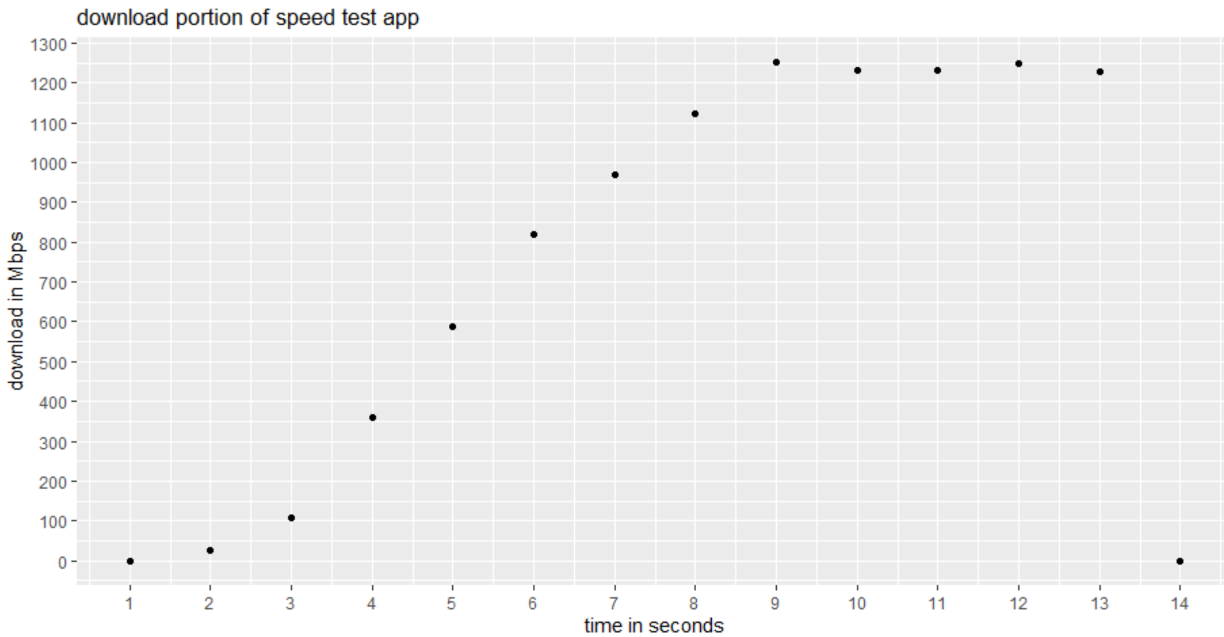


**Figure 5 – Wi-Fi 6 2400 Mbps PHY download progression during speed test**

# Background on Wi-Fi 6 Technology

To help us understand the new 802.11ax he mode Wi-Fi 6 protocol, let's put ourselves in the shoes of the developers of the standard. How can we improve upon the very successful 802.11 Wi-Fi system? Let's start with a very simple channel model. If we can estimate the delay spread, then we can determine the necessary guard interval between OFDM symbols needed to prevent inter-symbol interference. Once the guard interval has been established a more efficient FFT size can be selected to form the OFDM symbol.

The delay of a ray of light or other radio frequency wave that reflects off an object 400 feet away is 800 ns since light travels one foot each ns and the reflected ray must travel an additional 800 feet. This is illustrated in Figure 6. The average home size in the United States is 2700 square feet. A rectangle with sides of 37 feet and 73 feet has an area of 2700 square feet. The distance between the AP and the STA both inside the average home will be less than 70 feet. Reflections from signals with delay greater than 800 ns are due to objects outside the home or many long reflections inside the home. This indicates that the delay spread of the WLAN channel for indoor residential homes is well below 800 ns. This has been born out in practice since the introduction of 802.11a in 1999, the last century. The normal guard interval is 800 ns for 802.11a, 802.11g, 802.11n, 802.11ac. All these standards have proved well suited for wireless connectivity for indoor residential channels as well as office building and short-range outdoor applications.

 

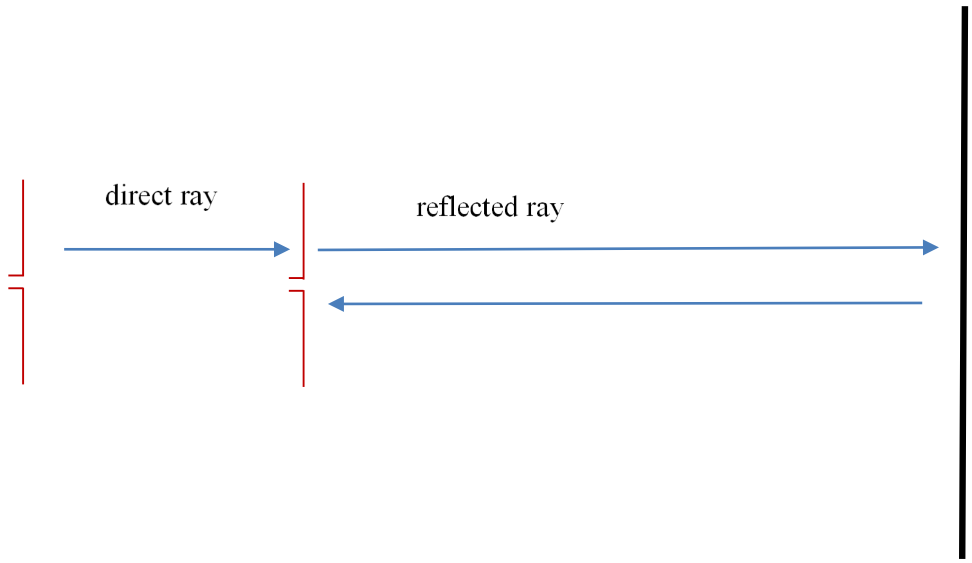


**Figure 6 – Illustration of extra path length of a reflected signal**

Channel 100 with 160 MHz channel width in the 5 GHz band has a center frequency of 5570 MHz as shown in Figure 7. An OFDM symbol with a 160 MHz channel width has a sampling frequency of 160 MHz and a sampling period of 6.25 ns. Equation 1 shows the formula and the calculation where Ts is the sampling period and Rs is the sampling rate; the sampling rate is expressed as 0.160 GHz so that the sampling period is calculated in ns. 800 ns guard interval between OFDM symbols requires 128 FFT time samples. The calculation of 128 FFT time samples for the guard interval is shown in equation 2. $N_{CP}$ is the number of FFT time samples in the guard interval, Tg is the guard interval of 800 ns, and Ts is the FFT sampling rate of 6.25 ns.

*Equation 1*

$$T_s = \frac{1}{R_s} = \frac{1}{0.160} = 6.25$$

*Equation 2*

$$N_{CP} = \frac{T_g}{T_s} = \frac{800}{6.25} = 128$$

 

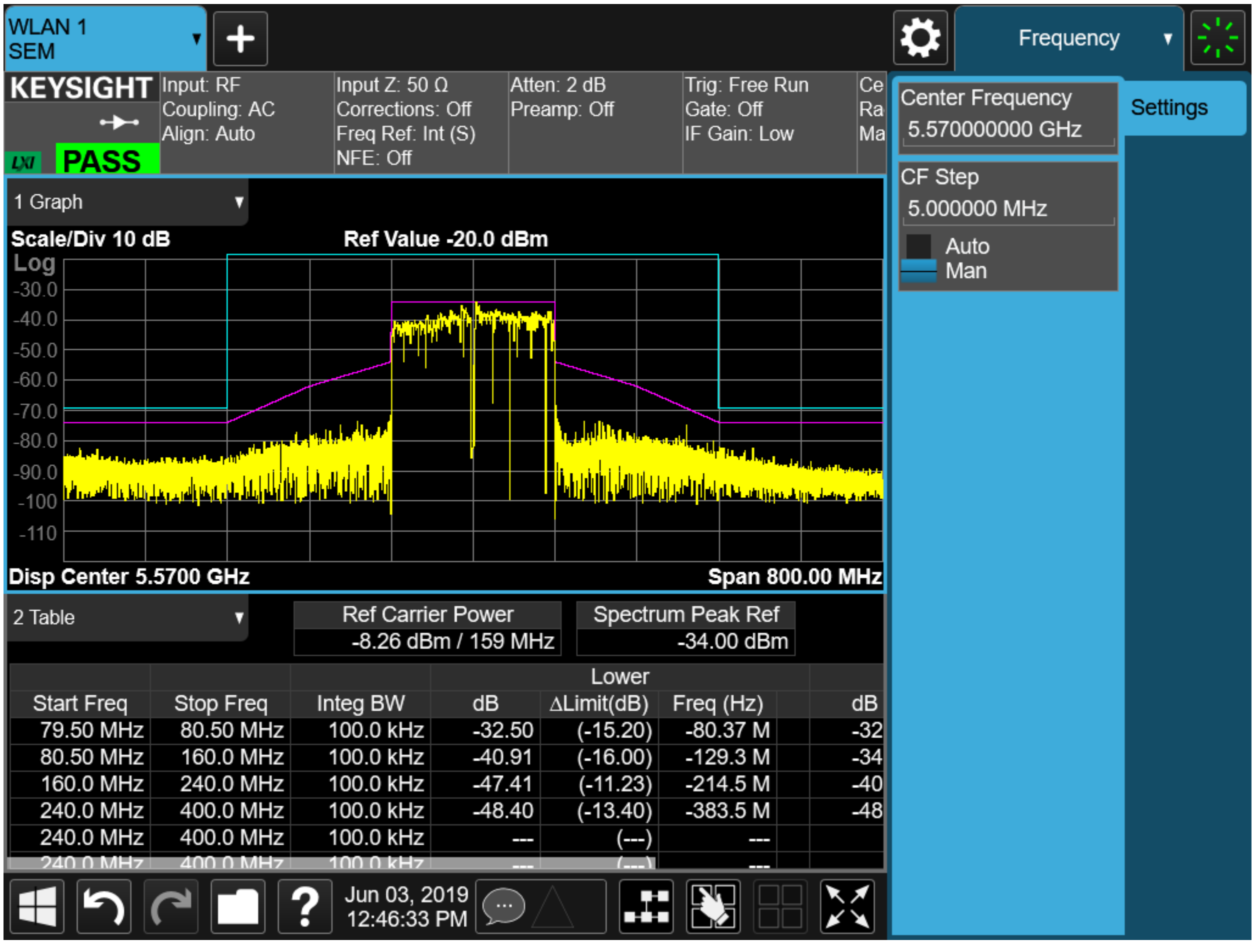


**Figure 7 – Primary channel 100 with channel width 160 MHz center frequecy 5570 MHz**

Wi-Fi 6 802.11ax he mode is 4 times more efficient than older modes. The guard interval is 1/16 of the symbol period rather than 1/4 of the symbol period. The FFT time samples used to create the guard interval between symbols are called the cyclic prefix or CP for short. Knowing the guard interval will help us determine the FFT size. To date Wi-Fi signals have had a guard interval that is ¼ the symbol period. With a CP of 1/16 the FFT size and 128 time sample CP the FFT size is 2048 as calculated in equation 3.

*Equation 3*

$$N_{FFT} = \frac{N_{CP}}{CP} = \frac{128}{\frac{1}{16}} = 2048$$

 

# FFT forms the OFDM Symbol

The spectral flatness of a 160 MHz channel width Wi-Fi 6 is shown in Figure 8. Notice that the radio standard is 802.11ax 160 MHz, the HE subcarrier spacing 78.125 kHz and the HE guard interval 1/16. The FFT index of the lowest frequency data subcarrier is -1012 and the FFT index of the highest frequency subcarrier is 1012. For a 2048 point FFT the subcarrier indices range from -1024 to 1023. The 12 lowest frequency subcarriers are set to zero and the 11 highest frequency subcarriers are set to zero to establish a frequency guard band between lower adjacent and upper adjacent channels.

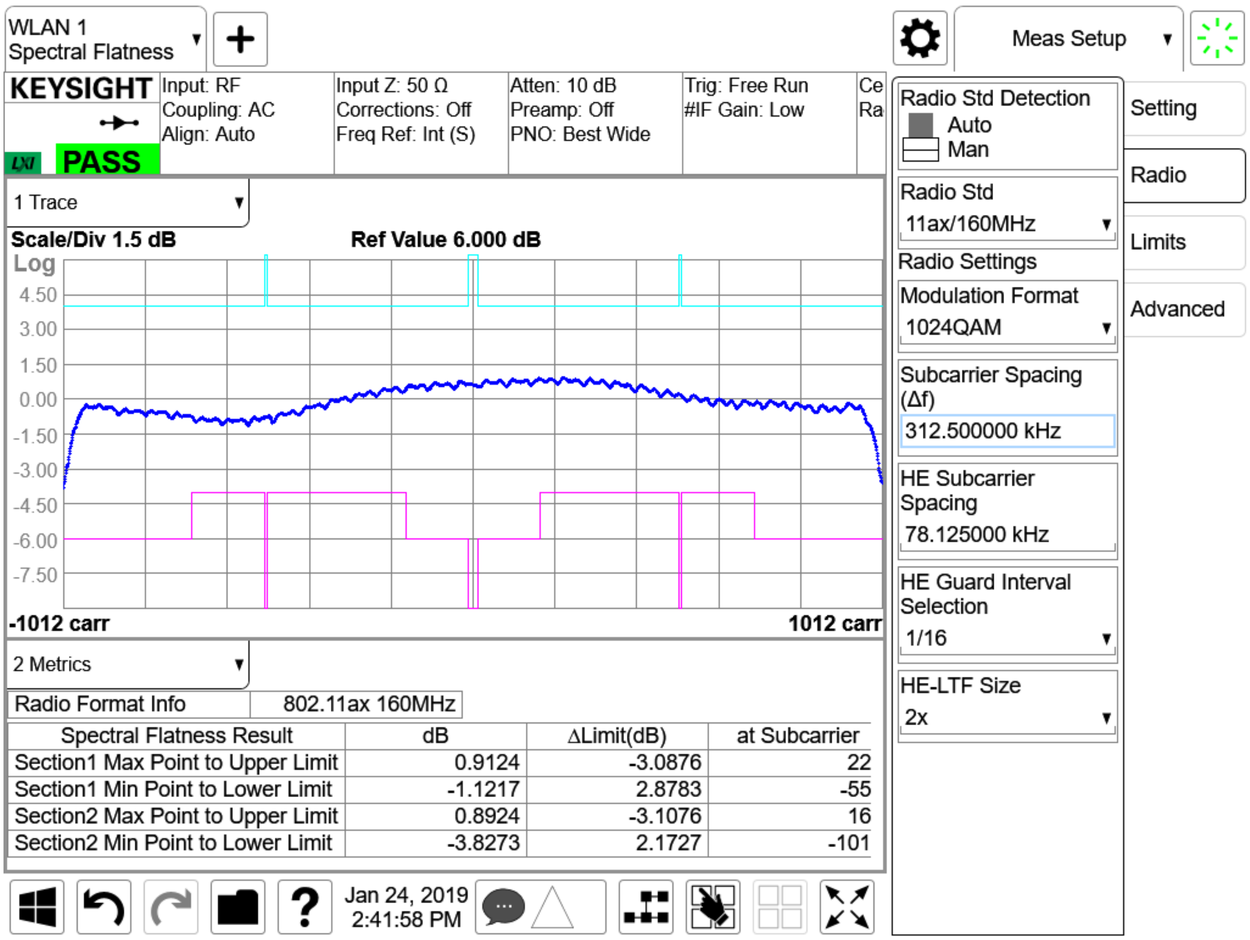


**Figure 8 – FFT size is 2048 for a 160 MHz channel width 802.11ax signal**

The shortest in time guard interval is 800 ns for he mode of 802.11. Longer in time guard intervals of he mode are 1600 ns and 3200 ns. The WLAN standard 802.11ax is designed for high efficiency, so the mode is called he. The Wi-Fi alliance Wi-Fi 6 is based upon the he mode IEEE 802.11ax standard. The guard interval provides a space between consecutive symbols. The guard interval is implemented as a cyclic prefix, abbreviated CP.

The term cyclic prefix is used since the first time samples of the IFFT of the OFDM symbol are repeated at the end of the symbol before the next symbol is sent. Since light travels one foot in one ns an 800 ns guard interval between symbols allows for reflections from objects 400 feet away to have a delay that is not long enough to result in inter-symbol interference.

 

800 ns guard interval is enough to prevent inter-symbol interference for most indoor WLAN channel conditions and even most short-range outdoor applications. Since the distance between AP and STA is less than 30 meters for indoor applications and less than 100 meters for outdoor applications reflected rays travelling greater than 800 meters are highly likely to encounter obstructions such as walls and trees. Long delayed multi-path rays suffer high attenuation after reflection, diffraction, passing through walls and trees. Due to attenuation from scattering objects rays with delay greater than 800 ns have negligible level relative to the rays taking a more direct path from AP to STA having delays less than 80 ns. A rectangular space with area of 5000 square feet has sides of 70 feet. With an AP placed in the middle of the rectangle, an STA in the middle of one side would have a direct path of 35 feet for a delay of 35 ns.

The guard interval of 1600 and 3200 ns, allowing for reflections 800 feet and 1600 feet away, benefit in longer range applications where the AP is higher in elevation and the STA is further away from the AP. The guard interval is selected based upon the delay spread of the channel. The Wi-Fi 6 802.11ax he mode guard interval of 800, 1600, and 3200 ns makes the protocol suitable for channels with delay spread less than the chosen guard interval.

Indoor residential, indoor office buildings, and short range outdoor channels in the 2.4 and 5 GHz band meet the delay spread limits of he mode. These are the channels of interest for a service provider delivering Gbps Internet access to residential and business customers over a hybrid fiber coaxial cable HFC network. The same is true for service providers delivering Gbps service to residential and business customers over other access architectures or a mix of access architectures.

An OFDM symbol with channel width of 160 MHz has an FFT sampling period of 6.25 ns. With an FFT size of 2048 the FFT duration is 12.8 µs as calculated in equation 4. The FFT is sometimes called the useful symbol time and that is why the symbol used for it is often $T_u$. Some folks object to the term useful symbol period since it implies that the guard interval is not useful, perhaps hurting the guard intervals feelings.

*Equation 4*

$$T_u = T_s \cdot N_{FFT} = 6.25 \cdot 2048 \cdot 10^{-3} = 12.8\,\mu s$$

The symbol period is the sum of the FFT duration $T_u$ and the guard interval $T_g$ as calculated in equation 5. The FFT duration is 12.8 µs and the guard interval is 800 ns = 0.8 µs so that the symbol period is 13.6 µs. The symbol period for older 802.11 OFDM symbols is 4 µs for normal guard interval. The FFT duration for older 802.11 OFDM modes is 3.2 µs. The FFT duration of he mode is 4 times longer than the FFT duration of older OFDM modes, 3.2 µs for older modes and 12.8 µs for he mode. Remember the he mode symbol period for normal guard interval of 13.6 µs, this is what we will use in the denominator to calculate the data rate of the he mode symbol for various PHY settings.

*Equation 5*

$$T_{symbol} = T_u + T_g \ = \ 12.8 \ + \ 0.8 \ = \ 13.6\,\mu s$$

The subcarrier spacing can be calculated from the inverse of the FFT duration. The subcarrier spacing of an he mode signal is 78.125 kHz as shown in equation 6. 1000 is used in the numerator dividing by 12.8 µs so that the resulting frequency spacing has units of kHz. The subcarrier spacing of older 802.11 OFDM modes is four time greater than he mode; 312.5 kHz for older modes compared to 78.125 kHz for he mode.

 

*Equation 6*

$$\Delta f = \frac{1}{T_u} = \frac{1000}{12.8} = 78.125\ kHz$$

Now we know the characteristics of the FTT that creates the he mode OFDM symbol. We know we need a 160 MHz channel width in the 5 GHz band. We are confident that the 800 ns guard interval will prevent inter-symbol interference in our customers homes. We want to know if we can deliver Gbps Internet service to our customers. We will need to calculate the data rate of the he mode symbol. We know the denominator, the symbol period. We need to know the numerator. For this we need to understand the number of spatial streams, the number of data subcarriers, and the modulation and coding of the signal.

# Modulation and Coding

Each data subcarrier of the FFT that forms and OFDM symbol is modulated. The modulation is adaptive, adjusting to the channel conditions to get the highest data rate possible for the signal to noise ratio at the time of transmission. The constellations used for modulating the data subcarriers in Wi-Fi 6 he mode are BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM and 1024-QAM. Table 1 lists the bit loading of the subcarriers, the name of the modulation corresponding to the bit loading and the SNR needed for $10^{-6}$ bit error rate without error correction coding.

**Table 1 - Bits Modulation and SNR**

| bits | modulation | SNR in dB |
|---|---|---|
| 1 | BPSK | 6 |
| 2 | QPSK | 12 |
| 4 | 16-QAM | 18 |
| 6 | 64-QAM | 24 |
| 8 | 256-QAM | 30 |
| 10 | 1024-QAM | 36 |

The measured constellation of a demodulated BPSK signal is shown in Figure 4. There are two constellation points, one point can represent a 0 and the other a 1. That is why BPSK modulation transmits 1 bit each symbol for the data subcarriers of the OFDM symbol.

The modulation options for he mode are the same as vht mode with the exception of the addition of 1024-QAM. There have been proprietary implementations of 1024-QAM but Wi-Fi 6 introduces 1024-QAM modulation as part of the standard allowing better device interoperability. The constellation diagram is shown in Figure 9 for an 802.11ax 160 MHz channel width signal. Since $2^{10}$=1024 with 1024 constellation points each point can represent 10 bits. 1024-QAM modulation conveys 10 bits for each data subcarrier in an OFDM symbol.

Adding LDPC coding to the modulation allows for more bits per subcarriers for a given signal to noise ratio. The bits that load subcarriers for modulation come from LDPC codewords. Low density parity check coding, take large blocks of information bits and form large codewords. When decoded the LDPC codewords use message passing algorithms to find the codeword based on the log likelihood ratio of the received signal. There are three different LDPC codeword block lengths; 648, 1296, and 1944 bits. The more bits in a LDPC codeword the better the coding gain, at the expense of latency and complexity. Smaller traffic demand may not be able to fill a 1944 bit codeword so a smaller codeword is used. There are four different coderates; 1/2, 2/3, 3/4, 5/6. For a coderate of 1/2 and a code word length of 1944 bits, the LDPC information block length is 972 bits. 972 bits are fed to the LDPC coder to form a 1944 bit codeword. The 1944 bits of the codeword bit load the data subcarriers of the OFDM symbol.

| **coderate** | **Codeword** | **Information** |
|---|---|---|
| **ratio** | **bits** | **bits** |
| 1/2 | 1944 | 972 |
| 2/3 | 1944 | 1296 |
| 3/4 | 1944 | 1458 |
| 5/6 | 1944 | 1620 |
| 1/2 | 1296 | 648 |
| 2/3 | 1296 | 864 |
| 3/4 | 1296 | 972 |
| 5/6 | 1296 | 1080 |
| 1/2 | 648 | 324 |
| 2/3 | 648 | 432 |
| 3/4 | 648 | 486 |
| 5/6 | 648 | 540 |

The receiver demodulates the signal with an FFT to determine the magnitude and phase of each data subcarrier. With the magnitude and phase measurement of enough data subcarriers for a codeword, the receiver calculates the log likelihood ratio of the 1944 bits of a codeword. The log likelihood ratio for each bit is calculated by measuring the distance from the received subcarrier vector and each of the possible transmitted constellation points for the modulated signal and making an estimate of the probability density function.

For a service provider, the important point to understand about LDPC codes are that they are 1) very powerful, 2) very long so complexity is high and latency and traffic demand need to be considered, and 3) the LDPC code rate must be known to determine the speed that customers will experience using Wi-Fi.

Table 3 shows the modulation, code rate, receiver level for each of the 12 modulation and coding schemes of 802.11ax Wi-Fi 6 he mode.

**Table 2 - 20 MHz 802.11ax Wi-Fi 6 Modulation and Coding**

| **MCS index** | **modulation** | **bits** | **coderate** | **bps/Hz** | **802.11 dBm** | **Sensitivity dBm** | **SNR dB** |
|---|---|---|---|---|---|---|---|
| 0 | BPSK | 1 | 1/2 | 0.50 | -82 | -95 | 3 |
| 1 | QPSK | 2 | 1/2 | 1.00 | -79 | -92 | 6 |
| 2 | QPSK | 2 | 3/4 | 1.50 | -77 | -90 | 8 |
| 3 | 16-QAM | 4 | 1/2 | 2.00 | -74 | -87 | 11 |
| 4 | 16-QAM | 4 | 3/4 | 3.00 | -70 | -83 | 15 |
| 5 | 64-QAM | 6 | 2/3 | 4.00 | -64 | -77 | 21 |

 

| MCS index | modulation | bits | coderate | bps/Hz | 802.11 dBm | Sensitivity dBm | SNR dB |
|---|---|---|---|---|---|---|---|
| 6 | 64-QAM | 6 | 3/4 | 4.50 | -65 | -78 | 20 |
| 7 | 64-QAM | 6 | 5/6 | 5.00 | -64 | -77 | 21 |
| 8 | 256-QAM | 8 | 3/4 | 6.00 | -59 | -72 | 26 |
| 9 | 246-QAM | 8 | 5/6 | 6.67 | -57 | -70 | 28 |
| 10 | 1024-QAM | 10 | 3/4 | 7.50 | -54 | -67 | 31 |
| 11 | 1024-QAM | 10 | 5/6 | 8.33 | -52 | -65 | 33 |

Modulations with higher bits per symbol also require higher signal to noise ratio and thus higher input level. When modulation level is increased so that two addition bits are loaded onto each subcarrier, the signal to noise ratio penalty is 6 dB. All things being equal 1024-QAM which has 10 bits per symbol needs 6 dB higher signal to noise ratio than 256-QAM which has 8 bits per symbol.

Boltzmann constant is 1.38E-23 Joules per degree Kelvin. The thermal noise power spectral density can be calculated by multiplying Boltzmann constant by the temperature. For temperatures encountered on earth, the thermal noise power spectral density when converted to dBm is about -174 dBm/Hz. For a 20 MHz channel width and 3 dB noise figure receiver the noise floor of the receiver is -98 dBm. With a receive signal level of -95 dBm and a noise floor of -98 dBm, the SNR is 3 dB. A 3 dB SNR is plenty for a BPSK and 1/2 LDPC code rate signal. With a 3 dB noise figure receiver and a demodulator that can work at 3 dB SNR for a BPSK 1/2 rate LDPC code the receiver sensitivity is -95 dBm. With four receivers and a maximum ratio combining gain of 6 dB, the sensitivity is -101 dBm per chain for MCS0 20 MHz channel width.

The IEEE dBm labeled column in Table 3 is the IEEE 802.11 receiver sensitivity threshold levels. The sensitivity dBm labeled column in Table 3 shows the levels for a 3 dB noise figure receiver that can demodulate MCS0 20 MHz at 3 dB SNR.

Figure 9 shows the constellation diagam of BPSK and the spectrum of the 20 MHz OFDM symbol. As seen in Table 3 MSC 0 uses BPSK modulation, binary phase shift keying. BPSK sends 1 bit of information, 0 has a phase of 180 degrees and 1 has a phase of 0 degrees as seen in the constellation measurement of Figure 9. The 20 MHz signal is divided into OFDM subcarriers. Each of the data subcarriers are BPSK modulated for MSC 0 carrying 1 bit for each data subcarrier. There are also left and right guard subcarriers, DC null subcarriers, and pilot subcarriers so not all of the FFT subcarriers carry data bits, but most do.

 

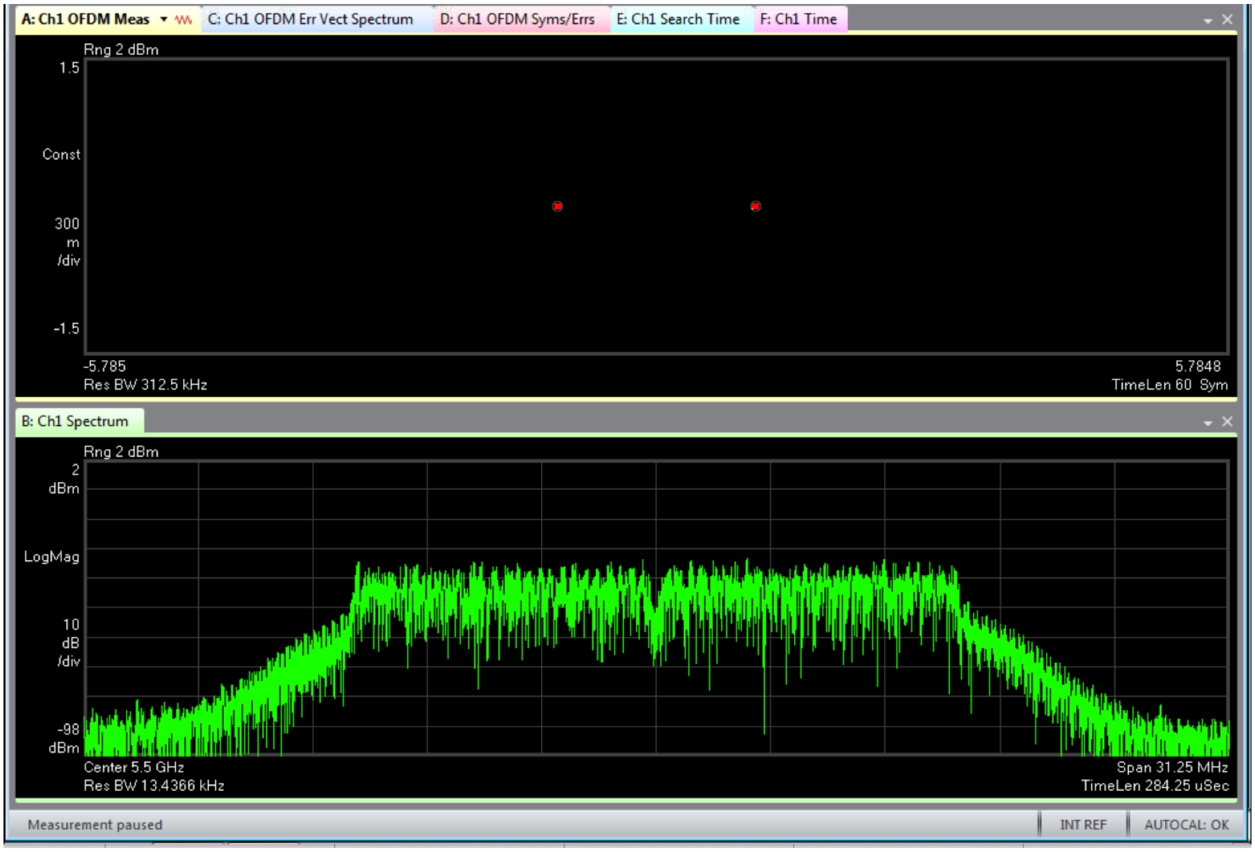


**Figure 9 – BPSK modulation has two constellation points sending 1 bit for each data subcarrier in the 20 MHz OFDM symbol.**

Figure 10 shows the measured constellation diagram of a 802.11ax 160 MHz MCS11 1024-QAM 5/6 rate LDPC signal. The constellation diagram has 1024 points. Each point of the constellation diagram is mapped to 10 bits. Thus 1024-QAM modulation carries 10 bits in each data subcarrier forming an OFDM symbol. Not all of these bits are information bits, the bits that modulate data subcarriers come form LDPC codewords, for MCS 11 the LDPC codeword rate is 5/6 so only 5 out of every 6 bits carry information. At the demodulator the final SNR must be 32 to 33 dB in order to demodulate MCS 11. With a 3 dB noise figure receiver, the receive level must be -56 dBm for a 160 MHz channel width MCS 11 signal. Since the noise floor of a 3 dB noise figure receiver is -98 dBm 20 MHz channel width, the noise floor for 160 MHz is 9 dB higher, -89 dBm. 33 dB above -89 dBm is -56 dBm. The 33 dB SNR needed for 1024-QAM 5/6 LDPC modulation is the sum total of all noise and interference into the receiver demodulator. In a well designed system, the noise will be dominated by the receivers noise figure and the fundamental thermal noise given the channel width. The transmitter EVM, error vector magnitude, is a contributing factor in the cumulative noise into the receiver. The transmitter EVM target should be about 10 dB better than the final required SNR where practical, this is a reasonable compromise between transmitter complexity and system impact.

 

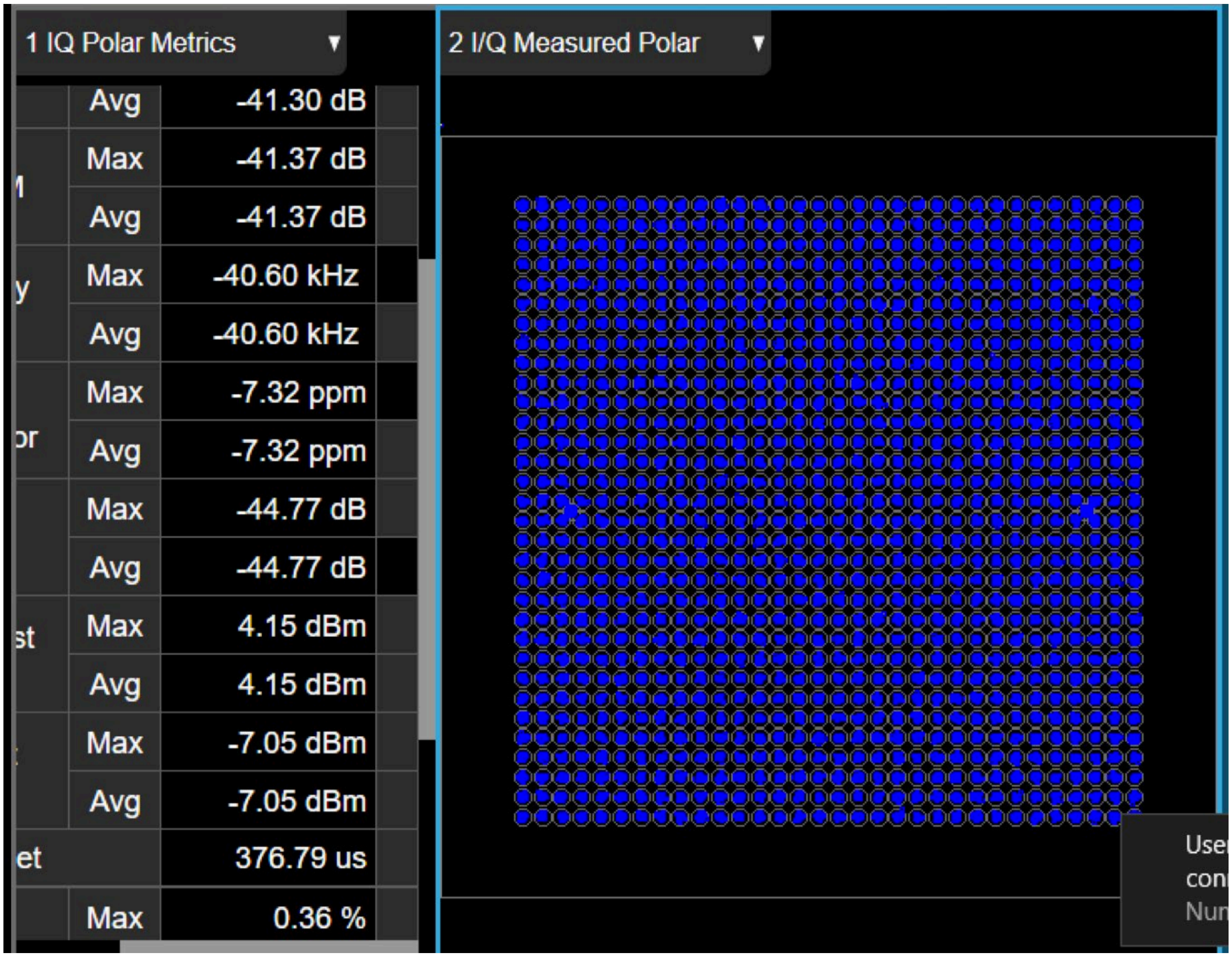


**Figure 10 – MCS 11 uses 1024-QAM modulation carrying 10 bits per subcarrier with measured MER and constellation diagram.**

The measured packet error rate versus estimated RSSI measured for various MCS indices for a 20 MHz 802.11ac signal are shown in Figure 11. The measured levels in Figure 11 correspond closely to the calculated levels in Table 2 which were based upon first principles of noise figure and modulation.

 

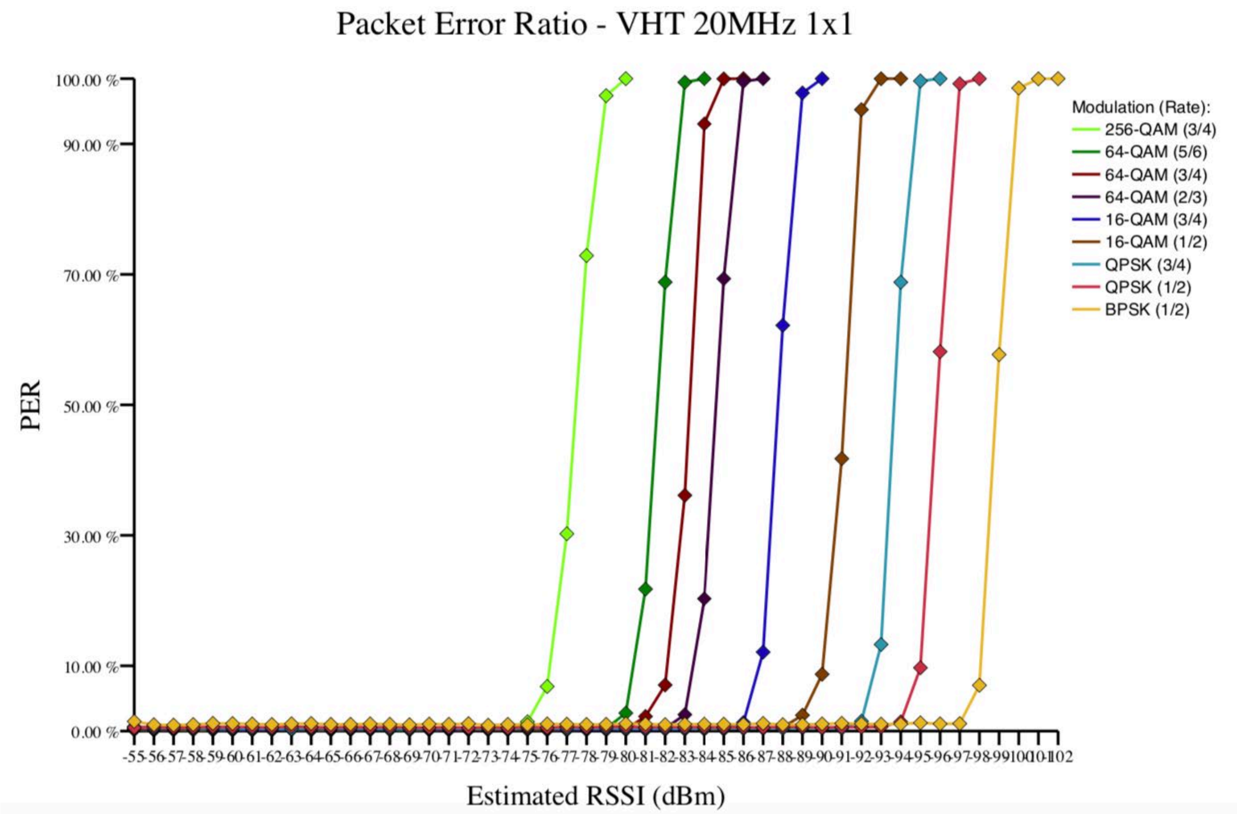


**Figure 11 – Measured Receiver sensitivty shows lower MCS levels work at lower received signal levels.**

Table 4 shows a summary of measurements made in a residential home. The STA is a 2x2 160 MHz Wi-Fi 6 device with a maximum PHY rate of 2400 Mbps. The STA is a PCIe M.2 card in a Windows 10 computer. The computer was moved throughput the house to get MCS11 all the way down to MCS1. The RSSI received into the four antennas of the 4x4 Wi-Fi 6 AP were measured and reported in Table 4. At a receive level just above -50 dBm, the STA ran at full 2400 Mbps with a download data rate of 1.44 Gbps. The download data rate was measured between computer connected to a 2.5 Gbps Ethernet port on the cable modem wireless router and the notebook computer with the 2400 Mbps PHY Wi-Fi 6 card. At further disances and more obstructions such as walls and floors, the RSSI dropped as did the MCS and the channel width along with the data rate.

The MRC, maximal ratio combining, uses the formula shown in the equation below.

*Equation 7*

$$P_{mrc} = 10 \cdot log_{10}\left(10^{\frac{P_{rx1}}{10}} + 10^{\frac{P_{rx2}}{10}} + 10^{\frac{P_{rx3}}{10}} + 10^{\frac{P_{rx4}}{10}}\right)$$

In Table 4, the four receiver levels measured by the AP are reported. For a single information stream it is possible to vectorially add the signals from all four antennas. This is calculated and reported in the column labeled MRC in Table 4 using Equation 7. This is sometimes referred to as receiver beamforming since the receive and take the four received signals and adjust the phase of each so that the vectors add constructively. This results in an equivalent receive level that is higher than that of each chain of the receiver individually.

**Table 3 - Measured levels, MCS, PHY rate, data rate moving throughout a residential home 2x2 160 MHz Wi-Fi 6 station**

| RX1 | RX2 | RX3 | RX4 | MRC | Mode | MCS | Nss | bw | GI | PHY | data |
|---|---|---|---|---|---|---|---|---|---|---|---|
| dBm | dBm | dBm | dBm | dBm | | index | streams | MHz | µs | Mbps | Gbps |
| -55 | -49 | -50 | -47 | -43.4 | he | 11 | 2 | 160 | 0.8 | 2401.9 | 1.44 |
| -55 | -56 | -54 | -56 | -49.1 | he | 10 | 2 | 160 | 0.8 | 2161.76 | 1.34 |
| -59 | -61 | -59 | -59 | -53.4 | he | 9 | 2 | 160 | 0.8 | 1921.54 | 1.23 |
| -65 | -58 | -56 | -62 | -53.0 | he | 8 | 2 | 160 | 0.8 | 1729.41 | 1.18 |
| -68 | -62 | -60 | -63 | -56.4 | he | 7 | 2 | 160 | 0.8 | 1441.17 | 0.945 |
| -68 | -64 | -61 | -68 | -58.2 | he | 6 | 2 | 160 | 0.8 | 1297.05 | 0.978 |
| -67 | -72 | -68 | -66 | -61.7 | he | 5 | 2 | 160 | 0.8 | 1152.94 | 0.645 |
| -70 | -70 | -66 | -69 | -62.4 | he | 4 | 2 | 160 | 0.8 | 864.7 | 0.687 |
| -72 | -71 | -71 | -75 | -66.0 | he | 5 | 2 | 80 | 0.8 | 576.47 | 0.39 |
| -78 | -72 | -76 | -76 | -68.9 | he | 4 | 2 | 80 | 0.8 | 432.35 | 0.342 |
| -80 | -79 | -74 | -79 | -71.3 | he | 3 | 2 | 80 | 0.8 | 288.23 | 0.22 |
| -83 | -79 | -81 | -82 | -75.0 | he | 1 | 2 | 80 | 0.8 | 144.11 | 0.126 |

**Table 4 - Measured results in each room of a residential home with 2x2 160 MHz Wi-Fi 6 station.**

| Location | RX1 | RX2 | RX3 | RX4 | MRC | mode | mcs | Nss | bw | GI | PHY | data | iperf |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Units | dBm | dBm | dBm | dBm | dBm | | index | streams | MHz | µs | Mbps | Mbps | Gbps |
| family room | -60 | -60 | -55 | -55 | -50.8 | he | 11 | 2 | 160 | 0.8 | 2401.5 | 1522.4 | 1.5 |
| office | -51 | -46 | -51 | -51 | -43.1 | he | 11 | 2 | 160 | 0.8 | 2401.5 | 1544 | 1.47 |
| kitchen | -58 | -60 | -58 | -58 | -52.4 | he | 11 | 2 | 160 | 0.8 | 2401.5 | 1501.5 | 1.42 |
| library | -63 | -53 | -53 | -58 | -49.2 | he | 11 | 2 | 160 | 0.8 | 2401.5 | 1542.3 | 1.45 |
| Annie's room | -50 | -57 | -53 | -55 | -47.0 | he | 11 | 2 | 160 | 0.8 | 2401.5 | 1515.5 | 1.5 |
| Sam's room | -68 | -63 | -67 | -73 | -60.4 | he | 8 | 2 | 160 | 0.8 | 1733.7 | 1213.8 | 1.23 |
| upstairs bath | -60 | -56 | -55 | -58 | -50.8 | he | 11 | 2 | 160 | 0.8 | 2401.5 | 1502.3 | 1.5 |
| Katie's room | -70 | -69 | -72 | -73 | -64.7 | he | 6 | 2 | 160 | 0.8 | 1295.3 | 911.5 | 0.881 |
| master bath | -65 | -74 | -69 | -70 | -62.4 | he | 7 | 2 | 160 | 0.8 | 1441 | 1060.1 | 1.02 |
| master bed | -81 | -80 | -75 | -80 | -72.3 | he | 3 | 2 | 160 | 0.8 | 575.9 | 477.3 | 0.455 |
| master bed | -80 | -78 | -74 | -78 | -70.9 | he | 4 | 2 | 160 | 0.8 | 858.5 | 514.7 | 0.531 |
| master bed | -77 | -76 | -74 | -77 | -69.8 | he | 4 | 2 | 160 | 0.8 | 862.3 | 671 | 0.665 |
| master bed | -84 | -80 | -79 | -83 | -75.0 | he | 4 | 1 | 160 | 0.8 | 394.7 | 264.7 | 0.23 |
| dining room | -66 | -62 | -60 | -67 | -56.8 | he | 9 | 2 | 160 | 0.8 | 1920.3 | 1328.1 | 1.3 |
| washer | -69 | -69 | -63 | -69 | -60.6 | he | 8 | 2 | 160 | 0.8 | 1727.9 | 1204.6 | 1.19 |
| powder room | -71 | -70 | -64 | -70 | -61.7 | he | 7 | 2 | 160 | 0.8 | 1441 | 1037.3 | 1.03 |
| garage | -75 | -72 | -67 | -72 | -64.5 | he | 7 | 2 | 160 | 0.8 | 1441 | 1060 | 1.02 |
| basement | -69 | -65 | -64 | -69 | -60.1 | he | 9 | 2 | 160 | 0.8 | 1921.5 | 1301.5 | 1.2 |
| front porch | -69 | -66 | -65 | -64 | -59.6 | he | 7 | 2 | 160 | 0.8 | 1441 | 1069.9 | 1.03 |
| back porch | -69 | -65 | -69 | -71 | -61.9 | he | 7 | 2 | 160 | 0.8 | 1441 | 1069 | 1.03 |
| mailbox | -74 | -71 | -67 | -72 | -64.2 | he | 6 | 2 | 160 | 0.8 | 1295 | 880.3 | 0.867 |
| back yard | -75 | -76 | -77 | -75 | -69.7 | he | 4 | 2 | 160 | 0.8 | 864.1 | 687.4 | 0.652 |

Table 5 shows download data rates, RSSI levels, MCS, channel width and other parameters measured in every room of the house as well as a few indoor to outdoor locations. These results match reasonably well with the theoretical and test set measured results. The download throughput was measured between a computer connected to the 2.5 Gbps Ethernet port of the cable modem wireless gateway and the notebook computer with 2x2 160 MHz 2400 Mbps PHY station. Of note is that 16 rooms of the house had measured data rate above 1 Gbps out of a total of 22 locations. The overall coverage was good both inside and outside the home.

 

# Data, Pilot, Null Subcarriers

Each data subcarrier is modulated with bits from LDPC codewords. We now know the bits per data subcarrier for each MCS index. But how many data subcarriers are there? The FFT size is 2048 for a 160 MHz he mode symbol.

The FFT of a 160 MHz OFDM symbol converts the frequency domain subcarriers into a time domain waveform for input to a digital to analog converter. The FFT size for a 160 MHz channel width in he mode is 2048, thus there are 2048 subcarriers. The types of subcarriers are null, data, pilots.

Null subcarriers are place at each end of the channel width spectrum and at the carrier frequency. The null subcarriers at the ends of the spectrum allow for a guard band in the frequency domain between channels. The null subcarriers at the carrier center frequency allow the receiver to work around DC offset since for a direct conversion receiver the carrier frequency will be translated to a baseband DC.

The 160 MHz subcarrier assignment consists of two adjacent 80 MHz channel width OFDM symbols. It is possible to demodulate the left side of the 160 MHz OFDM symbol and the right side of the OFDM symbol with an 80 MHz channel width demodulator. You can try this for yourself if you have a signal analyzer that can demodulate he mode signals. For channel 100 and 160 MHz channel width the center frequency is 5570 MHz. The center frequency is set to 5570 MHz and the demodulator channel width set to 160 MHz will demodulate the entire 160 MHz OFDM symbol.The center frequency can be set to 5530 and the channel width to 80 MHz to demodulate just the left half of the 160 MHz signal. Likewise, the center frequency can be set to 5610 and the channel width set to 80 MHz to demodulate just the upper half of the 160 MHz OFDM symbol. In fact it is even possible to create a 160 MHz channel width signals with two antennas, each antenna transmitting only half of the 160 MHz signal.

The 160 MHz 802.11ax signal is just two side by side 80 MHz channel width signals. Let's therefore take a closer look at the 80 MHz channel width signal. The FFT size for an 802.11ax he mode signal is 1024, half that of a 160 MHz signal. The lower guard band consists of 12 subcarriers while the upper guard band consists of 11 subcarriers. We do not after all wish to have the subcarriers of two different channels too close to each other in frequency. 5 DC subcarriers are set to zero in the middle of the spectrum. The 80 MHz channel width he signal has 16 pilots. That leaves 980 data subcarriers in an 80 MHz channel width he signal. Equation 8 shows the allocation of subcarriers in an 80 MHz channel width he signal.

*Equation 8*

$$1024\ FFT\ size\ =\ (12\ lower\ guard\ band) + (5\ DC)\ + (11\ upper\ guard\ band)\ + (16\ pilots) + (980\ data)$$

*Equation 9*

$$R_b = \frac{N_d \cdot b \cdot r}{T_{symbol}} = \frac{980 \cdot 10 \cdot \frac{5}{6}}{13.6} = 600\ Mbps$$

With the number of data subcarriers, the modulation bits per symbol, the LDPC code rate, and the symbol period, the data rate of the symbol can be calculated. As shown in Equation 9

the data rate is 600 Mbps for MCS11 1204-QAM, 5/6 rate LDPC code for an 80 MHz he mode symbol with 800 ns guard interval. 600 Mbps for 80 MHz channel width and single spatial stream for Wi-Fi 6 is worth committing to memory. If you can remember 600 Mbps per spatial stream for 80 MHz channel then the relationship between channel width and number of chains can be easily understood and derived for both AP’s and STA’s. An AP with 8x8 and 80 MHz has a 4800 Mbps PHY. Why? One spatial stream has 600 Mbps so 8 spatial streams have 4800. An AP with 4x4 and 160 MHz also has a PHY rate of 4800 Mbps. With twice the channel width, 160 MHz compared to 80 MHz, the 600 Mbps is multiplied by 2 giving 1200 Mbps, then 1200 Mbps is multiplied by 4 for 4 spatial streams to reveal the 4800 Mbps PHY rate. A 2x2 phone with 80 MHz channel width has a 1200 Mbps PHY, 2 spatial streams times 600 Mbps per spatial stream. And a 2x2 160 MHz computer has a 2400 Mbps PHY, 2 times 600 to account for 160 MHz channel width, and 2 times 1200 to account for two spatial streams, yielding 2400 Mbps PHY rate. Don’t worry if you are confused about the use of spatial streams, that is covered in the next section.

A 160 MHz channel width has 2 times 980 equals 1960 data subcarriers. That's a lot of subcarriers for one station. The 12 lowest frequency subcarriers and the 11 highest frequency subcarriers are set to zero to provide a guard band between adjacent channels. Subcarriers at the center of the channel around the carrier local oscillator are set to zero to avoid a DC offset in the direct converted baseband signal. The 160 MHz he mode signal has 7 null subcarriers in the band center.

Pilot subcarriers are needed in order to estimate frequency offset and channel frequency response. Since the symbol rate is known to be 13.6 µs, the phase of a pilot can be measured over two consecutive symbols and the frequency offset can be calculated by dividing the phase difference by the symbol period. The channel frequency response can be estimated by comparing two pilots at different subcarriers frequency.

# Spatial Streams

MIMO allows for multiple spatial streams to be sent in one OFDM symbol when multiple antennas and chains are used in both the transmitter and receiver. With an AP having four transmit chains and an STA having two receive chains the channel matrix has two rows and four columns. The elements of the channel matrix are the impulse response between a transmit antenna and a receive antenna.

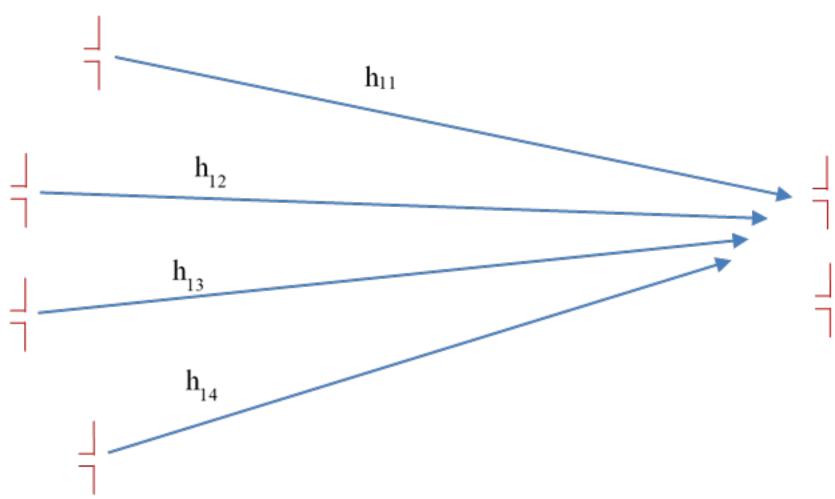


**Figure 12 – Diagram of channel matrix with 4 transmitters and 2 receivers**

 

Figure 12 Shows a diagram of the paths between four transmitters and two receivers. The channel matrix transmit antenna and each receive antennas, 12 impulse response elements in all. The relationship between the input signals and the output signals illustrated in Figure 12 and mathematically described in Equation 10 is a matrix equation with measured output a 2 element vector Y and four element input vector X. If an inverse to the 2 by 4 channel impulse response matrix H can be calculated, then the input signals can be calculated by knowing the received signals and the channel matrix. When multi-path due to obstructions in the home allow the channel matrix to be inverted, then two spatial streams can be sent in one OFDM symbol. It turns out fortunately, that with 4 transmit antennas and 2 receive antennas it is quite easy to get a 2400 Mbps PHY rate at reasonable distances in an indoor residential environment. The four transmit antennas can send two spatial streams, one spatial stream into one antenna pair and another spatial stream into the other antenna pair. Additionally, the two antennas sending a single spatial stream and incorporate 2 element beamforming in order to increase the SNR at the receiver and improve the MCS level.

*Equation 10*

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

*Equation 11*

$$E_\theta = j\omega\mu \frac{2I_m}{\beta} \frac{e^{-j\beta r}}{4\pi r} \sin\theta \frac{\cos\left(\left(\frac{\pi}{2}\right)\cos\theta\right)}{\sin^2\theta}$$

The equation for the electric field of a half wave dipole in the far field is show in Equation 11. The elements of the channel matrix shown in Equation 10 can be determined from Equation 11 in the ideal case of half wave dipole antennas with a direct line of sight path between transmitter and receiver and no reflections from surrounding objects. The electric field is a complex directionally dependent vector with amplitude that falls off as the inverse of the distance between the two antennas, r in Equation 11. The wave length of a 5.5 GHz signal is 54 mm, the phase of the electic field cycles through 360 degrees every wavelength, the $e^{-j\beta r}$ in Equation 11. The electric field above the half wave dipole is zero when θ = 0 degrees in the floor directly above the AP antenna and the electric field is a maximum when the AP and STA are on the same floor θ = 90 degrees.

In a customers home, the channel is much more complicated with many reflected rays and attenuation from walls and floor. The path between scattering objects follows the formula of Equation 11. The elements of the channel matrix are the complex vector sum of all the direct and reflected rays between a transmit antenna and a receive antenna.

The condition for two spatial streams is met when the eigenvalues of the channel matrix multiplied by it's complex conjugate transpose has two nonzero values. This condition is not met unless there are multipath reflections. In free space there will only be one spatial stream. Fortunately, there is enough multipath in residential homes for two spatial streams and high MCS rates with a 4x4 AP and 2x2 STA.

Now we have everything needed to calculate the data rate of an OFDM symbol. The symbol period is 13.6 µs. The number of data subcarriers in an 80 MHz channel width is 980 and twice that for 160 MHz channel. The bit loading is determined by the MCS index. In Equation 12, the PHY rate is calculated to be 2400 Mbps for a 2x2 STA with 160 MHz channel width for MCS 11.

*Equation 12*

$$R_b = \frac{N_{SS} \cdot N_d \cdot b \cdot r}{T_{symbol}} = \frac{2 \cdot 2 \cdot 980 \cdot 10 \cdot \frac{5}{6}}{13.6} = 2400\ Mbps$$

# PHY Rate and Speed Test Relationship

Sometimes there is confusion between the data rate of an OFDM symbol and the download rate of a file from the Internet to the customers computer or the result of a speed test. They both after all, are called data rate and have the same units of Mbps. For example, Figure 4 shows an example where the data rate of the OFDM symbol is 2400 Mbps while the result of a speed test measures a download rate of 1200 Mbps. The PHY rate of the OFDM symbol is determined by the channel conditions while the 1200 Mbps measured on the speed test is determined by many factors include speed test server, Internet path, WAN, speed, computer settings, other spectrum users, etc.

To avoid confusion for these two related but not identical metrics, the data rate of a particular OFDM symbol is referred to as a PHY rate whereas the download speed of a file from the Internet to the customers computer is referred to as data throughput. Both are data rates, and both are measured in Mbps generally for he mode signals, although bits/sec, MB/s, GB/s, kbps, Gbps are equally valid units of measure.

A PHY rates greater than the target data throughput is a necessary but not sufficient condition. If the PHY rate is less than the target data rate then it is not possible to get the download speed we are trying to deliver to our customers. For example, if the PHY rate is 17.2 Mbps for a 40 MHz channel width at MCS0 and one spatial stream, as will be explained later in the paper, the measured download throughput was 16 Mbps, it is simply impossible to deliver 1 Gbps download rate when the PHY rate is 17.2 Mbps. Not going to happen. The flip side of this line of reasoning is that many factors in addition to PHY rate determine the data throughput experienced by a customer. These factors include preambles, aggregation, spectrum sharing, scheduling, network processor loading, latency from Internet server to CMTS, DOCSIS feed to Wi-Fi. A PHY rate of 2400 Mbps does not mean that speed test results will always be 1200 Mbps. Because of this difference between PHY rate and data throughput, the PHY rates are often incorrectly called "theoretical". Nothing could be further from the truth. A PHY rate of 2400 Mbps will happen in customers homes all the time if they have a 2x2 160 MHz Wi-Fi 6 network adapter in their computer. In fact, the download speed measured in static and radio silence channel conditions with tools designed to generate as much throughput as possible are much more "theoretical" than PHY rates. PHY rates quoted in the Wi-Fi 6 device specifications such as 2400 Mbps happen all the time whereas the throughput measurements made in radio silence and static channel conditions with tools to generate maximum throughput will never happen in customers homes. Customers do not have radio silence due to neighbors and other radio devices inside the home, people and pets and things will be moving in the home and outside the home creating dynamic channel conditions, and customers will be using applications that have a different download and upload demand than test tools.

# Resource Units and OFDMA

The FFT duration of a Wi-Fi 6 symbol is 12.8 µs. For the standard guard interval of 800 ns the symbol period is 13.6 µs. The ratio of the guard interval to the FFT duration is 1/16 so that guard interval is only 5.88% of the symbol period. The efficiency in this sense is 4 times greater for Wi-Fi 6 than preceding OFDM Wi-Fi versions. A 2x2 160 MHz Wi-Fi 6 STA has a peak PHY rate of 2400 Mbps. When not running a speed test or downloading a many GB file from a Gbps server the traffic demand is much less than required to fill up 160 MHz wide symbols. So the subcarriers of an OFDM symbol are divided up into smaller resource units allowing multiple STA's to create a single OFDM symbol. This is called OFDMA since multiple access to the resource is accomplished by allocating users resource units. Resource units, RU, are blocks of subcarriers making a full OFDM symbol.

OFDMA is a key part of Wi-Fi 6. OFDMA uses frequency division as a multiple access scheme. Rather than each STA taking turns in time using all the channel width of a symbol, multiple STA's can use different blocks within the channel width at the same time in a single OFDM symbol. Since the tones generated by each STA are formed from a synchronized FFT they are orthogonal. The tones from many STA's are called orthogonal because they do not interfere with each other. Orthogonal signals do not interfere with each other so they do not require the same guard band between resource blocks that non-orthogonal signals do. That is why OFDMA is much more efficient than simple FDM systems. An FDM system would be AM radio where each radio station is assign a block of spectrum and guard bands are needed between channels. Another example is DOCSIS 3.0 channel bonding. The QAM signals that are bonded are not orthogonal, while the symbol rate is 5.3 MHz the channel spacing is 6 MHz. Orthogonal tones in 802.11ax are spaced at 78.125 KHz equal to the symbol rate. As we've seen the guard interval needed to prevent inter-symbol interference reduces the spectral efficiency of OFDM signals.

For a 20 MHz channel width, there are 2 pilots in a 26-tone resource block, 4 pilots in a 52 and 106 tone resource block, 8 pilots in a 242-tone resource block, and 16 pilots in a 484 and 980 tone resource block. This is show in Table 6

**Table 5 - OFDMA tones and pilots for each resource unit, RU**

| tones | pilots |
|---|---|
| 26 | 2 |
| 52 | 4 |
| 106 | 4 |
| 242 | 8 |
| 484 | 16 |
| 996 | 16 |

In determining the allocation of subcarriers to resource units the 802.11ax task group started at the beginning; the original 802.11a OFDM symbol. The 802.11a signal is shown in Figure 13, the active tones are spread out over 20 MHz and the EVM of the 48 data subcarriers in red and 4 pilot subcarriers in white are shown. The FFT size of an 802.11a signal is 64, consisting of 52 active tones with 4 pilot tones.

52 tones with 4 pilots was selected as a resource unit in he mode. The 48 data tones for this RU size matches the data tones of an 802.11a signal. The occupied bandwidth of 48 tones spaced at 78.125 kHz is

4.1 MHz. Simulations of packing efficiency versus RU bandwidth during the 802.11ax task group work revealed that above 2.5 MHz the efficiency dropped. A smaller RU size was needed.

The 52 RU was divided into two. The smallest RU size was decided to be 26 tones with 2 pilots. The RU having 26 tones occupies 2.0 MHz of spectrum and has a maximum PHY rate of 29.4 Mbps with two spatial streams.

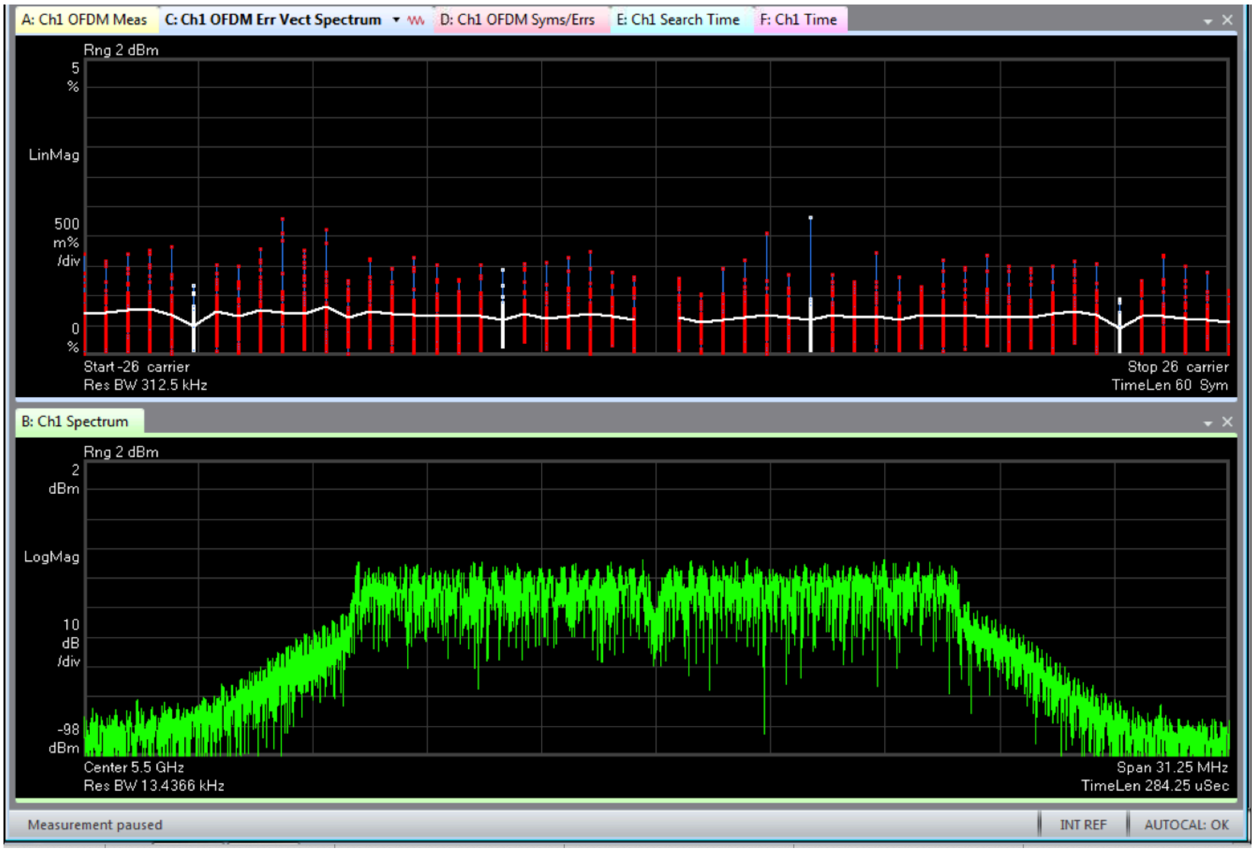


**Figure 13 – Back to the drawing board, 802.11ax task group formed resource units, RU, to match original 802.11a signal**

While it may seem that 802.11a signals are hopelessly old school in these times, in fact 802.11ax still makes use of 802.11a signals. Signalling messages are still sent with 802.11a protocol at 6, 12, 24 Mbps data rate in 20 MHz channels with 48 data subcarriers and 4 pilots for a total number of active subcarriers. As shown in figure 14, a block acknowledgement, Block ACK, after receiving successfully a 160 MHz channel width 802.11ax MCS11 1200 Mbps PHY data burst, the Block ACK does not just send one of these 802.11a 20 MHz channel width signals but eight of them. Each 20 MHz segment of the 160 MHz channel width contains an 802.11a block ACK.

 

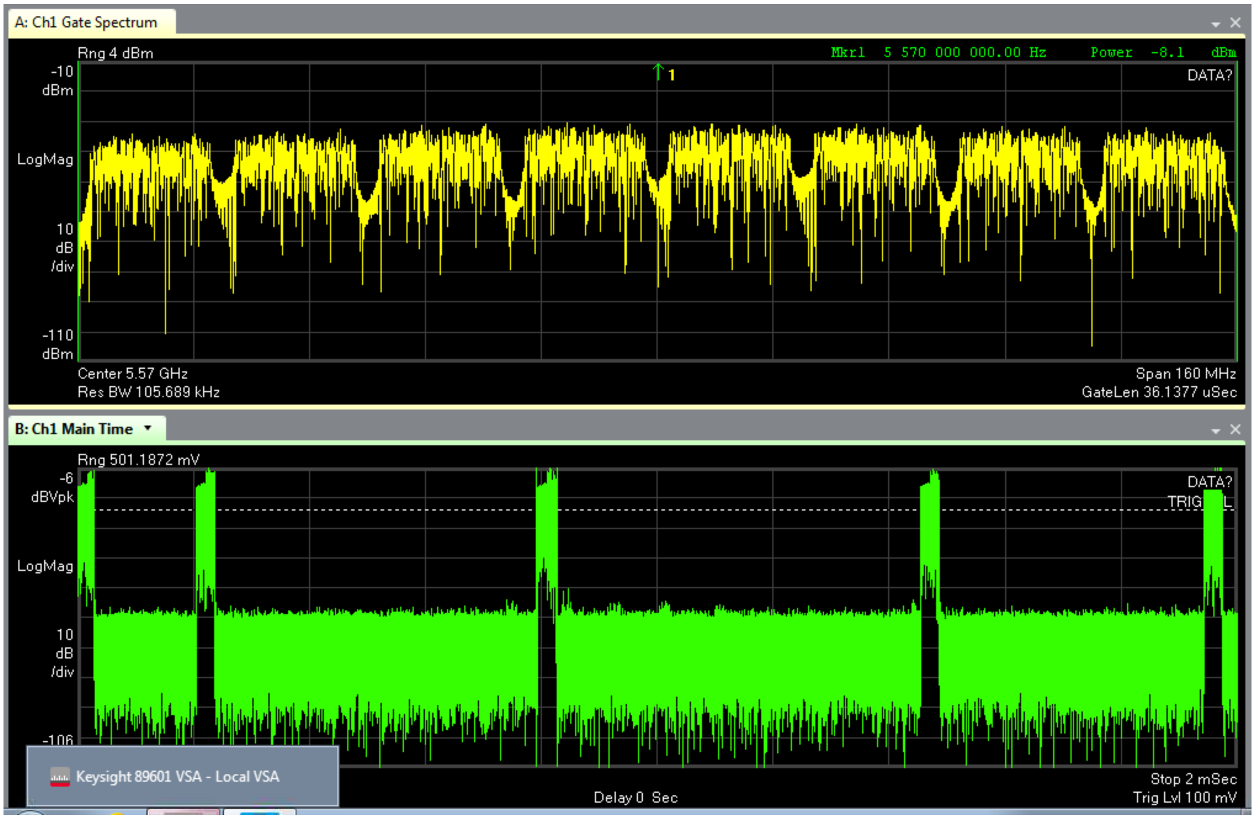


**Figure 14 - 802.11a signal are still used in Wi-Fi 6, here for Block ACK**

To verify that each of the 20 MHz spectrum blocks are indeed 802.11a signals, the vector signal analyzer demodulator was set to a center frequency of 5520 MHz, just above the primary channel 100. The demodulator was set to 802.11a mode. The measured constellation is shown in figure 15. The modulation is 16-QAM for the block ACK with data rate 24 Mbps and 52 active tones. The duration in time of these block ACK's measured 28 µs. The time duration of the block ACK is measured in figure 16. The block ACK contains two OFDM symbols and preamble. The symbol time for 802.11a is 4 µs so the two symbols of the block ACK occupy 8 µs. The 802.11a preample occupies 20 µs.

 

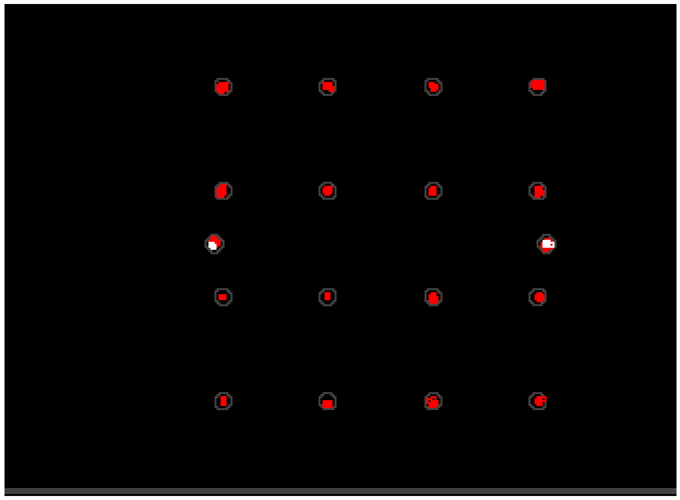

**Figure 15 - 802.11a constellation for 24 Mbps Block ACK 16-QAM**

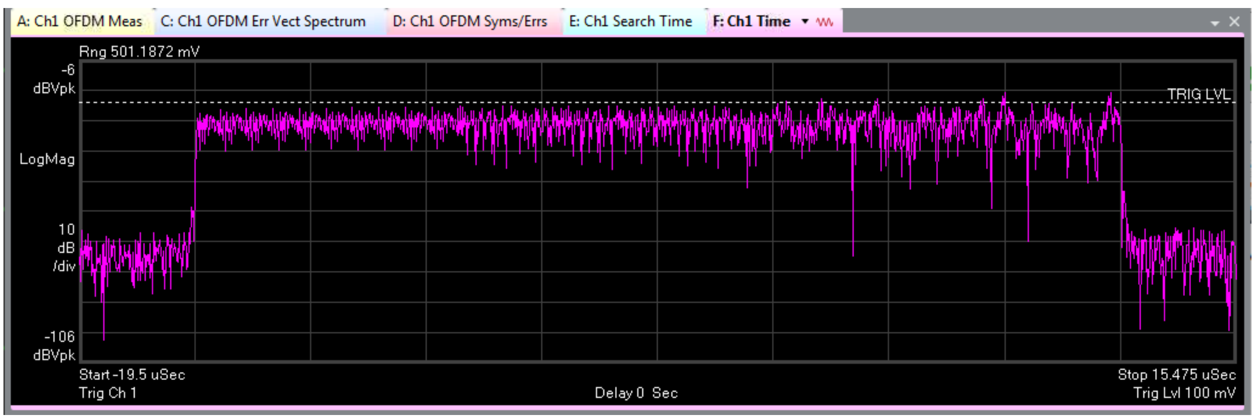


**Figure 16 - Time duration of 24 Mbps 802.11a signal, 1/8 of the total ax Block ACK**

**Table 6 - OFDMA resource units RU, for 2x2 STA**

| RU | 2.0 | 4.1 | 8.3 | 18.9 | 37.8 | 76.6 | MHz |
|---|---|---|---|---|---|---|---|
| MCS | 26 | 52 | 106 | 242 | 484 | 996 | tones |
| 0 | 1.8 | 3.5 | 7.5 | 17.2 | 34.4 | 72.1 | Mbps |
| 1 | 3.5 | 7.1 | 15.0 | 34.4 | 68.8 | 144.1 | Mbps |
| 2 | 5.3 | 10.6 | 22.5 | 51.6 | 103.2 | 216.2 | Mbps |
| 3 | 7.1 | 14.1 | 30.0 | 68.8 | 137.6 | 288.2 | Mbps |
| 4 | 10.6 | 21.2 | 45.0 | 103.2 | 206.5 | 432.4 | Mbps |
| 5 | 14.1 | 28.2 | 60.0 | 137.6 | 275.3 | 576.5 | Mbps |
| 6 | 15.9 | 31.8 | 67.5 | 154.9 | 309.7 | 648.5 | Mbps |
| 7 | 17.6 | 35.3 | 75.0 | 172.1 | 344.1 | 720.6 | Mbps |
| 8 | 21.2 | 42.4 | 90.0 | 206.5 | 412.9 | 864.7 | Mbps |
| 9 | 23.5 | 47.1 | 100.0 | 229.4 | 458.8 | 960.8 | Mbps |
| 10 | 26.5 | 52.9 | 112.5 | 258.1 | 516.2 | 1080.9 | Mbps |
| 11 | 29.4 | 58.8 | 125.0 | 286.8 | 573.5 | 1201.0 | Mbps |

Table 7 shows the PHY rate for two spatial streams for each MCS index for each RU size. The RU size is expressed in MHz of occupied bandwidth in the first row and number of tones in the second row. The smallest PHY rate is RU 26 tones with MCS0 having a data rate of 1.8 Mbps. The largest PHY rate is 1201 Mbps for RU 996 tone occupying 76.6 MHz of bandwidth with MCS11. This should be familiar by now, the 1200 Mbps maximum PHY rate of a 2x2 80 MHz Wi-Fi 6 phone.

Frequency division multiplexing and time division multiplexing are duals of each other. Two stations running at 80 MHz channel width on the same channel and 50% duty cycle have equal throughput to two stations running at 40 MHz chanel width with 100% duty cycle on separate channels. There is no inherent advantage in throughput of one method over the other.

With perfect implementation running at twice the channel width half the time equals running at half the channel width all the time. It is in the imperfections of the implementation that in certain cases one may have advantages over another.

OFDMA implementation in he mode is a good example.  In some cases stations are better off running at full channel width and sharing the same channel either with time division or with MU-MIMO spatial division multiplexing based upon antenna beam forming.

 

While in other cases stations are better off each running in a separated block of subcarriers within the channel width at the same time.

OFDMA and MU-MIMO are complementary technologies. MU-MIMO works best in high SNR regions with high throughput demand. OFDMA works best in low SNR regions with low thorughput demand.Consider a 2x2 160 MHz Wi-Fi 6 STA, the PHY rate is 2400 Mbps.

By multiplying 2400 Mbps PHY rate by the symbol time of 13.6 microseconds we see that each symbol needs to be loaded with 32,640 bits. Most applications just do not generate enough bits consistently fill 2400 Mbps data rate symbols. When traffic demand is low and PHY rate high, latency, memory overloading, and zero filled symbols negatively impact customer experience. With a 2400 Mbps PHY rate it is unlikely that enough stations each with low traffic demand could fill the pipe.

So while the 2400 Mbps PHY may be inefficent at low traffic demands, it is a mute point since it still works fine. But as the users get further away from the AP and more walls, floors and obstacles attenuate the signal, the PHY rate drops. At lower PHY rates stations can benefit from OFDMA. A station can only transmit at a finite level, many are limited to around +20 dBm of transmit power.

Transmit power of stations need to be restricted for regulatory reasons and for battery life. Without OFDMA, two stations may transmit at 80 MHz channel width taking turns in time. The +20 dBm transmit level of each station is spread out over the full 80 MHz. With OFDMA, the two stations can transmit each in an adjacent 40 MHz channel width at the same time. The +20 dBm transmit level of each station is now spread out over the 40 MHz channel. The power spectral density of each station transmission is increased by 3 dB.

The signal to noise ratio at the AP receiver is increased by 3 dB. With 4 stations running in uplink OFDMA mode the SNR increase is 6 dB. With 8 stations running in uplink OFDMA mode the SNR increase is 9 dB. A 9 dB increase in SNR can increase the MCS level, resulting in a throughput improvement.

# Speed Tests and File Downloads

Figure 17 shows a screen shot of a 2x2 160 MHz Wi-Fi 6 STA inside a notebook computer. The speed test result is 1129 Mbps download and 38.26 Mbps upload. The PHY rate is consistent 2400 Mbps, he mode, 160 MHz channel width, MCS11, 1024-QAM, 5/6 LDPC code rate, 2 spatial streams. An iperf3 download from the 2.5 Gbps Ethernet LAN port of the router to the STA measured a download throughput of 1.43 Gbps.

 

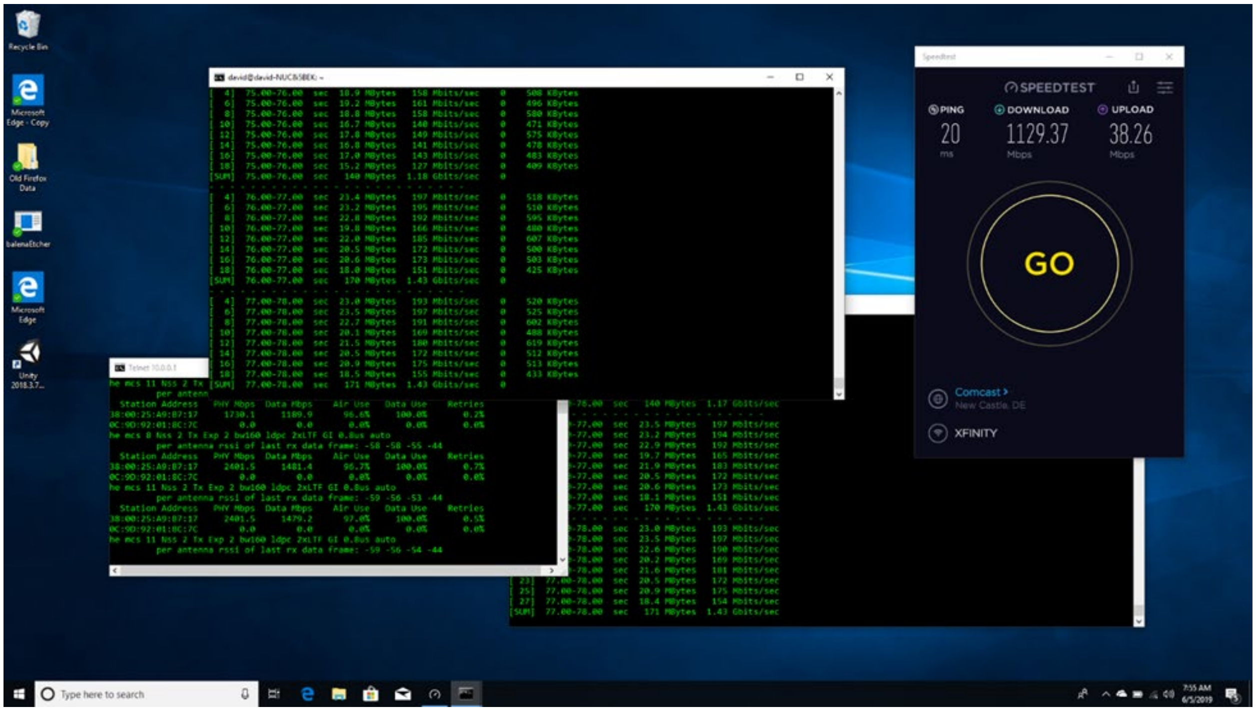


**Figure 17 - Screen shot of notebook computer with 2400 Mbps Wi-Fi 6 2x2 160 MHz station**

 

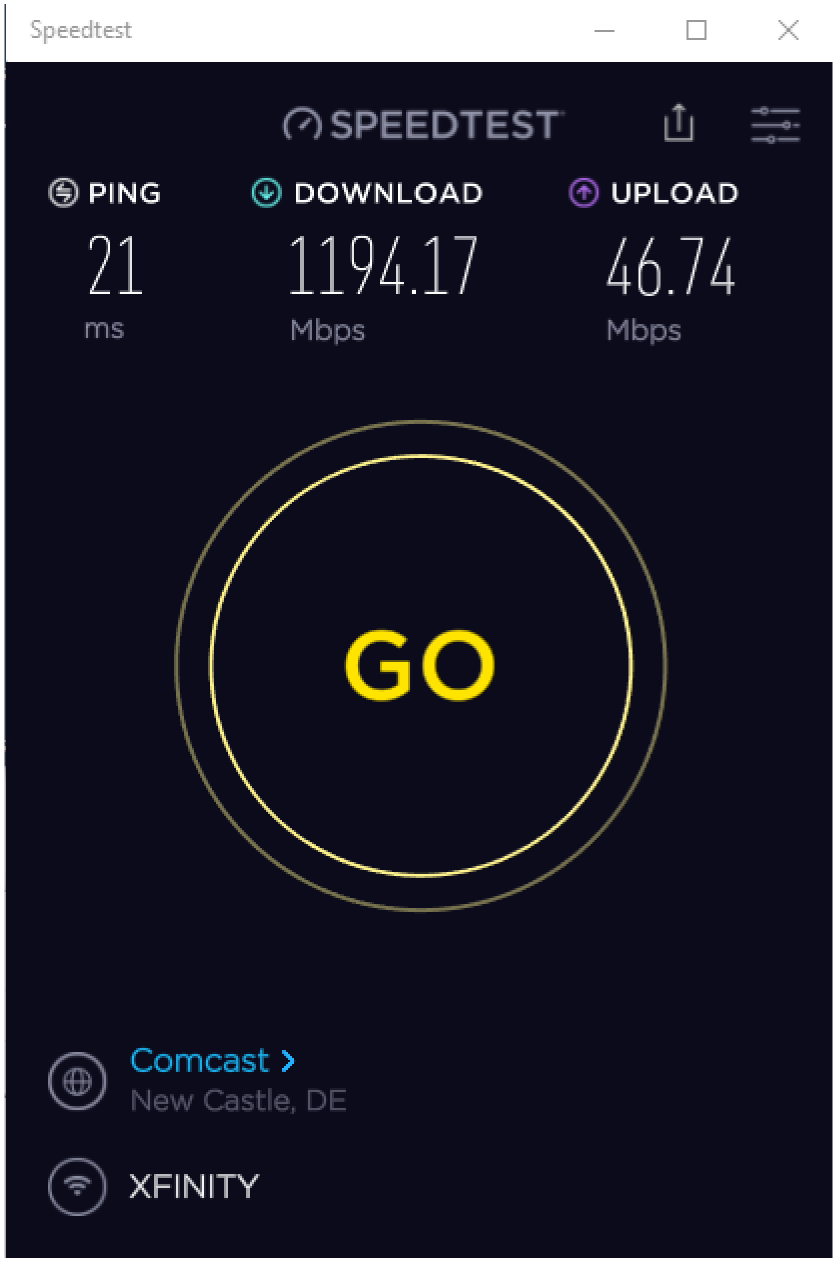


**Figure 18 - Speed test with 2400 Mbps PHY notebook computer 2x2 160 MHz Wi-Fi 6**

Figure 19 shows the screen shot of a speed test with a 2x2 80 MHz Wi-Fi 6 phone. The download speed was 838 Mbps and the upload speed was 39.9 Mbps. The PHY rate was 1200 Mbps, he mode, 80 MHz channel width, MCS11, 1024-QAM, 5/6 LDPC code rate, 2 spatial streams.

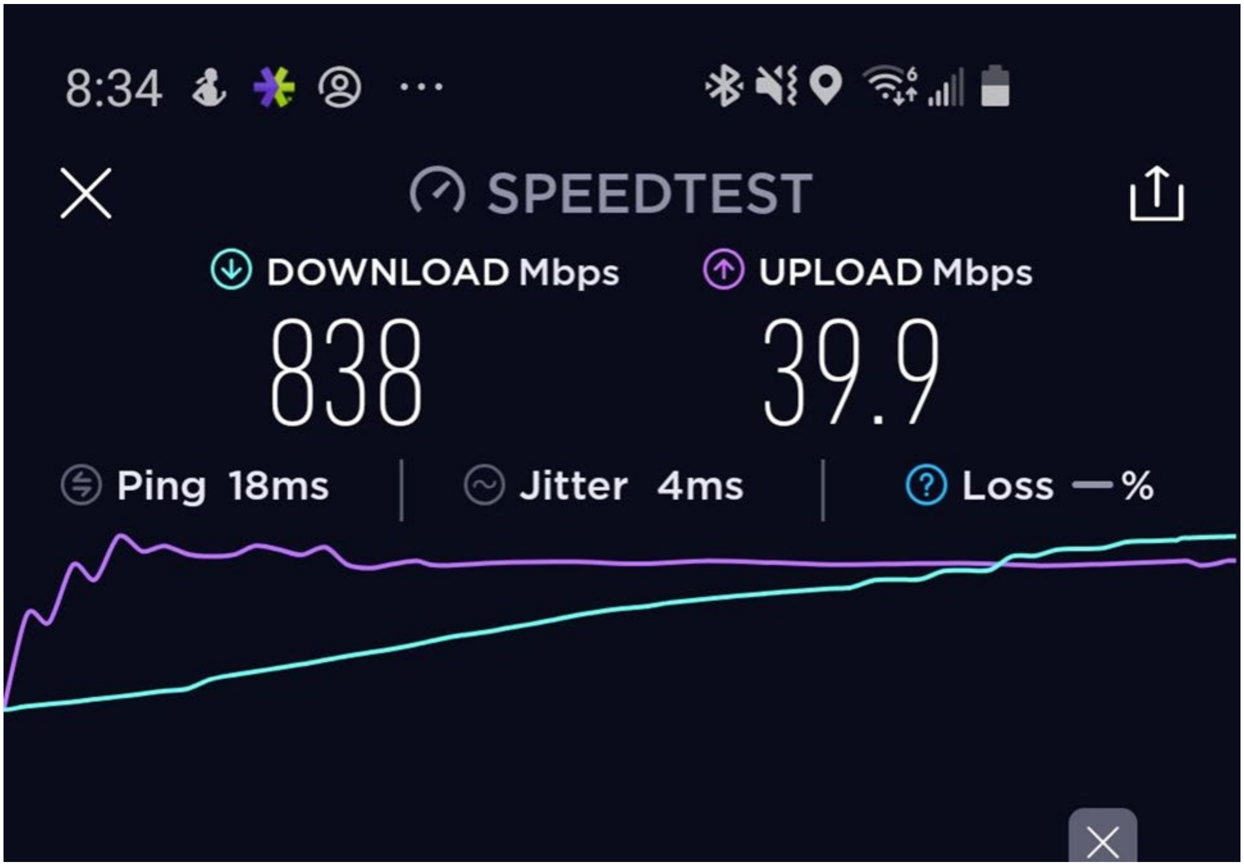


**Figure 19 - Speed test with phone having 1200 Mbps Wi-Fi 6 2x2 80 MHz station**

# Conclusion

Wi-Fi 6 based on the IEEE standard 802.11ax adds many critical features for service providers. Wi-Fi 6 is key to delivering consistent, reliable, stable Gbps service with whole home coverage. First, the speeds are higher, with 1200 Mbps symbol data rate for many phones and 2400 Mbps symbol data rate for many notebook computers. The paper has shown examples of the phone delivery speed test results of 800 Mbps and the notebook computer delivering speed test results of 1200 Mbps. Second, Wi-Fi 6 adds OFDMA as a new multiple access network. This allows many devices each with a small amount of traffic demand to all be served with a shared symbol, each device using only a small number of subcarriers of the OFDM symbol. Ensuring that the customer traffic demand is much less than the offered capacity is the key to consistent, reliable, stable service. Delivering 1200 Mbps speeds with a 2400 Mbps symbol rate allows for other users of the unlicensed spectrum such as neighbors as well as many other lower traffic demand devices in the customers home.

# Abbreviations

| | |
|---|---|
| AP | access point |
| STA | station |

 

| | |
|---|---|
| bps | bits per second |
| FEC | forward error correction |
| HFC | hybrid fiber-coax |
| HD | high definition |
| Hz | hertz |
| ISBE | International Society of Broadband Experts |
| SCTE | Society of Cable Telecommunications Engineers |
| MIMO | Multiple input multiple output |
| OFDMA | Orthogonal frequency division multiple access |
| FFT | Fast Fourier Transform |
| | |