How Broadband Customers Can Benefit from Newfangled Wi-Fi Multiple User Features

A Technical Paper prepared for SCTE by

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

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

1. Introduction

Historically, Wi-Fi is a polite protocol. Users will take turns in the time dimension to access the radio interface, sending and receiving messages. As the number of devices in the home has grown, more efficient multiple-user technologies have been introduced. The objective is to utilize these advanced multiuser features to benefit broadband customers in a tangible way. Techniques to improve the speed of a single user can be readily observed by customers with a simple speed test. The benefits of multiple user technologies require several devices and applications working in tandem. Laser focus on how technology benefits customer experience rather than technology for technology's sake is key. A traffic model that accurately reflects the situation in customers' homes is critical in applying multiuser technology that improves customer experience.

For multiuser techniques such as Multiple User Multiple Input Multiple Output (MU-MIMO) and Orthogonal Frequency Division Multiple Access (OFDMA) to work, a confluence of devices and applications must meet. The customer's devices must have multiple-user capability. Not all devices can take advantage of multiuser technology. Sometimes, the probability of several devices using applications that need access to the Wi-Fi radio signal at the same time is low; when low probabilities multiply the overall probability gets exponentially lower. The trick is to weed out the low probability use cases and focus on the commonly occurring use cases. This paper identifies the commonly occurring use cases for multiuser Wi-Fi technology and describes the theory behind multiple user techniques of multiple antenna spatial streams, spectrum resource unit allocation, and spatial frequency reuse. The paper sorts out aspects that are mostly for show from the technologies that lead to better user experience.

2. Begin with the fundamentals

The cosine of 0 degrees is 1 while the sine of 0 degrees is 0. The cosine of 90 degrees is 0 while the sine of 90 degrees is 1. The sine and cosine wave functions are in quadrature, simply offset in phase by ninety degrees, $\frac{\pi}{2}$ radians. This property allows information to be sent on the amplitude of the cosine wave and sine wave at the same time. The trick is to read the amplitude of the cosine wave at the phase of 0 degrees when the sine wave is nulled out, and the amplitude of the sine wave at phase 90 degrees when the cosine wave is nulled out. Figure 1 shows a unit circle as an aid to visualize the quadrature property of sine and cosine waves. This is the familiar quadrature amplitude modulation (QAM). In the cable world we are so familiar with these signals that we give them a nickname, "QAMs". QAMs carry a multiplex of video streams in a 6 MHz channel width. Many QAMs are combined, each with different center frequency. This is frequency division multiplexing, FDM. Wi-Fi uses QAM and FDM as well, yet in a slightly different way.

OFDM, orthogonal frequency division multiple access, is a form of FDM with the restriction that the signals are orthogonal. The FDM used with DOCSIS and video QAMs contain each multiplexed signal within an assigned 6 MHz block of spectrum. The signals do not exceed their 6 MHz block. By contrast, the frequency multiplexed signals in OFDM are not contained in frequency at all, even though they do tend to die off further away from the center frequency. In fact, each signal goes on in frequency forever.

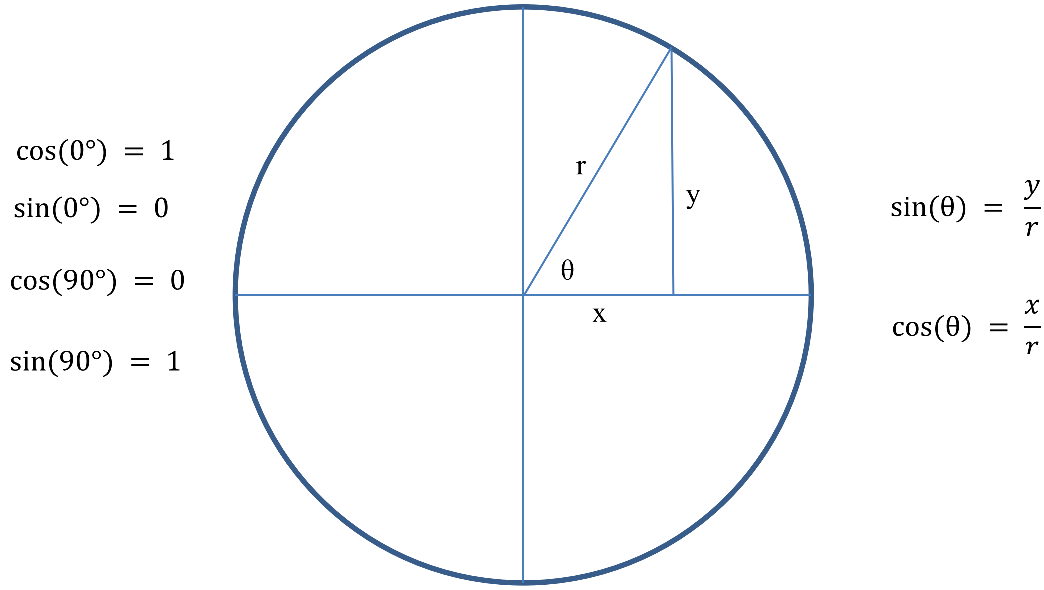

Figure 1 - Unit circle illustrating quadrature signals

A periodic signal can be represented by a Fourier series expansion, an infinite sum of sine and cosine waves with discrete frequencies that are multiples of the inverse of the period. A periodic signal in the frequency domain consists of uniformly repeating spectral lines. Periodic functions can be useful, such as clocks, but since they last forever in time, they do not make for high-speed information transfer.

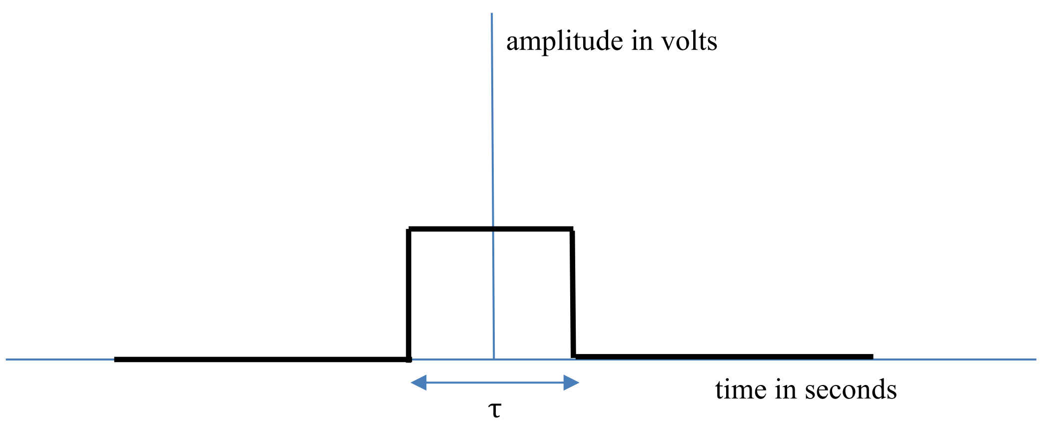

Figure 2 Impulse response for sending high speed information in amplitude

A good signal for fast information transfer is a quick impulse function as shown in Figure 2. The impulse function, unlike the periodic function, is contained in a finite chunk of time. Being finite in time makes the impulse response go on forever in frequency. The frequency response of the time impulse function is determined by the Fourier transform shown in Equation (1).

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)e^{-j\omega t}dt \tag{1}$$

$$e^{j\theta} = cos(\theta) + j\sin(\theta) \tag{2}$$

The time domain impulse function as shown in Figure 2 is even and symmetric. Euler's formula shown in Equation (2) allows the exponential function of an imaginary argument to be broken up into real cosine and imaginary sine parts. The sine function is odd. When integrated with an even function the imaginary sine part of $e^{-j\omega t}$will vanish leaving only the real cosine part of $e^{-j\omega t}$ to integrate. The cosine function is even and symmetric as is the impulse function. The integration can be performed only from 0 to τ/2 and the result multiplied by 2.

$$F(\omega) = 2\int_{0}^{\frac{\tau}{2}} cos(\omega t)dt \tag{3}$$

The sine function has a slope of 1 at 0 degrees phase just as the cosine of 0 phase is 1. The sine function has a slope of 0, flat top, at phase 90 degrees just as the cosine function is 0 at 90 degrees. The derivative of the sine function is the cosine function. The anti-derivative or integral of the cosine function is the sine function. Knowing the integral of the cosine is the sine function allows the Fourier transform of an impulse response to be evaluated shown as a sinc() function in Equation (4).

$$F(\omega) = 2\int_{0}^{\frac{\tau}{2}} cos(\omega t)dt = 2\frac{sin(\omega t)}{\omega}\Big|_{0}^{\frac{\tau}{2}} = \frac{\sin\left(\frac{\omega\tau}{2}\right)}{\frac{\omega}{2}}$$

$$\omega = 2\pi f \qquad \tau = \frac{1}{f_0}$$

$$F(\omega) = \frac{sin\left(\frac{\pi f}{f_0}\right)}{\pi f} \tag{4}$$

At f =0 the Fourier transform of the impulse function goes to zero in both the numerator and denominator. L'Hôpital's rule is needed to determine that the Fourier transform of the impulse response is $1/f_0$ when f is zero. This is the peak amplitude of the frequency response. At any frequency that is a non-zero positive or negative integer of f_0 the frequency response of the impulse is zero. We can take advantage of these periodic nulls by frequency shifting other impulses by an integer multiple of f_0.

Figure 3 plots the frequency domain response of the impulse determined in Equation (4). The frequency response of the impulse peaks at a frequency of zero and nulls whenever the frequency is a positive or negative integer multiple of f_0.

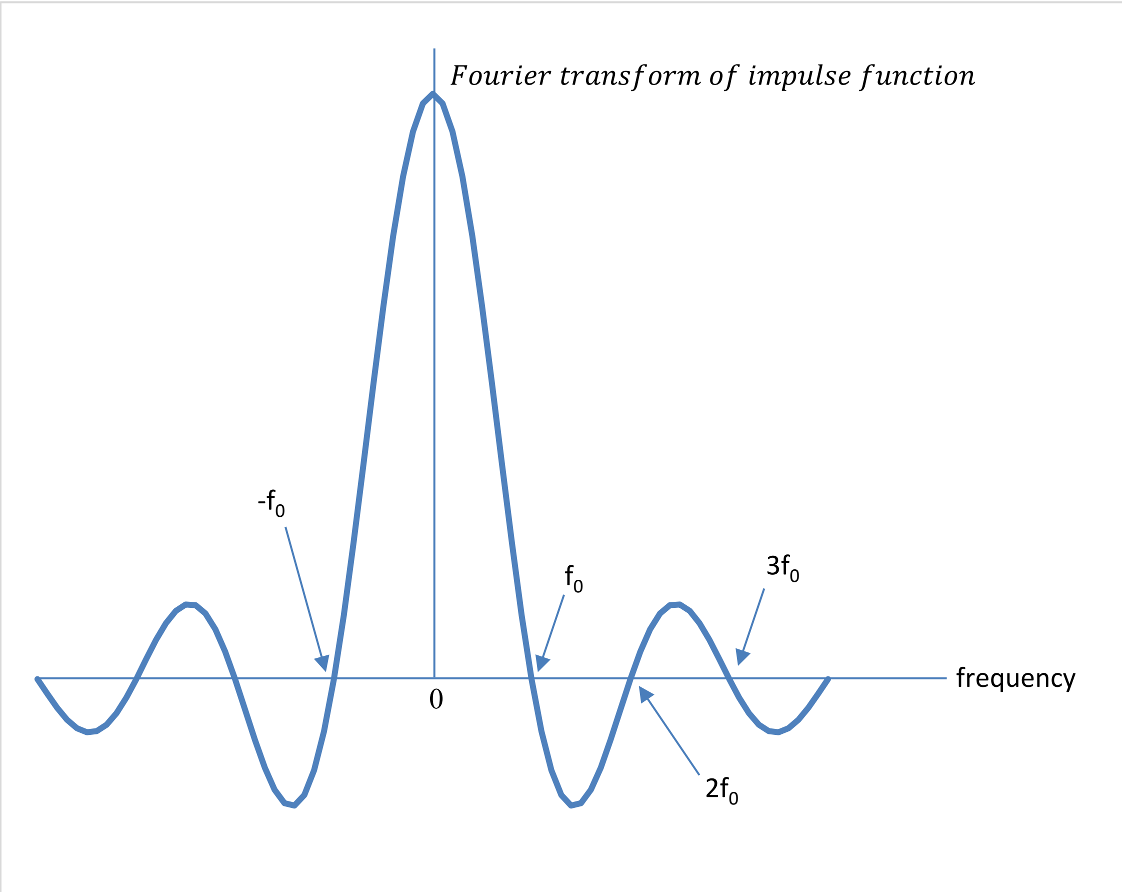

Figure 3 - Impulse response in the frequency domain illustrates orthogonality

By multiplying the impulse by $e^{j\omega_0 t}$ the Fourier transform is shifted in frequency. The frequency shift property of the Fourier transform is derived in Equation (5). Multiplying the impulse by $e^{j\omega_0 t}$ is a form of QAM as revealed in Equation (2). The impulse multiplied by $e^{j\omega_0 t}$ can be thought of as a tone with a frequency of f_0. In OFDM and OFDMA, tones are QAM modulated.

The Fourier transform of the impulse response has a peak at zero and periodically nulls every multiple of f_0 both positive and negative as shown in Figure 3. Another impulse can be shifted in frequency by f_0 and added. The two impulses will overlap in both the frequency and time domain. However, in the frequency domain the first impulse peaks at a null in the second impulse while the second impulse peaks at a null in the first impulse. The two impulses are said to be orthogonal. This is the "O" in OFDM. The information contained in the amplitude of the two impulses can be demodulated by taking the Fourier transform of the combined time domain waveform and sampling the result at 0 and f_0 . We can add as many orthogonal impulses as we wish and still demodulate with a Fourier transform and sampling every f_0 .

$$\int_{-\infty}^{\infty} \left(f(t)e^{j\omega_0 t}\right)e^{j\omega t}\,dt = \int_{-\infty}^{+\infty} f(t)e^{j(\omega-\omega_0)t}\,dt = F(\omega-\omega_0) \tag{5}$$

OFDM does this slightly differently, but the principle is the same. First, the frequency domain subcarriers are QAM modulated. An inverse fast Fourier transform (FFT) converts the signal to the time domain. The receiver demodulates the multiplexed subcarriers with an FFT and sampling. The impulse function and Fourier transform used to understand the principle of orthogonal signals in an OFDM symbol are continuous in both the time and frequency domain. They represent the waveforms after the transmitter digital to analog converter and before the receiver analog to digital converter. In the digital domain both time and frequency representations are finite and discrete. The discrete Fourier transform (DFT), is a version of the Fourier transform. The fast Fourier transform, is an efficient method of calculating the DFT. The DFT is shown in Equation (6).

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-j\frac{2\pi}{N}kn} \quad k = 0,1,\ldots,N-1 \tag{6}$$

Table 1 kHz tones and ns

kHz	tones	ns
20,000		50
10,000	2	100
5,000	4	200
2,500	8	400
1,250	16	800
625	32	1600
312.5	64	3200

A 64-point FFT with a time sampling of 50 ns has a subcarrier spacing of 312.5 kHz covering 20 MHz in the frequency domain and 3.2 µs in the time domain. Table 1 illustrates the relationship of channel width, tones, and time duration. A 6 Mbps signal used for beacons, probes, and other control and management frames uses a 64-point FFT with a 3.2 microsecond time duration in a 20 MHz channel width. Forty-eight of the subcarriers carry one half of a data bit. 800 ns guard interval is inserted to prevent inter symbol interference. The bit rate of a symbol, often referred to as PHY, can be calculated (48*0.5)/(3.2+0.8) = 6 Mbps.

The orthogonal subcarriers can be created all at once by an access point (AP) or station client wi-fi network adapter (STA), this is OFDM. Many stations can create orthogonal subcarriers that combine at the AP to form a complete OFDM symbol. This is called uplink (UL) OFDMA. The "A" stands for access since the resource that is being shared for multiple access is tones in the frequency domain of an OFDM symbol. OFDMA was introduced in 802.11ax along with a change in the subcarrier spacing. The subcarrier spacing for an IEEE 802.11ax high efficiency, he mode, signal is one fourth that of earlier modes. With a channel width of 160 MHz the FFT size of an he mode symbol is 2048. The subcarrier spacing is 78.125 kHz and the FFT duration is 12.8 µs. The normal guard interval is 800 ns so that the symbol time is 13.6 µs. The details of 802.11ax subcarriers, guard time, modulation, and coding are found in reference [1] and not repeated in this paper.

Multiple access can use the time and frequency domain. The space domain can also be used for multiple user access to the radio channel in several ways. Simply separating networks in space is one way. As the coverage falls off in one wireless network another wireless network can reuse the frequency and time resources. Spatial reuse employs transmit level control and coordinated transmissions that help multiple wireless networks to use shared time and frequency resources.

When multiple transmitters and receivers are used in a channel with strong reflections from scattering objects, multiple spatial streams can send information using the same time, spectrum, and space. With two transmitters and two receivers, two spatial streams can be sent. There are four paths from the two transmit antennas to the two receive antennas. This forms a 2x2 channel matrix. If the channel matrix can be inverted the receiver can calculate the two input signals by multiplying the output signal with the inverse of the estimated channel matrix.

Likewise, with four transmitters and four receivers four spatial streams can be sent. This poses a bit of a dilemma since most phone, tablet, and notebook wireless adapters are 2x2. A 4x4 AP can send four spatial streams and yet only two spatial streams to a 2x2 STA. This is a bit of a waste of the AP capability.

In general, this is not so bad. Four spatial streams at the highest PHY rates with 4x4 AP and 4x4 STA turn out to be quite rare. A 4x4 AP and a 2x2 STA turns out to be a performance sweet spot. The combination of two spatial streams and beamforming with a 4x4 AP to a 2x2 STA works at high PHY rate at good distance in residential multipath channels. Even so, MU-MIMO comes to the rescue by allowing a 4x4 AP to send four spatial streams to 2x2 STAs. We just need to have two or more 2x2 STAs with MU-MIMO capability.

3. Types of multiuser techniques in Wi-Fi 6e 802.11ax

The wireless access point for a residential broadband service connects many customer devices. Homes with broadband service may have multiple users with each user having several devices. A family of four active users, each with both a notebook computer and smart phone, along with two television sets and many home security and automation and health devices, provides a useful canonical example. There are three dimensions in which users can share access to the wireless network: space, time, and frequency.

In the time dimension each user gets a slice of time to use the wireless network. In the downlink from AP to STA all users receive the same signal and just need to know which time slice is meant for them. This is referred to as time division multiplexing (TDM). In the uplink from STA to AP the user must contend for a time slice or be assigned a time slice so that only one STA transmits to the AP at a time. This is referred to as time division multiple access (TDMA).

In the frequency domain each user is assigned a different portion of the channel width. The channel is broken up into tones and each tone is individually modulated with data. A discrete Fourier transform implemented with a fast Fourier transform that is a mathematical technique which makes modulating many tones over a channel-width very efficient. The 160 MHz channel width of a Wi-Fi 6 signal is created with a 2048-point FFT. The tones are spaced by 78.128 kHz with an FFT duration of 12.8 µs. In the uplink from STA to AP, OFDMA allows multiple devices to transmit at the same time with each STA assigned different tones of the FFT symbol. In the downlink from AP to STA, OFDMA transmits a full FFT symbol by the AP that is received by all STAs with each STA assigned tones. Equation (7) shows the calculation of the subcarrier spacing and FFT duration for a 160 MHz channel width and 2048-point FFT forming a Wi-Fi 6/6e he mode 802.11ax OFDMA symbol.

$$\mathrm{B} \ = \ 160 \times 10^6 \ \mathrm{Hz} \quad N_{FFT} \ = \ 2048 \quad \Delta f = \frac{B}{N_{FFT}} = 78.128 \times 10^3 Hz \ \ T_u = \frac{1}{\Delta f} = 12.8 \times 10^{-6} s \tag{7}$$

It is important to realize that there is no theoretical difference between time division and frequency division multiplexing regarding channel capacity or throughput. Allowing users to take turns in time or allowing users to use the channel at the same time over portions of the channel width results in the same efficiency. The details of the use case and the channel characteristics will determine if one technique has advantages over the other for a given situation. Accessing the channel in the time domain requires quite a bit of set up. To address the hidden node problem, a request to send signal is sent, followed by a clear to send reply, followed by the data transmission, and wrapped up with an acknowledgement. An interframe spacing is required between each of these bursts. A channel busy assessment, and potentially a backoff, is required before each transmission. The transmissions themselves have a preamble so that the payload data symbols can be demodulated. Even with a PHY rate of 2400 Mbps, there is a lot of set up that makes the channel usage inefficient for small amounts of data throughput. Here is where OFDMA may have an advantage over TDMA. In the case where many users have a small amount of data to transmit, rather than go through all the set up for each one at a time, efficiency is achieved by setting up all the devices to work at the same time on small chunks of the channel width, OFDMA.

The space dimension is a bit different as it depends heavily on the reflections due to scattering objects in the home. Multiple spatial streams of information can be sent at the same time and same frequency. This is possible when there is difference in the space dimension that allows the information streams to be sorted out. In the downlink direction when the STAs are in different physical locations, beamforming may be possible to create constructive interference to the desired station and destructive interference to the undesired station. With beamforming an information stream can be sent to one station with a null towards another station. Then a second information stream can be sent to the other station with a null to the first station.

The uplink space dimension multiple access is more of a true MU-MIMO. Here each station can send an information stream to the access point. The access point receives the signal from all the stations. Multiple inputs from the station's transmitters are received by the multiple antennas of the access point. The access point then makes a channel estimate and determines the many input signals by multiplying the channel inverse matrix by the receive vector. The key difference between uplink and downlink MU-MIMO is that the downlink requires a priori beamforming while uplink all processing can be performed after signal reception.

Five multiuser techniques in Wi-Fi 6e 802.11ax work together when many users are trying to access the wireless network. OFDMA and MU-MIMO work both in the downlink from AP to STA and the uplink from STA to AP. OFDMA and MU-MIMO work together. OFDMA and MU-MIMO are key building blocks of spatial reuse. Orthogonal frequency division multiple access, OFDMA, divides the OFDM symbol with many subcarriers over the channel width into resource units assigned to individual stations.

4. DL MU-MIMO

The maximum PHY rate with four spatial streams and 160 MHz channel width is 4800 Mbps. Each spatial stream with a 160 MHz he mode channel width at MCS11 is 1200 Mbps. Four spatial streams require a minimum 4x4 AP and 4x4 STA. Four transmit antennas and four receive antennas are needed for four spatial streams. Most wireless adapters in phones, tablets, and notebook computers are 2x2, some with 80 MHz channel width and others with 160 MHz channel width. These 2x2 devices are limited to two spatial streams. Downlink (DL) MU-MIMO enables the 4x4 AP to fully utilize four spatial streams by sending information streams to many 2x2 wireless adapters at the same time. A 4x4 AP and two 2x2 STAs has the same multiple input multiple output structure as a 4x4 transmitter sending spatial streams to a 4x4 receiver. In both cases there are four transmit antennas and four receive antennas and 16 paths from antenna to antenna.

A critical difference between a 4x4 transmitter sending MIMO spatial streams to 4x4 receiver and DL MU-MIMO is that the stations do not receive all four signals. The receivers cannot make a channel estimate and invert the four-by-four channel matrix and then multiply by the four-vector output to determine the four input signals. Instead, the stations provide beamforming feedback based upon channel sounding that the AP can use to send multiple spatial streams that add at one station and subtract at another.

In practice we find that with a 4x4 AP four spatial streams do not often happen while three spatial streams at the highest MCS rate are common at reasonable distances. With four vertically polarized half wave dipoles spaced 5/4 wavelength apart, the optimum DL MU-MIMO is in the azimuthal direction. With stations spaced in various adjacent rooms from the AP, three spatial streams at the highest MCS rate can be measured. Table 2 shows such an example. This is a DL MU-MIMO measurement with a 4x4 AP and two wireless adapters in notebook computers with 80 MHz channel width, 2x2 MIMO configuration, and 1200 Mbps maximum PHY rate. With a 1200 Mbps maximum PHY rate, a single device can download at most between 900-1000 Mbps. The maximum PHY rate of a single he spatial stream with 80 MHz channel width is 600 Mbps. Three spatial streams have a maximum PHY rate of 1800 Mbps. With 1800 Mbps PHY rate a TCP throughput of 1200 Mbps is possible. The measurement shown in Table 2 finds a total TCP throughput of 1285 Mbps. This is an important use case in delivering Gbps broadband service to customers. For example, if the broadband service has a peak speed of 1.2 Gbps then a single 2x2 80 MHz 802.11ax wireless adapter cannot by itself deliver the full broadband speed. However, several devices together can combine to exceed 1.2 Gbps Wi-Fi speed. This works well with two, three, and four DL MU-MIMO stations. We find that three DL MU-MIMO stations are the sweet spot, having slightly higher aggregate download speed than two or four stations.

The access point is 4x4 160 MHz 4800 Mbps PHY. The stations are 1200 Mbps PHY, 2x2, 80 MHz. The 80 MHz channel width 2x2 STAs used in the measurement of DL MU-MIMO in Table 2 provide beamforming feedback consisting of 10 angles every fourth subcarrier over the full 80 MHz. This powerful beamforming results in high PHY rate and throughput in both SU and MU operation. DL MU-MIMO shown in Table 2 is 5 GHz band with 80 MHz channel width devices.

Table 2 - DL MU-MIMO Measurement 1200 Mbps PHY Stations

STA	PHY Mbps	Data Mbps	bw MHz	mcs	Nss	mu-mimo
0	617.6	450.9	80	11	1	96.9%
1	1136.7	834.1	80	10.5	2	100.0%
sum		1285.0				

In Table 3 the stations are 2400 Mbps PHY, 2x2, 160 MHz, operating DL MU-MIMO in the 6 GHz band with 160 MHz channel width. Table 3 shows a measurement sample with two 160 MHz wireless adapters using DL MU-MIMO to download TCP at over 2 Gbps. Each device alone can download at around 1.6 to 1.8 Gbps TCP with a maximum of 1.92 Gbps. DL MU-MIMO increases the number of spatial streams to three, resulting in a capacity increase and an aggregate download for two devices over 2 Gbps, something not possible in single user, SU mode.

Table 3 - DL MU-MIMO Measurement Two 2400 Mbps PHY Stations

STA	PHY Mbps	Data Mbps	Channel width MHz	MCS	Spatial streams	MU-MIMO
0	1310.0	755.8	160	11	1	90.9%
1	2401.0	1400.8	160	11	2	99.0%
sum		2156.6				

From Wireshark captures of the beamforming feedback from the 2x2 160 MHz 802.11ax stations used for the DL MU-MIMO measurement, only a single set of ten angles is reported. The beamforming for both SU and MU do not seem to work as well for these 160 MHz devices compared to 80 MHz devices with richer beamforming feedback over the full channel width. The PHY rates and throughput of the 160 MHz channel devices are still greater than the 80 MHz devices given the doubling in the number of data subcarriers. Yet, the 80 MHz channel width devices work better than the 160 MHz devices when normalized for spectrum use.

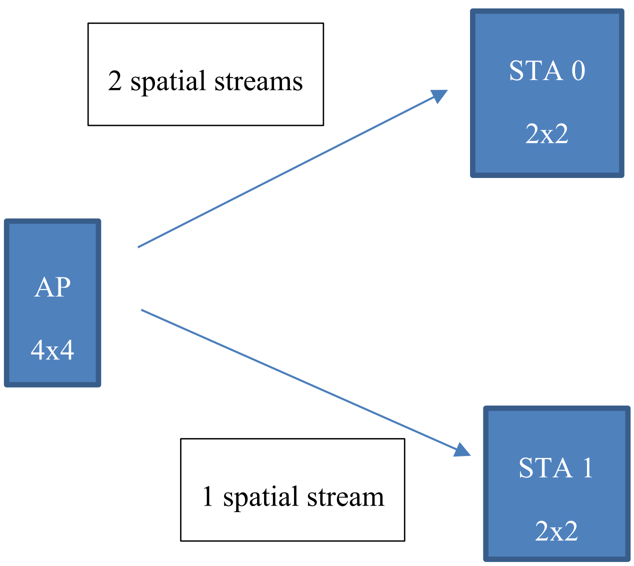

Figure 4 - DL MU-MIMO Example Block Diagram

Table 4 shows a sample measurement of DL MU-MIMO with three 160 MHz wireless adapters. In this sample, the devices were further away from the AP and the MCS rate dropped to between 8 and 9. As a result the sum of the data rates downloaded by the three devices was 1.5 Gbps, less than the maximum at the highest PHY rate, yet still an improvement over SU operation at these distances. DL MU-MIMO increases capacity of the wireless networks only when several devices have large files to download at the same time from Internet servers capable of Gbps downloads with all devices in high SNR conditions with good multipath reflections.

Table 4 – DL MU-MIMO Measurement Three 2400 Mbps PHY Stations

STA	PHY Mbps	Data Mbps	Channel width MHz	MCS	Spatial streams	MU-MIMO
0	1696.8	782.4	157.5	8	2.0	97.7%
1	1246.3	595.3	157.9	8.7	1.3	69.2%
2	959.2	180.5	159.2	9.0	1.0	99.35
sum		1558.2				

DL MU-MIMO requires quite a bit of traffic demand from several capable devices at close range. Applications do not often generate enough traffic for DL MU-MIMO packets to be sent. An application downloading a large movie on a smart phone would seem to be ideal for MU-MIMO. However, when tried, the application downloaded the movie to the phone at 10 Mbps, not enough for DL-MU-MIMO.

5. UL MU-MIMO

Uplink multiuser multiple-input multiple-output allows several stations to transmit spatial streams at the same time. The access point collects the signals from each station and sorts out the spatial streams. UL MU-MIMO is pure MIMO whereby the receiver can process all the streams after reception rather than relying on a priori adaptive beamforming as in the case for DL MU-MIMO.

UL MU-MIMO has the advantage of significant spatial diversity and angle of arrival of spatial streams as the stations transmitting the streams can be in different locations relative to the access point.

Multiple stations can each transmit a spatial stream to the AP at the same time. The AP has multiple antennas and receivers. Each of the AP antennas receive a combination of all the signals from the stations. The spatial streams of independent information are all mixed together at each AP receiver. Without strong multipath in the channel and good channel estimation at the AP, the information streams from each station would be hopelessly jumbled. Each antenna of the stations to each antenna of the AP has an impulse response defined by the attenuation and delay of the direct path and various reflections from scattering objects.

The Fourier transform of the impulse response from antenna to antenna in the presence of multipath reflections reveals a frequency response that would need to be characterized in a single carrier system. OFDM comes to the rescue for UL MU-MIMO since each tone is narrow and can be considered as a flat frequency response. Thus, each antenna-to-antenna path is treated on a tone-by-tone basis and characterized by a single complex number per tone representing the Fourier transform of the impulse response. In practice the channel matrix is adequately characterized by the phase differences between the various paths.

UL MU-MIMO the AP estimates the channel matrix, inverts the channel matrix, and multiplies the inverted channel matrix by the received vector to determine the input signals from each of the stations. Thus, all the information streams from the stations can be decoded.

6. DL OFDMA

Downlink orthogonal frequency division multiple access divides the spectrum into tones and assigns resource units consisting of continuous tones to multiple stations. In general, with heavy traffic, DL OFDMA does not increase capacity. DL MU-MIMO increases channel capacity when stations are in a high signal to noise ratio (SNR), zone and enough traffic demand is there to fill the pipe. DL OFDMA is complementary in the sense that it helps when stations are in a low SNR zone with small amounts of data to transmit. Here SNR is defined as the average power of the transmitted signal at the receiver demodulator divided by the average noise and interference level from all sources expressed in dB. DL OFDMA does not improve the link budget in the same way as UL OFDMA. While stations in theory could take advantage of the lower noise floor of a smaller resource unit allocation, devices tend to demodulate the full downlink channel width and do not measure improved sensitivity due to DL OFDMA.

DL OFDMA is observed when devices are far enough away to forfeit DL MU-MIMO capacity increase and when traffic demand is low. One of the big advantages observed with DL OFDMA relates to the scheduler. With SU and many devices competing for wireless resources there is a tendency for one device to dominate the throughput. With several devices downloading at the same time one device may have very high throughput while the other devices are stuck at low throughput. DL OFDMA is much better at sharing the channel with each device downloading at close to the same throughput.

DL MU-MIMO takes a heavy traffic demand from multiple devices able to utilize DL MU-MIMO and a considerable amount of time. Typically, about 200 Mbps or more from several devices for over one minute is required to see DL MU-MIMO packets. By contrast, DL OFDMA packets make up a large proportion of traffic even with small amounts of traffic and the setup is very quick.

7. UL OFDMA

Uplink orthogonal division multiple access allows multiple stations to transmit at the same time with each using a different part of the channel width. UL OFDMA improves the link budget in the uplink. Each station can only transmit so much power. The maximum transmit level in the 2.4 GHz band for a typical wireless adapter in a notebook computer ranges from +17 to +21 dBm per chain with two chains in a 20 MHz channel width. Restrictions on out of band radiated emissions often results in different transmit power on some channel settings. 5 GHz band station transmit level typical ranges from 10 to 18 dBm per chain with two chains. The wireless adapter in the notebook computer used for 160 MHz channel width measurements in this paper is a type accepted with 5 dBi antenna gain in the 5 GHz band and transmit level of about +15 dBm per chain with two chains for a 160 MHz HE0 signal at 5570 MHz, +17 dBm per chain for an 80 MHz HE0 signal at 5530 MHz, +17 dBm per chain for a 40 MHz HE0 signal at 5510 MHz, and +18 dBm per chain for a 20 MHz HE0 signal at 5500 MHz. Note that the power spectral density and thus the received SNR, increases when the channel width decreases. The 160 MHz channel width case has 12 dB lower signal to noise ratio at the AP receiver than the 20 MHz channel width, 9 dB due to higher receiver noise level at 160 MHz compared to 20 MHz, and 3 dB due to the increase in transmit level at 20 MHz compared to 160 MHz. Therefore, the uplink channel width will drop to 20 MHz at the cell edge in the 5 GHz band. In the 6 GHz band for low power indoor operation the effective isotopic radiated power (EIRP) of the power spectral density is regulated and the behavior at cell edge is different. Figure 5 shows a measurement of the uplink dynamic range with PHY rate improving with the received signal strength indicator (RSSI).

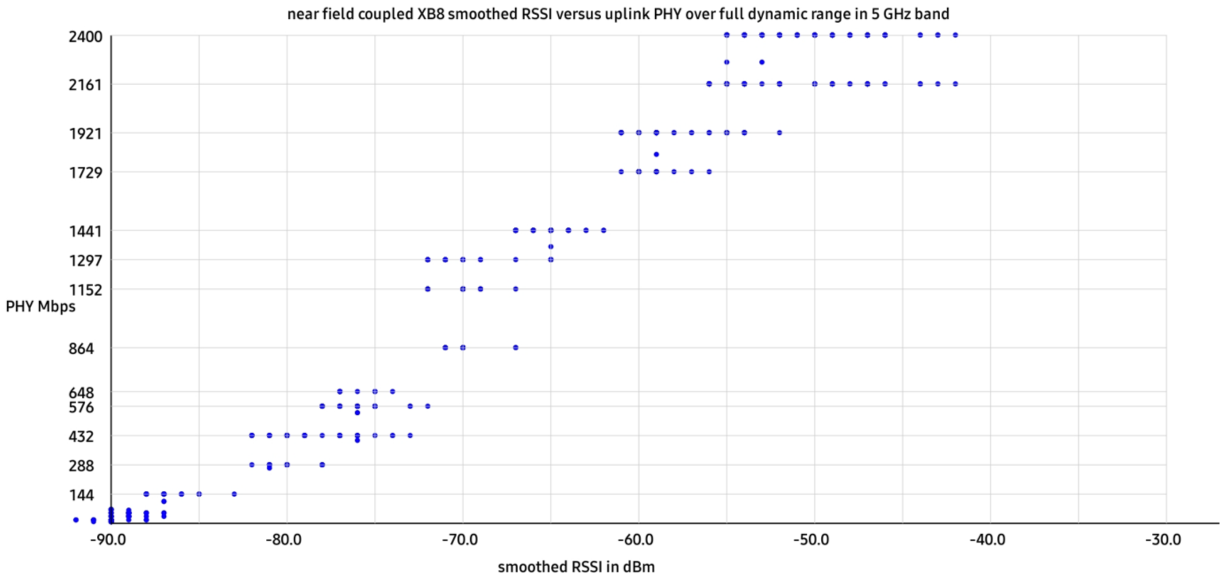

Figure 5 - Dynamic Range in the uplink

Table 5 shows a sample of measurement results with two computers uploading at the same time in the 6 GHz band. Both the AP and the STA fall below the restrictions for low power indoor operation. The coverage is good throughout the home used for the measurement. Shown in Table 5 are cell edge conditions with stable connection and throughput, but connectivity will be lost at further distance between the AP and STA or more obstructions. Both stations are 2x2 wireless adapters in notebook computers with 160 MHz channel width capability and 2400 Mbps maximum PHY rate. The channel width remains at 160 MHz since under the regulatory limit of -1 dBm EIRP per MHz the uplink does not benefit from reduced channel width. UL OFDMA accounts for all the uplink packets with about 1000 tones allocated to each station. The PHY rate of each station is about 70 Mbps and the total upload rate was measured at 49 Mbps. Both stations sent two spatial streams at the lowest MCS rate of 0.

Table 5 – UL OFDMA Measurement Two 2400 Mbps PHY Stations 6 GHz band

STA	rssi	PHY	Data	Channel width	MCS	Spatial streams	ofdma	tones
	dBm	Mbps	Mbps	MHz				
0	-85	72.5	32.9	160	0	2	100%	1002.7
1	-85	73.5	16.0	159	0	2	100%	1014.3
sum			48.9					

Table 6 shows a sample measurement in the 5 GHz band with two 2x2 80 MHz stations having a maximum PHY rate of 1200 Mbps. Both stations are notebook computers using a common Unix based operating system. The sample measurement shown in Table 6 is the lowest observed UL OFDMA RSSI levels at the AP while making measurements of the two computers uploading data throughout a two-story residential home as well as outside the home with coverage up to 100 meters. Both stations have an uplink RSSI at the AP of -86 dBm. The channel width was 80 MHz with each station assigned about 484 tones with 100% UL OFDMA packets. The total throughput was 26.4 Mbps with PHY rates of 35 and 47 Mbps. Both stations transmitted two spatial streams at the lowest MCS level of 0.

Table 6 – UL OFDMA Measurement Two 1200 Mbps PHY Stations 5 GHz band

STA	rssi	PHY	Data	Channel width	MCS	Spatial streams	ofdma	tones
	dBm	Mbps	Mbps	MHz				
0	-86	35.2	12.7	80	0	2	100%	491
1	-86	47.4	13.7	79	0.3	2	100%	497
sum			26.4					

The 160 MHz stations in the 6 GHz band utilized UL OFDMA down to a receive level at the AP of -86 dBm. The 80 MHz stations in the 5 GHz band utilized UL OFDMA down to a receive level at the AP of -86 dBm. Is this good? Why were these the lowest observed levels? To answer these questions and better understand what is going on, let us review noise floor and Boltzmann constant. The thermal noise floor of the receiver is determined by Boltzmann constant and the noise figure of the low noise amplifier.

Ludwig Boltzmann developed statistical mechanics to understand the physics of steam engines. Boltzmann constant relates temperature to energy. Boltzmann constant applies equally well for determining the thermal noise in a receiver due to the vibrations of electrons. The thermal noise density is -174 dBm per Hz at room temperature of 300 Kelvin, equal to 25 degrees Celsius and 77 degrees Fahrenheit.

$$E = k_b T \tag{8}$$

$$k_b = 1.380649 \times 10^{-23} \tag{9}$$

$$N_0 = 10log_{10}(1000 \cdot 1.380649E - 23 \cdot 300) \tag{10}$$

$$N_0 = -174 \frac{dBm}{Hz} \tag{11}$$

The receiver noise floor referenced to the antenna input terminals depends upon the thermal noise density, the noise bandwidth, and the noise figure of the low noise amplifier. A 3 dB noise figure is a reasonable expectation for an AP allowing for a 1 dB noise figure low noise amplifier and 2 dB of losses through the switch, filters, and traces to the antenna.

$$N = N_0 + F + 10 \cdot \log_{10}(\mathrm{B}) \tag{12}$$

$$B = 20\, MHz$$

$$N = -174 + 3 + 10 \cdot \log_{10}(20E6)$$

$$N = -98\, dBm \tag{13}$$

The receiver noise floor at room temperature with a 3 dB noise figure receiver in a 20 MHz channel width is -98 dBm.

Table 7 – Receiver noise floor and channel width for 3 dB noise figure at room temperature

B	N
MHz	dBm
20	-98
40	-95
80	-92
160	-89

In the 6 GHz band for low power indoor operation the AP is restricted to +5 dBm EIRP per MHz and the STA is restricted to -1 dBm EIRP per MHz. The AP can transmit +16 dBm per chain with four chains, 2.15 dBi half wave dipole antenna elements, 3 dB beamforming gain with two spatial streams.

Table 8 – EIRP regulation in the US for 6 GHz low power indoor access points

EIRP per MHz	5.00	dBm/MHz
channel width	160.00	MHz
channel width	22.04	dBMHz
EIRP	27.04	dBm
Antenna Gain	2.15	dBi
Beamforming Gain	3.00	dB
total transmit level	21.89	dBm
chains	4.00	
transmit level per chain	15.87	dBm per chain

The station EIRP per MHz in the 6 GHz band for low power indoor operation is -1 dBm per MHz. A 2x2 station with half wave dipole antenna element gain is limited to +16 dBm per chain transmit level for a 160 MHz channel width signal.

Table 9 – EIRP regulation in the US for 6 GHz low power indoor stations

EIRP per MHz	-1.00	dBm/MHz
channel width	160.00	MHz
channel width	22.04	dBMHz
EIRP	21.04	dBm
Antenna Gain	2.15	dBi
Beamforming Gain	0.00	dB
total transmit level	18.89	dBm
chains	2.00	
transmit level per chain	15.88	dBm per chain

Most stations transmit 6 to 9 dB lower than the levels shown in Table 9. The phones used to make the measurements of MU-MIMO and OFDMA in the 6 GHz band operate at +7.5 dBm per chain with two chains and antenna element gain of -6 dBi. The notebook computers used to measure MU-MIMO and OFDMA operate at +10 dBm per chain with two chains in the 6 GHz band with 160 MHz channel width.

The wavelength is calculated by dividing the speed of light by the frequency. In Equation 14, c is the speed of light, f is the frequency in Hz, and λ is the wavelength in meters. Table 10 shows the wavelength in mm for 2.4 GHz band channel 1, 5 GHz band channel 100, and 6 GHz band center frequency of a 160 MHz channel width signal having primary steering channel 69.

$$c = 299{,}792{,}458\ m/s\ speed\ of\ light \quad (14)$$

$$\lambda = \frac{c}{f} \quad (15)$$

Table 10 – Relationship between frequency and wavelength for 2.4, 5, 6 GHz bands

frequency	wavelength
MHz	mm
2412	124.3
5500	54.5
6345	47.2

The free space path loss at a reference distance is denoted A_0 measured in dB. The reference distance is denoted by d_0 measured in meters. A_0 is calculated as a function of d_0 and λ as shown in Equation (16).

$$A_0 = 20 \cdot log_{10}\left(\frac{4\pi d_0}{\lambda}\right)$$

(16)

A log normal path loss model can be applied for distances beyond the reference distance. L is the log normal path loss in dB. A_0 is the free space path loss at the reference distance d_0 in meters. The distance between the AP and STA in meters is d. L_{floors} is the loss through floors and L_{walls} is the loss through walls. N_σ is a log normal probability distribution with standard deviation σ, typically around 3 dB. Equation 17 shows the IEEE 802.11 log normal path loss model for indoor residential channel.

$$L = A_0 + 35 \cdot log_{10}\left(\frac{d}{d_0}\right) + L_{floors} + L_{walls} + N_\sigma$$

(17)

The Friis transmission equation was derived in 1945 at Bell Labs by Harald T. Friis. R is the received level in dBm, EIRP is the effective isotopic radiated power equal to the transmitter power level plus the transmitter antenna gain, L is the log normal path loss in dB, G is the antenna gain of the receiver. A version of the Friis transmission equation in shown in Equation (18).

$$R = EIRP - L + G$$

(18)

Table 11 shows the distance d in meters for a 6 GHz band signal with channel width 160 MHz for each MCS level along with the PHY rate in Mbps and the maximum TCP throughput in the uplink for a low power indoor station at -1 dBm EIRP per MHz. This table does not include wall and floor loss or the log normal probability distribution factor. As can be seen the distance is quite far at 132 meters.

The wall and floor loss is a wild card. Often the wall and floor loss is not that much. Drywall attenuation may only be around 1 dB. Plaster with wire mesh can be 20 dB attenuation or more. Brick and concrete can have high attenuation. Even some glass sliding doors can have high attenuation. The indoor residential IEEE 802.11 path loss model uses a floor attenuation that is quite high at 20 dB for a single floor. This is much higher than often observed in practice. The wall attenuation used in the calculation references the IEEE 802.11 model of 5 dB per wall. Using these factors for the case of one floor and two walls the additional 30 dB attenuation reduces the coverage distance to 18 meters for the lowest MCS rate. Eighteen meter coverage is still not bad considering the high wall and floor attenuation.

An important point to notice is MCS 6 at a distance of 43 meters. The receive level in the uplink is -69 dBm. The PHY rate is 1297 Mbps and the TCP throughput is 1037 Mbps. This is the lowest level that will still deliver over 1 Gbps speed to the customer.

Table 11 – Distance, receive level for 160 MHz channel width uplink low power indoor station EIRP -1 dBm per MHz

MCS	Rx	PHY	TCP	d 6 GHz
	dBm	Mbps	Mbps	m
0	-86	144	115	132
1	-83	288	230	108
2	-81	432	345	95
3	-78	576	461	78
4	-74	864	691	60
5	-70	1152	922	46
6	-69	1297	1037	43
7	-68	1441	1152	40
8	-63	1729	1383	29
9	-61	1922	1538	25
10	-58	2161	1729	21
11	-56	2401	1920	18

8. Spatial Reuse

There are two different types of spatial reuse. PD uses power detection. SRP uses spatial reuse parameters contained within an OFDMA trigger.

Power detection spatial reuse lowers transmit level based upon neighbor's RSSI. The channel busy threshold for an 802.11 signal is -82 dBm. The energy detection threshold for a non-802.11 signal is -62 dBm. Oftentimes real devices deviate from the threshold levels called out in the IEEE 802.11 standards.

If the RSSI of a neighbor device, be it AP or STA, exceeds -82 dBm then the channel is determined to be busy. After an exponential time back-off the transmitter will be checking for channel busy once more, hoping for an opportunity to transmit when no non-802.11 signal exceeds -62 dBm and no 802.11 signal exceeds -82 dBm. Then the AP or STA will transmit.

Power detection spatial reuse allows the AP or STA to transmit even when an 802.11 neighbor signal exceeds -82 dBm. To reuse the time and frequency resources efficiently in two different locations the transmit power is reduced in proportion to the neighbor RSSI. If the neighbor RSSI is -72 dBm then the transmit level is reduced by 10 dB. If the neighbor RSSI is -62 dBm then the transmit level is reduced by 20 dB.

In effect, power detection spatial reuse keeps the interference toward a neighbor wireless network no worse than full power with -82 dBm threshold while allowing for more transmit opportunities. The power detection method will work with any device, even devices without spatial reuse capability.

The SRP method is much more interesting, and powerful. SRP requires all participants to have spatial reuse capability. The UL OFDMA trigger of a neighbor contains the information needed to reuse time and frequency resources in different locations without interference. The path loss to the neighbor can be calculated by subtracting the measured RSSI from the neighbor transmit level read in the trigger. The trigger will advertise an acceptable level of interference to the UL OFDMA transmission. A transmit level can thereby be calculated that can work over top the neighbor UL OFDMA signal without interference.

9. Putting It All Together With Real Devices and Applications

Consider an illustrative use case with a phone, a notebook computer, and two television sets. All four of these devices have the same Wi-Fi capabilities, including multiple user. The four stations have a maximum PHY rate of 1200 Mbps. There are many different types of Wi-Fi clients. Some have 160 MHz channel width while others only operate at 80 MHz channel width. The devices tested for MU operation with a mix of traffic were 80 MHz channel width wireless adapters, which is very common. Each device has different application needs and different throughput capabilities. A mix of devices is shown in Figure 6.

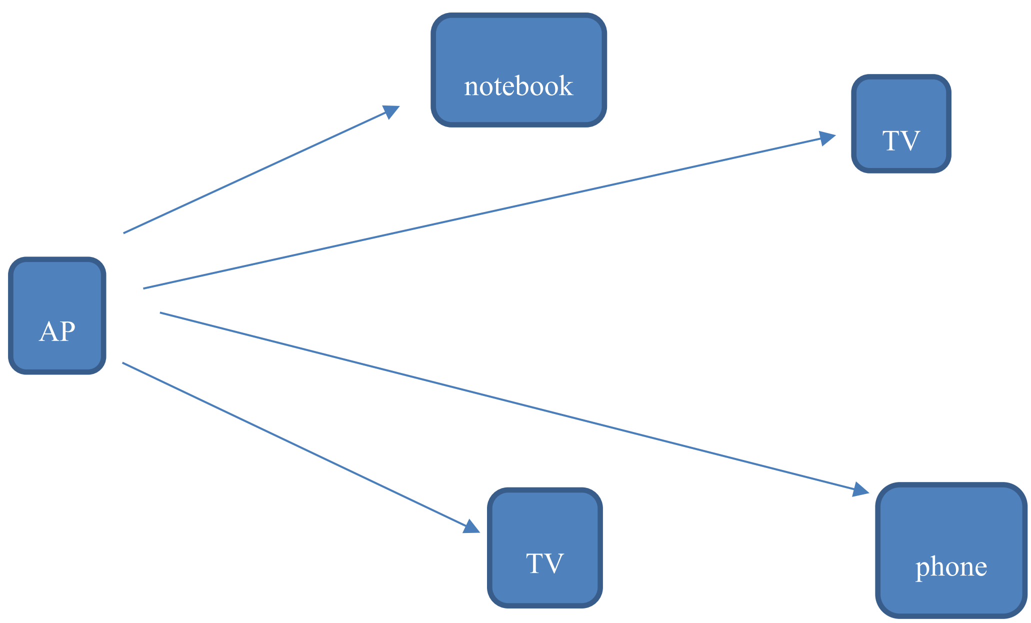

Figure 6 - Traffic mix

The measurement procedure begins with verifying broadband service from each of the devices used for the test. The cable modem wireless router used has four Ethernet LAN ports, three 1 Gbps speed and one 2.5 Gbps speed. A computer with a 2.5 Gbps USB-C network adapter is connected to the 2.5 Gbps Ethernet LAN port of the router. A speed test taken on the computer connected to the 2.5 Gbps Ethernet LAN port of the router measured 1.4 Gbps download. This verifies that this computer has a broadband connection at the full speed of the service.

Next, a computer with a 6 GHz band, 2x2 MIMO, 160 MHz channel width, 2400 Mbps PHY rate is connected to the 6 GHz band radio of the cable modem wireless gateway and a speed test is run at close range. The locations necessary for the highest PHY rate of 2400 Mbps are in the same room, and adjacent rooms on the same floor, or directly upstairs or downstairs of the AP. The speed test, although not as consistent as the DOCSIS to Ethernet speed, measured 1.3 Gbps download speed. This verifies the full broadband speed from DOCSIS WAN to 6 GHz radio.

While it is convenient and sometimes useful for testing purposes to measure from Ethernet LAN to Wi-Fi, it is imperative to include DOCSIS to Wi-Fi testing and verification since this accounts for almost all customer traffic. The phone and computer used in the mixed traffic MU testing measured download speed tests between 800 and 900 Mbps. The phone and computer wireless adapter were 2x2 MIMO, 80 MHz channel width, 1200 Mbps PHY. The set up shown in Figure 7.

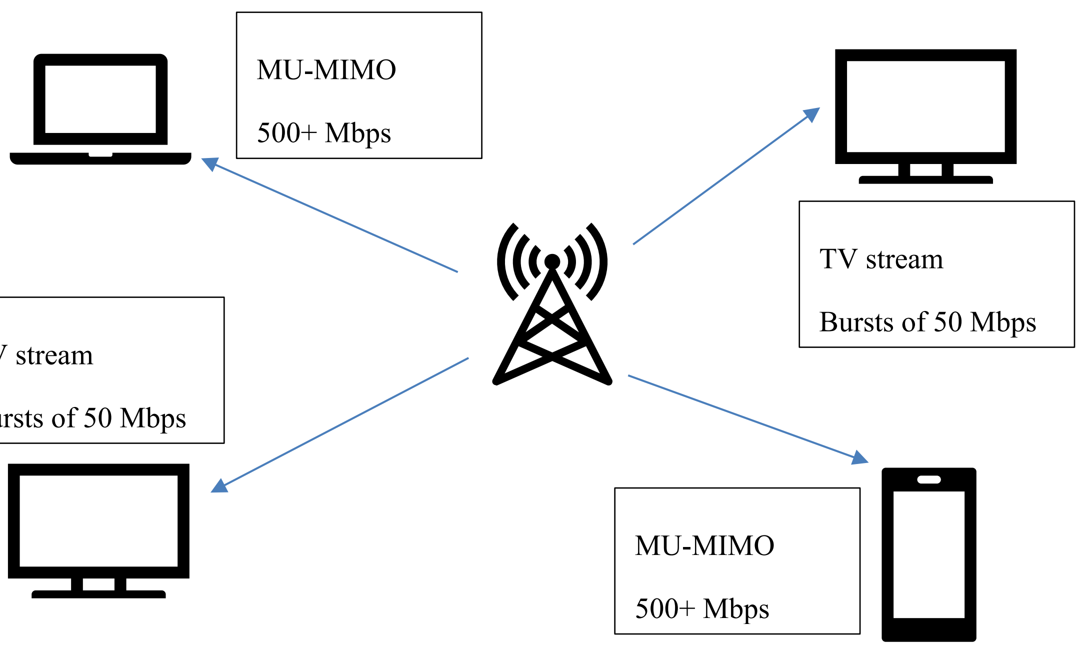

Figure 7 - DL MU-MIMO and UL OFDMA traffic mix

Generating traffic demand to form DL MU-MIMO required using iperf3 on the client phone and notebook computer with a server connected to the 2.5 Gbps Ethernet port of the cable modem wireless router. Traffic exceeding 1 Gbps was measured even though no individual station was capable on its own to download at 1 Gbps. Thus, DL MU-MIMO allowed the total of multiple devices working together to exceed that of any one device.

In addition to the download of large files to the computer and phone, two television sets with the same wireless adapters were used for streaming video. The statistics of the measured throughput listed in Table 12 and the graph of throughput for each device over time is shown in Figure 8. The television sets had bursty traffic with peaks of about 50 Mbps and average of 10 Mbps. The computer and phone had aggregate download speed that exceeded 1 Gbps employing DL MU-MIMO and UL OFDMA at the same time as the two video streams operating without impairment.

Table 12 - Statistics of Throughput with Four MU devices

Stat	phone	computer	TV1	TV2	Sum
average	455.9132	407.8673981	15.32821	8.530408	887.6392
std	126.2928	208.0782331	9.354155	14.13454	152.5777
max	917.4	785.2	49.7	64.5	1212

While these measurements focused on DL MU-MIMO, UL OFDMA was used for the lower bandwidth upload response. This is a good example of the various multiple user techniques working together for a better overall user experience.

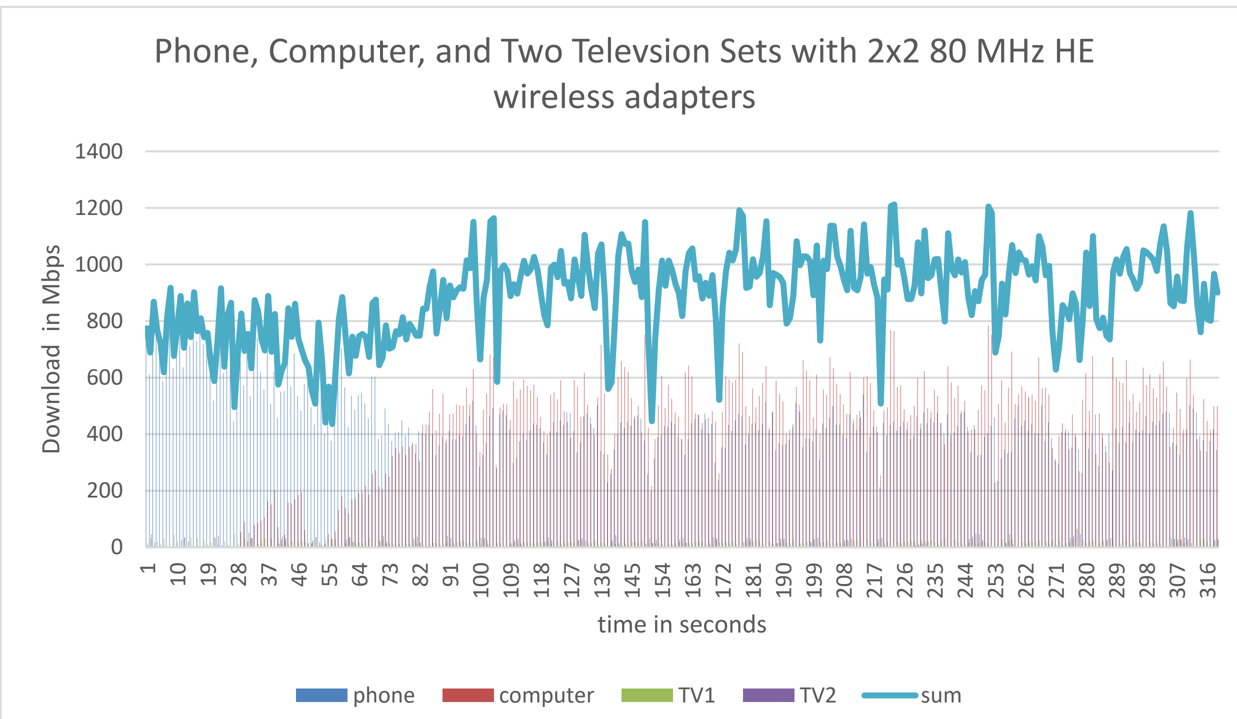

Figure 8 - DL MU-MIMO and UL OFDMA Measured traffic mix

As seen in Figure 8 the sum of traffic often exceeds 1 Gbps and even peaks at 1.2 Gbps. This is a good example of MU techniques helping to deliver Gbps broadband service when devices work together. Alone, none of these devices can use the full broadband service. Yet working together, the customer receives the benefit of the full speed of the broadband service.

10. Conclusion

UL MU-MIMO and spatial reuse are promising technologies customers can look forward to with newer devices and upgraded drivers with Wi-Fi 6e/7 wireless adapters. Common Wi-Fi 6 wireless adapters in notebooks, phones, and tablets have 2x2 MIMO with 80 MHz channel width and a maximum PHY rate of 1200 Mbps with drivers that have enabled DL MU-MIMO and both UL and DL OFDMA. When more than one of these devices uses the wireless network at the same time these multiple user technologies kick in. At close range with high traffic demand from more than one such device downlink frames are MU-MIMO while uplink frames are OFDMA. Further away, under low signal to noise ratio conditions, the downlink and uplink frames are OFDMA. The beamforming feedback in these devices provides the ten angles every fourth subcarrier over the full 80 MHz channel width. DL MU-MIMO provides aggregate throughput that is not possible with SU operation. OFDMA improves the uplink link budget, not at the very channel edge where connectivity is soon lost, but increased PHY rates and aggregate throughput in the upload for signals as low as -86 dBm in an 80 MHz OFDMA channel.

Wireless adapters are readily available for notebook computers and some phones and tablets with a maximum PHY rate of 2400 Mbps. These devices have 160 MHz channel width in the 5 and 6 GHz band with 2x2 MIMO. Getting the full broadband service of 1.2 Gbps or higher is readily delivered in SU mode. With a maximum PHY rate of 2400 Mbps, there is a healthy margin of error to deliver 1.2 Gbps service, the MCS rate can drop to 6 when the channel is unused by neighbors or the PHY rate can be close to the maximum and still deliver 1.2 Gbps while sharing the spectrum with neighbors. These devices take full advantage of DL and UL OFDMA when several devices are active at the same time. These devices also can improve download aggregate throughput with DL MU-MIMO. Download speed from two 2400 Mbps PHY devices with DL MU-MIMO exceeded a throughput of 2.1 Gbps. This is not possible with SU operation. Still, this only worked with both computers in the same room and even then, only occasionally. The beamforming feedback from the 160 MHz channel width devices was not sufficient for robust DL MU-MIMO. Still, with the SU mode able to deliver 1.2 Gbps speeds with plenty of margin and both DL and UL OFDMA working well, this does not seem to be much of a concern for overall user experience. Certainly, customers will always benefit from 160 MHz channel width devices.

Finally, the benefits of DL MU-MIMO and UL OFDMA were illustrated with two television sets streaming video while a phone and a tablet downloaded TCP at maximum throughput. The video streaming works flawlessly with periodic bursts of throughput of about 50 Mbps averaging out at about 10 Mbps. Neither the phone nor the computer is capable of downloading over 1 Gbps since their maximum PHY rate is 1200 Mbps. Yet, the sum of the throughput of all four devices quite often exceeded 1 Gbps thanks to DL MU-MIMO working in tandem with UL OFDMA.

Abbreviations

AP	access point
bps	bits per second
DFT	discrete Fourier transform
DL	downlink
DOCSIS	Data over cable service interface specification
EIRP	Effective isotopic radiated power
FDM	Frequency division multiplex

FFT	Fast Fourier transform
HD	high definition
he	High efficiency
Hz	hertz
K	kelvin
Mbps	Mega (million) bits per second
MIMO	multiple input multiple output antennas
MU	multiple user
OFDM	Orthogonal frequency division multiplex
OFDMA	orthogonal frequency division multiple access
PD	Power detect
PHY	Physical the bit rate of a single OFDM symbol
RSSI	Received signal strength indicator
SNR	Signal to noise ratio
STA	Station client Wi-Fi network adapter
SCTE	Society of Cable Telecommunications Engineers
SRP	Spatial reuse parameter
SU	Single user
TDM	Time division multiplex
TDMA	Time division multiple access
UL	uplink

Bibliography & References

[1] The Importance of Wi-Fi 6 Technology for Delivery of Gbps Internet Service, David John Urban, Comcast, Cable-Tec Expo 2019 SCTE ISBE 2019 Fall Technical Forum