Wi-Fi 7 Meets World

Utilizing 802.11be Features to Increase Customer Application Reliability

A technical paper prepared for presentation at SCTE TechExpo24

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1. Introduction

There are many features of Wi-Fi 7, the new version of Wi-Fi based upon the IEEE 802.11be standard. Broadband service providers are rolling out next generation gateways with Wi-Fi 7 and customers are beginning to see Wi-Fi 7 phones, tablets, and computers for sale. This paper explores the features of Wi-Fi 7 that improve reliability of the connection to customer devices running the applications that customers use. The simplest and most effective method to reduce lag, measured in milliseconds (ms) as latency and jitter is to ensure that the capacity of the communications channel far exceeds the traffic demand. The first step is a traffic demand model. This paper measures the traffic demand for common customer applications with common devices. The following step is to provide capacity exceeding demand with a margin of safety. The extremely high throughput of Wi-Fi 7, typically 5.8 Gbps, makes ensuring capacity exceeds demand quite easy. But this only applies to a single high-end device at close range with traffic that can take advantage of the high throughput without being overwhelmed by overhead. The tricky part is delivering the capacity that exceeds demand for customer applications for many devices of widely varying capability, from old to new, fast to slow, near and far. This paper reveals the tools of Wi-Fi 7 that can be utilized to meet customer reliability requirements.

2. The Beat Goes On: Here Comes the Next Generation of Wi-Fi

Broadband service providers in recent public investor conferences have observed that this is one of the most competitive broadband environments. Higher speeds on the wide area network (WAN) and fast and reliable Wi-Fi that covers both inside and outside the home are critical factors in maintaining competitiveness. A broadband service provider reported in a public earnings call that 70% of their customers subscribe to speeds of over 500 Mbps and that 30% of their customers subscribe to speeds of over 1 Gbps. Wi-Fi 7 technology provides critical tools in delivering the speeds that broadband residential customers are paying for to the devices that they are using.

A broadband HFC service provider reported in public investor conferences that 40% of their footprint is mid-split, double from a year ago. By the end of the year, 50% of the footprint will be upgraded to mid-split. Mid-split phase prepares the plant for DOCSIS® 4.0 multiple Gbps symmetrical service at scale. The only way to download and upload to phones, notebooks, and computers at speeds of 2 Gbps is with Wi-Fi 7, 320 MHz channel width network adapters.

Many broadband service providers have virtualized their networks by moving much of the functionality of the CMTS and video QAM distribution to the cloud, including both public and private clouds as well as hybrid public/private cloud architecture. This allows service providers to introduce changes to the distribution network much faster than in the past when physical hardware changes were required to upgrade service levels and features. In the past, the home WLAN network may have been a generation or two ahead of the distribution WAN network. Wi-Fi architects may no longer be able to count on a slow-moving WAN architecture in order to stay ahead of the game. The introduction of Wi-Fi 7 is a critical factor in ensuring the WLAN keeps up with the WAN. And it should be noted that the introduction of Wi-Fi 7 access points (AP) and extenders will also help increase the overall WLAN capacity even when the customer has only older Wi-Fi devices. This will be shown later in the paper.

Broadband service providers have announced that they are expanding the coverage of their networks for multiple Gbps symmetrical service. Network extensions will allow even more homes to enjoy the benefits of WLAN architecture based upon Wi-Fi 7.

More residential homes are moving from broadcast and linear video offerings to streaming services. A growing customer segment is attracted to lower cost bundles of broadband and streaming applications based upon innovative video operating systems in both television sets and streaming set top boxes, delivered over a cloud architecture without traditional linear video. The consumption of data from video streams averages between 5 Mbps to 40 Mbps. Since this demand for data is more consistent than other forms of data demand such as web browsing or file downloads, video streaming increases monthly overall data consumption. However, the average throughput of video streaming is much lower than the peek speed capabilities of Wi-Fi 7 devices. Still, it will be shown in this paper that Wi-Fi 7 is critical for a mix of heavy video streaming and other high speed broadband applications such as large file downloads for updates, offline video viewing, and even web browsing.

Two mechanisms allow many devices to stream and still serve the needs of many other connected devices. Greater speed for Wi-Fi 7 devices and Wi-Fi 7 mesh node serving older non-Wi-Fi 7 devices. Multiple link operation (MLO), 320 MHz channel width, and 4K-QAM provides Wi-Fi 7 stations with faster speed to enable higher peaks of throughput in keeping video buffers full with lower duty cycles. Wi-Fi 7 AP and mesh combinations keeps older devices working at the highest possible physical layer interface (PHY) rates on older devices while backhauling on different band and channels using Wi-Fi 7 technology.

Residential broadband service providers have reported in public investor calls consumption of over 700 gigabytes (GB) per month per home and increasing at a double-digit year over year rate. That level of consumption corresponds to a long-term average consumption of 2.16 Mbps. If the consumption is largely contained within a 6-hour period during the day, then the average consumption during active usage would be 8.6 Mbps. At a peak to average data consumption ratio of 100 to 1 then peaks of 860 Mbps would be needed. Wi-Fi 7 devices are able to download and upload at 2 Gbps real world throughput providing a good margin of safety for reliable service delivery. Things get more complicated as the distance gets farther, obstacles scatter the radio wave signals, and older devices are added to the mix. These complications are explored in the following sections.

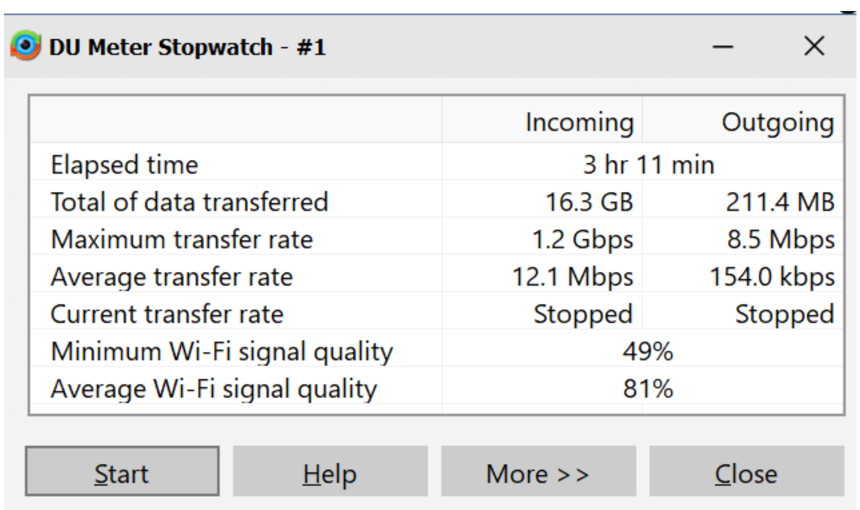

Figure 1- Peak and Average Data Consumption for mix of applications.

Figure 1 shows an example of a measurement of data consumption matching a 100 to 1 peak to average data consumption ratio. The measurement was taken over a three-hour period on a single device, a Windows 11 notebook computer with a Wi-Fi 7 320 MHz channel width network adapter. The measurement began with the download of a 6 GB file from a website capable of downloading at 1.2 Gbps peak. The large file download at the beginning of the measurement made the peak to average ratio quite low. Following the large file download, the traffic was generated with web browsing, email, and video streaming which, over time, lowered the average data consumption, eventually verifying that a 100 to 1 peak to average data consumption ratio is reasonable.

3. The Demand for Packet Transport

When architecting a bridge, the first thing to consider is the span. What does the bridge need to cross? How long does the bridge need to be? The next consideration is determining what will cross the bridge. How many cars and trucks or pedestrians will cross at the same time? How fast will they travel and how much do they weigh? Finally, the architect designing the bridge must determine what may go wrong in the environment. What force of wind may the bridge need to withstand? What will happen if a ship loses power and crashes into the bridge?

The architect of a wireless LAN network for a residential broadband service faces analogous questions. Packets need to be transported between the WAN gateway to customer devices such as phones, tablets, computers, television sets, and IoT devices. How large are these packets? How many packets? How fast do they need to be delivered? What will go wrong in the environment that may prevent or delay the delivery of these packets? The packet transport demand of each household is unique and always changing. New devices and applications increase traffic demand incessantly.

Web browsing and email involves a process of downloading the web page or email contents and then spending time reading the downloaded information before requesting more content to be downloaded. The result is a high peak to average data consumption ratio since large amounts of data are downloaded quickly followed by long delays before the next download request to consume the data by the user. This pattern of data consumption can be exploited in shared broadband channels with high peak single user capacity relative to the overall average consumption.

Consider a 1.2 Gbps shared data channel with twenty users having an average data consumption of 10 Mbps each. The total average data consumption is 200 Mbps, leaving peak excess capacity of 1 Gbps. For high peak to average data consumption for applications such as web browsing and email, the users will not be able to distinguish between a shared data channel of 1.2 Gbps and dedicated point to point links of 1 Gbps. The latter requires network capacity of 20 Gbps.

Video streaming is a prime driver of data consumption. Video streaming can have more consistent demand than the download and read pattern of web browsing and reading and writing email. However, video devices use buffer memory to exploit the high peak speed of many wired and wireless networks and mask some of the packet loss and intermittent speeds of some of these networks. Video could be delivered with a constant bit rate of 3 Mbps, but any disruption in the ability of the network to constantly provide the demand for 3 Mbps will result in loss of video. Streaming video typically peaks the traffic to fill buffers with a variable bit rate. At the beginning of a video stream, lots of data may be downloaded as fast as the network allows in order to fill the video buffer. Once the buffer is full, data consumption may periodically peak at much lower data rates in an effort to keep the buffer full. This provides more flexibility to adjust to changes in the network. A slower network will download more often at a lower rate, while a faster network will download less often at higher rates.

Another driver of data consumption, both peak and average, is large file downloads for such things as operating system upgrades. An upgrade can easily download many GB of data. Some streaming video and music services allow for downloading for offline viewing. A movie or TV show can easily download several GB of data. And again, the less wait the better. For portable devices such as phones or tablets, a customer may want to download the video content as fast as possible in order to head out the door. Downloading a large file from the Internet can create a peak data consumption demand of as much a 1 Gbps for several minutes.

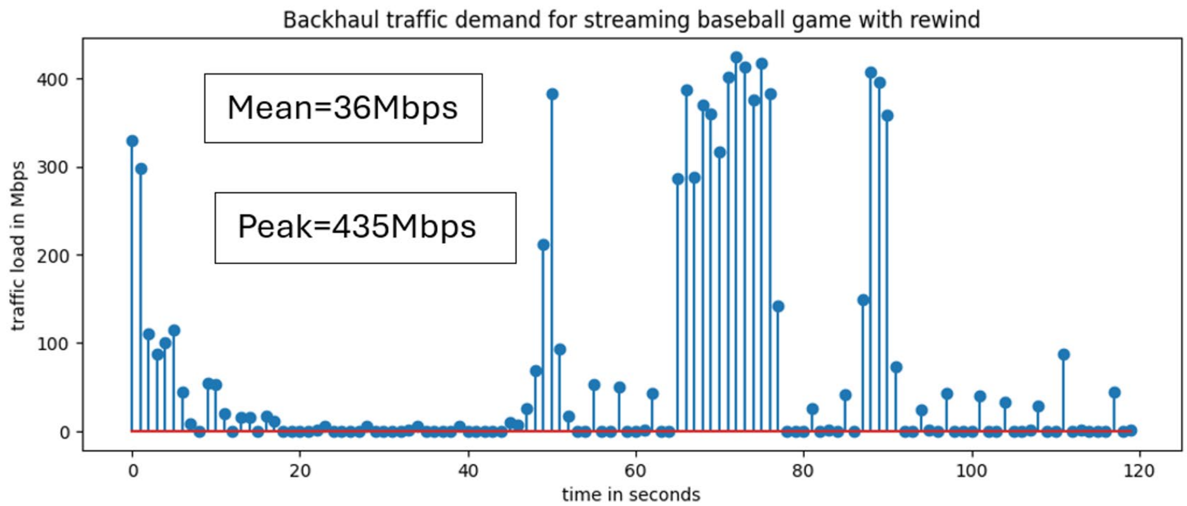

Figure 2 - Backhaul traffic demand streaming baseball game.

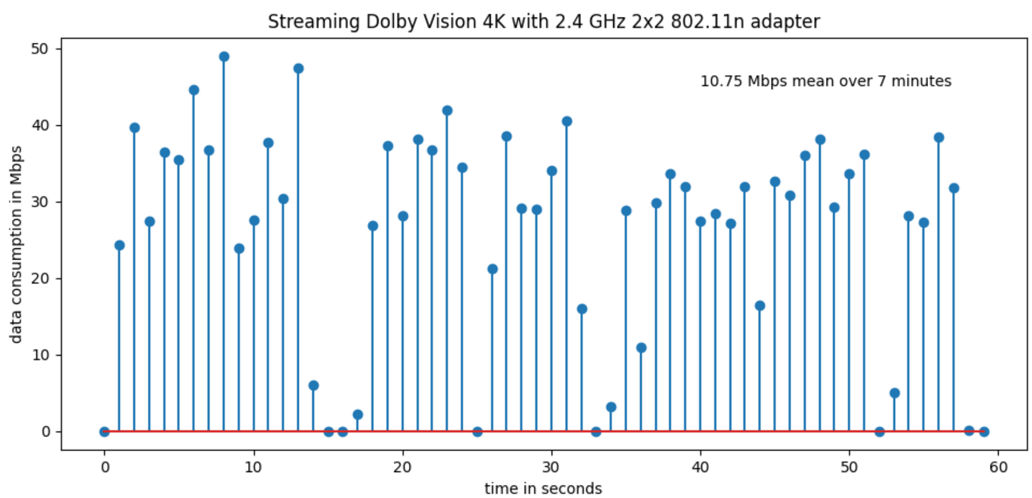

Figure 3 - Streaming Video with 802.11n network adapter transmits greater than 54% of the time greater than 1 Mbps.

Many wireless network adapters with different capabilities must be served in a broadband residential service home. Some devices with lower PHY rates require lots of airtime. Figure 2 shows the data consumption streaming Dolby Vision 4K video overtime for one minute.

The plot zooms in on a time period of one minute. The bursty nature of the signal can be observed. Statistics such as PHY rate, data consumption, air use, data use, retries, channel width, MCS, number of spatial streams, OFDMA, MU-MIMO were collected over a 7-minute period. The measurements are averaged over a one second interval.

The average PHY rate during bursts of transmission measured 130 Mbps. The maximum PHY rate of the network adapter in the 2.4 GHz band was 144 Mbps with 20 MHz channel width using IEEE 802.11n technology. 21% of the measured seconds reported the maximum PHY rate of 144.4 Mbps.

The data consumption measured over a one second interval measured 0.0 Mbps 49% of the time. The duty cycle of the signal was thus, 51%. A single 802.11n device streaming video in the 2.4 GHz band consumes more than half of the capacity in the band. Wi-Fi 7 devices can help by using the 2.4 GHz band more efficiently and thus, freeing up airtime for older less efficient devices. Better yet, Wi-Fi 7 devices can use the 6 GHz band that older devices cannot use and thereby not impact the older devices access to bandwidth at all.

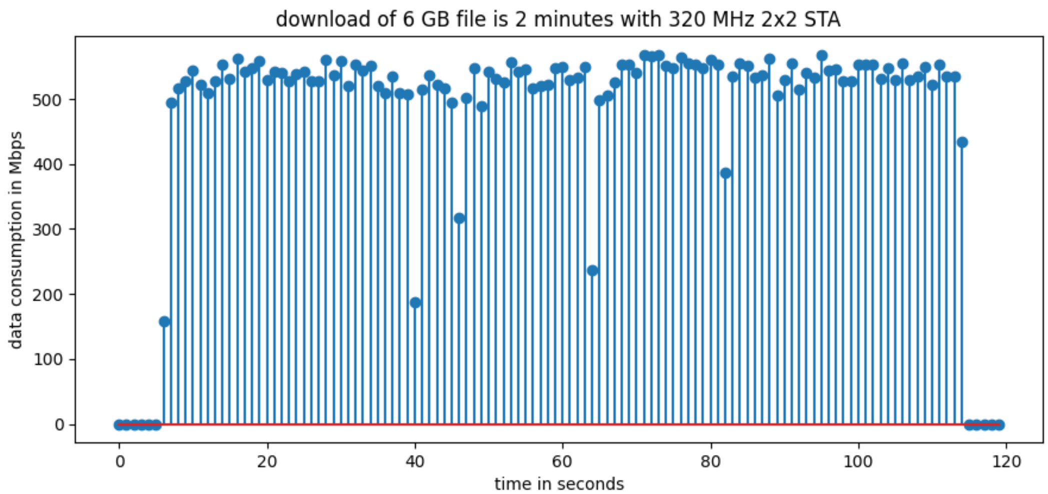

Figure 4 - Download of 6GB file in two minutes with 320 MHz 2x2 STA

The mean PHY rate when download exceeded 100 Mbps was 2379 Mbps with an average MCS of 5.7, having a maximum MCS of 9 and minimum of 4. The channel width was always 320 MHz and the number of spatial streams was always 2.

The approach to deriving a traffic model employed in this study consists of measuring packet transfer of devices during applications. The applications include downloading large files for system updates and program installation, video streaming and video meetings, web surfing. Devices include phone, notebook and desktop computer and TV.

4. Wi-Fi 7 Computers and Phones Come to the Market

The WAN measurements in this paper used a DOCSIS 4.0 full-duplex (FDX) cable modem Wi-Fi 7 wireless router in a laboratory setting connected to a vCMTS RPHY node. Some measurements were made in a residential home using an Ethernet wireless router with Wi-Fi 7 AP using a DOCSIS 3.1 cable modem for WAN.

4.1. Windows 11 Notebook Computer with Wi-Fi 7 Network Adapter

The preferred band can be set to 6 GHz in the Windows 11 network adapter driver. The Wi-Fi 7 network adapter can be found using the program Device Manager. The notebook computer used for some of the measurements was one of the first computers on the market with a Wi-Fi 7 320 MHz network adapter off the shelf. The driver used in these measurements employed PCIe generation 2 single lane, which limits peak throughput to around 2.5 Gbps and makes rate adaptation more difficult.

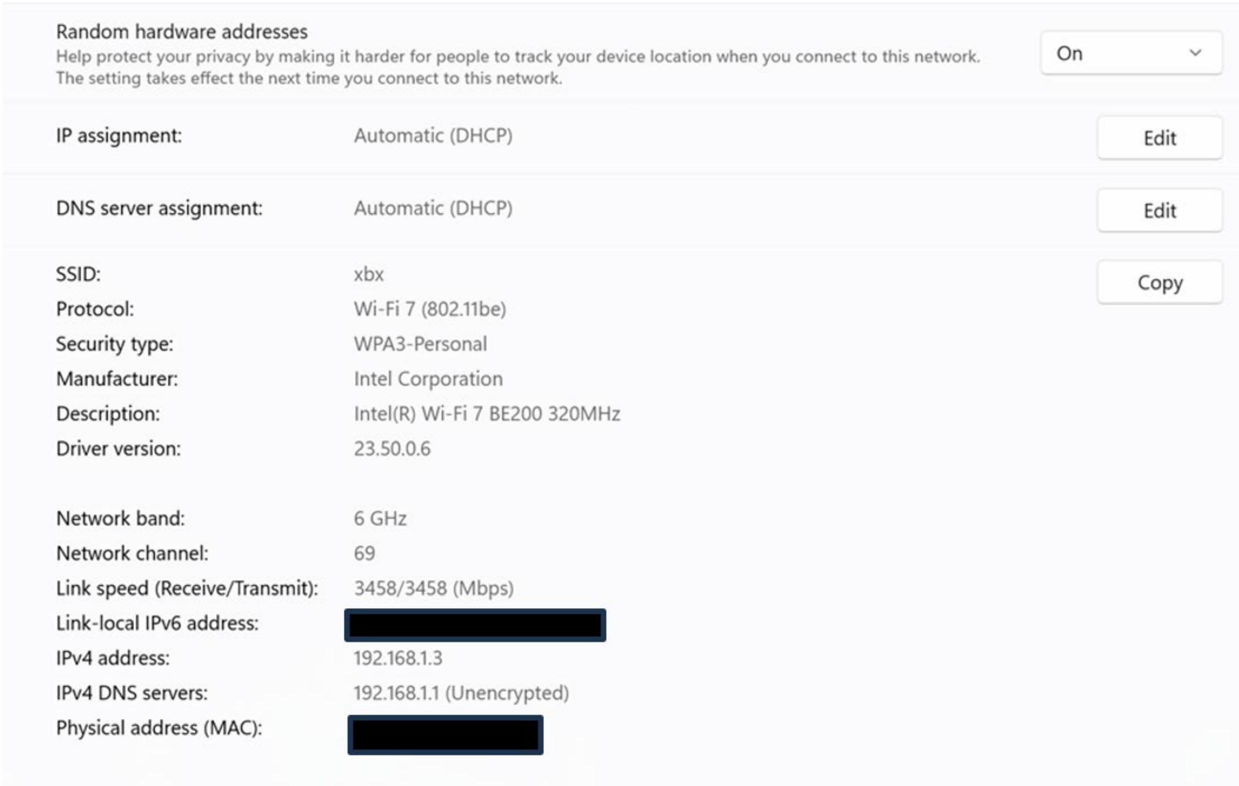

Figure 5 - Screenshot of Wi-Fi network adapter settings connected to Wi-Fi 7 AP.

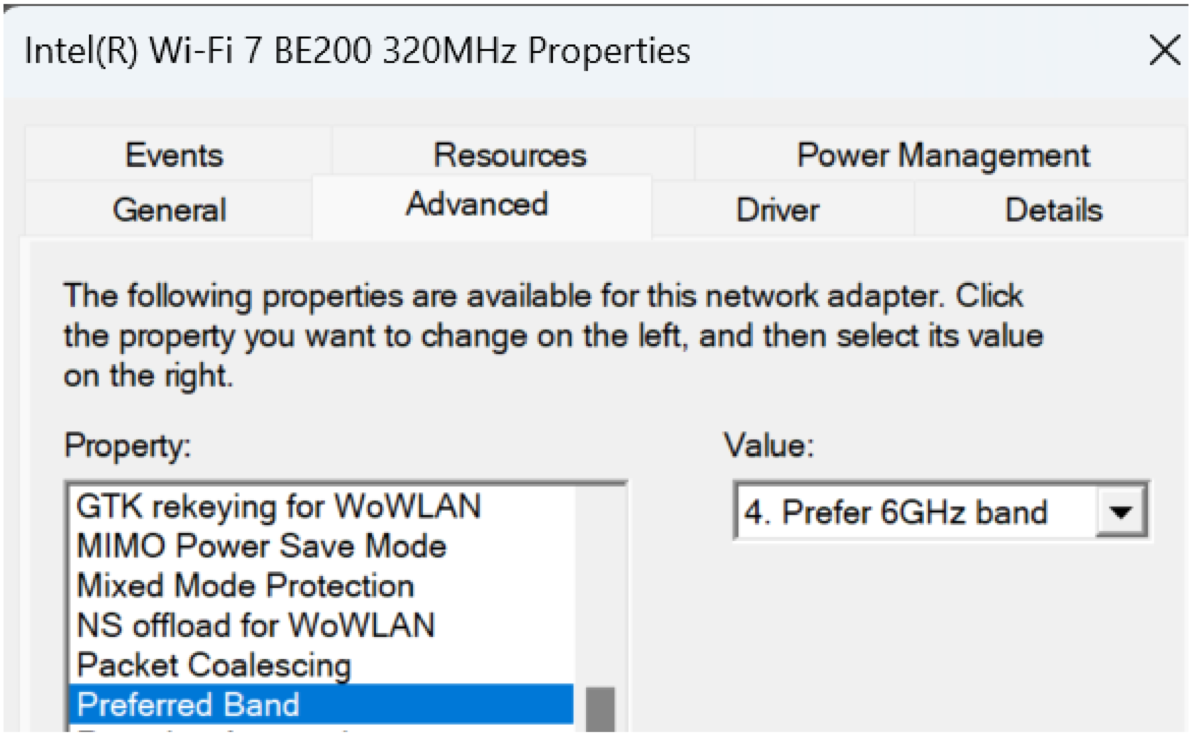

Figure 6 - Remember to set driver setting to prefer 6 GHz band.

LAN speed tests from the 10 Gbps Ethernet port of the wireless router to the Windows 11 PC with Wi-Fi 7 network adapter were limited to about 3 Gbps due to the use of single lane PCIe gen 3 interface to the radio. Unsigned drivers with Windows 11 test mode were also tested, wherein the single lane PCIe interface to the M.2 wireless adapter card was set to PCIe gen3. Linux versions were tested with the same M.2 card with PCIe gen3. In our testing, the throughput was not different than measured in this paper with a production PC and production driver.

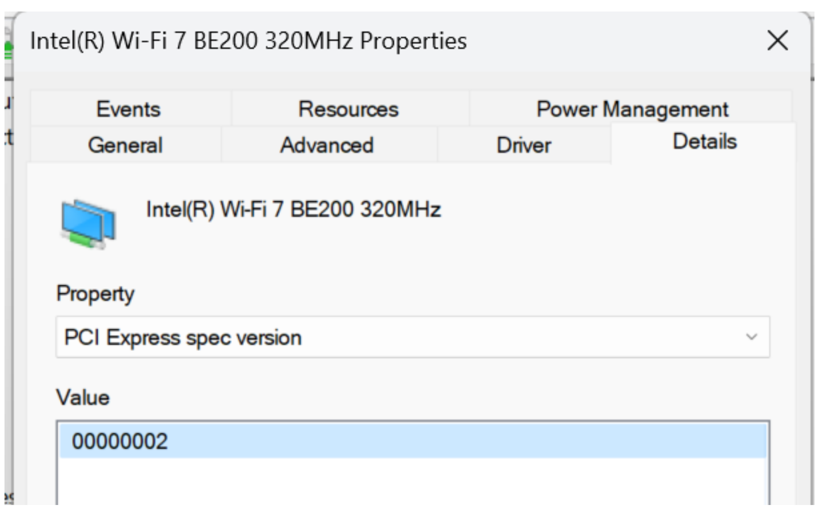

Figure 7 - PCIe setting of the Windows 11 PC Wi-Fi 7 network adapter driver.

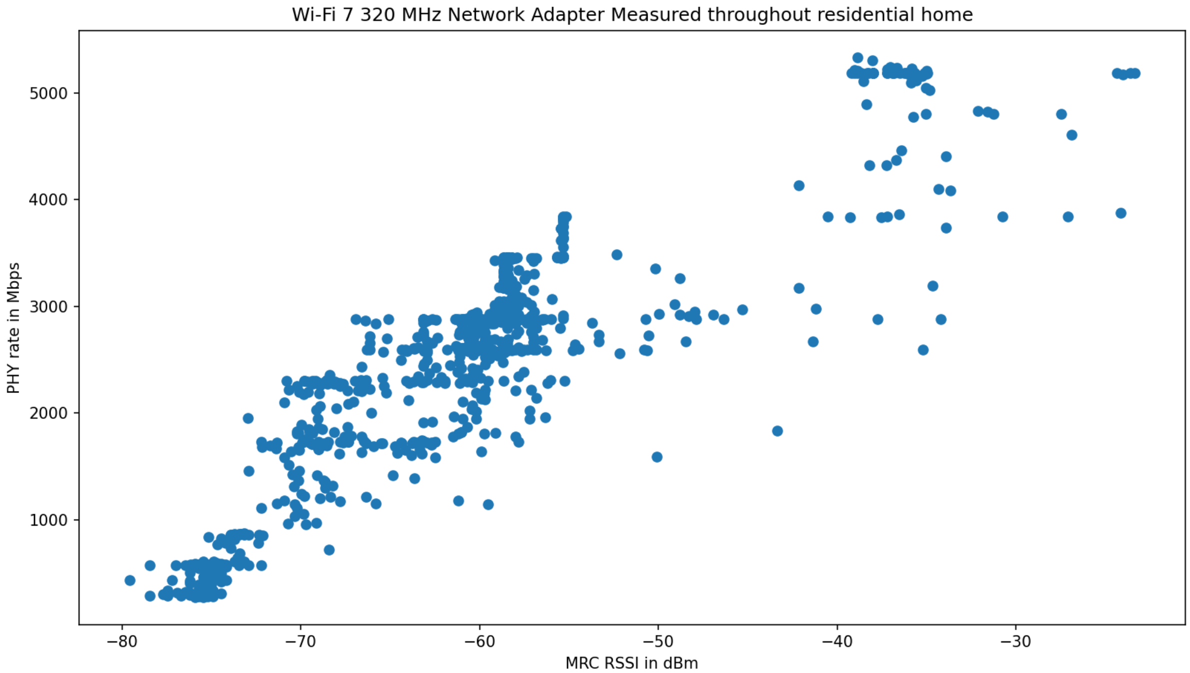

Figure 8 - Scatter plot of Wi-Fi 7 320 MHz Network Adapter PHY Mbps versus MRC RSSI

Figure 2 shows the scatter plot of PHY rate in Mbps versus the maximum ratio combining (MRC) received signal strength indicator (RSSI) of a Wi-Fi 7 320 MHz network adapter in the Windows 11 notebook computer while walking throughout a residential home. The data is taken from the AP.

4.2. Flagship 2024 Smart Phone with 320 MHz Channel Width Wi-Fi 7

At a line-of-sight distance of 21 inches between four half-wave dipole vertically polarized antennas at the AP and the Wi-Fi 7 phone, the MCS varied between 11 and 12 while downloading TCP traffic with a 6 MB window and 8 TCP streams. The server was connected to a 10 Gbps Ethernet port of the AP router. The maximum TCP throughput measured 3.54 Gbps and the average over one minute download measured 3.19 Gbps. The PHY rate on the phone downlink varied between 4.8 Gbps and 5.1 Gbps.

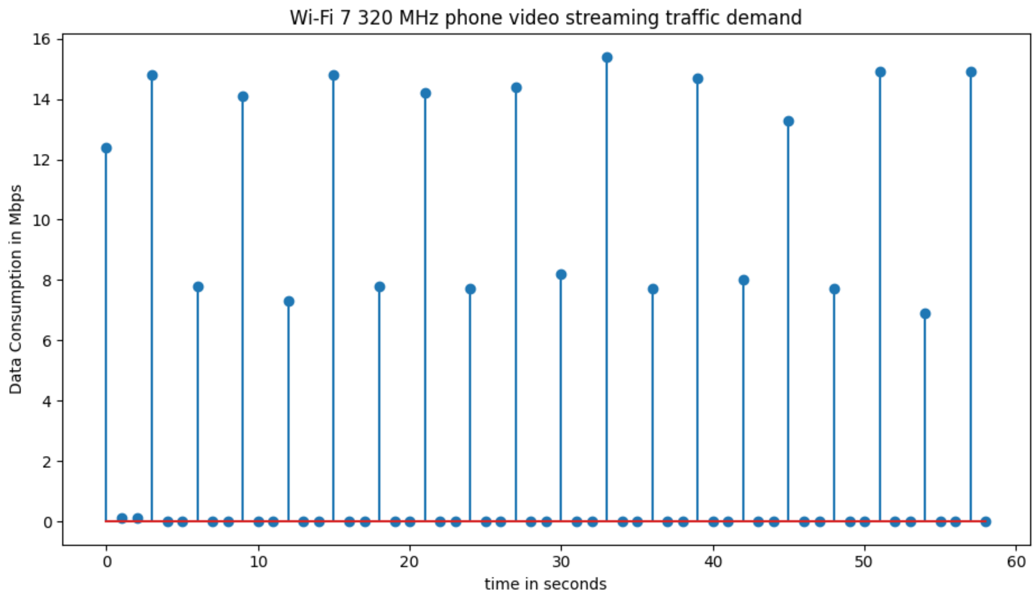

Figure 9 - Wi-Fi 7 320 MHz Phone Video Streaming Traffic Demand

The average throughput of the video stream measured 3.7 Mbps with peak demand of 16.7 Mbps over a measurement interval of 422 seconds. As can be seen in the plot, two seconds without any traffic demand is followed by a peak download of either around 15 Mbps or 8 Mbps.

Using an Android speed test application with the phone connected to the 6 GHz band using a 320 MHz channel width the measured download and upload speed is consistently above 2 Gbps.

5. Multiple Link Operation

A new feature of Wi-Fi 7 is multiple link operation that allows more than one radio band to be used at the same time. Traffic can be sent over both the 5 and 2.4 GHz bands at the same time or 6 and 2.4 GHz at the same time as well as other band combinations dependent upon device network adapter implementation. The characteristics of the three Wi-Fi bands are different which may make it sometimes desirable to run traffic over different bands under different conditions or even traffic over two bands at once.

The 2.4 GHz band tends to have better propagation characteristics, particularly when it comes to wiggling around doors and windows when wall and floor attenuation is high. However, 2.4 GHz suffers from the presence of 802.11b signals, Bluetooth, and 802.15 based signals such as Zigbee and RF4C. The channel width in the 2.4 GHz band is limited to 20 MHz. While 40 MHz channel width is an option for IEEE 802.11n and newer 802.11 standard based protocols in the 2.4 GHz band, the benefit of 40 MHz channel width is not worth the cost in terms of wider equivalent noise bandwidth. This is due to the fact that many popular client network adapters working in the 2.4 GHz band limit themselves to 20 MHz in an effort to co-exist better with Bluetooth. Bluetooth is often used on phones, tablets and computers for audio resulting in Wi-Fi network connectivity and Bluetooth audio needing to work at the same time. Time division multiplexing whereby the Wi-Fi signal and the Bluetooth signal do not need to work at the same time is the most effective method of co-existence. Still, if Bluetooth and Wi-Fi do need to work at the same time, then interference can be minimized with a narrow channel width of 20 MHz and as much frequency separation as possible.

The 5 GHz band allows for channel width of 160 MHz and is thus much faster than the 2.4 GHz band. While propagation in the 5 GHz band in non line-of-sight conditions is sometimes worse than 2.4 GHz, in many cases the noise floor elevation in the 2.4 GHz band results in the 5 GHz band having better range than the 2.4 GHz band. Whenever coverage in the 5 GHz band allows for solid connectivity then the 5 GHz band is preferable over the 2.4 GHz band.

The 6 GHz band allows for channel width of 320 MHz and for devices that support 320 MHz channel width, nothing can beat the 6 GHz band. The coverage area of the 6 GHz band with 320 MHz channel width is quite good. So, in almost all cases 320 MHz channel width capable devices will work best in the 6 GHz band. The 320 MHz channel width helps with the range of the 6 GHz band at a given amount of minimum throughput.

There are several modes of MLO. One mode is simultaneous transmit receive (STR), in which one band can transmit while at the same time another band can receive. STR MLO requires at least two radios. Most network adapters since the introduction of the IEEE 802.11ac standard in 2013 have a separate 2.4 GHz band and 5 GHz band radio. The frequency separation between the 2.4 and 5 GHz bands is wide enough that making two radios is more sensible than making a single radio capable of tuning over both bands. The 5 and 6 GHz bands occupy a contiguous band of spectrum beginning at 5150 MHz and ending at 7125 MHz in the US albeit with several portions of the spectrum forbidden. (Urban, 2023). Thus, it makes sense to have a single radio that covers both 5 and 6 GHz bands in client devices. APs have separate 5 and 6 GHz band radios with filters that allow reception of one band and transmission in another band at the same time since APs serve many devices in both bands at the same time.

One intriguing use of MLO technology applies to the case of Wi-Fi 7 phones limited to 160 MHz channel width. With only 160 MHz channel width, these phones will not be able to download and upload 2 Gbps the way 320 MHz channel width devices can. With MCS=13 and Nss=2 with 160 MHz channel width, the PHY rate is 2.8 Gbps, enough for 2.2 Gbps throughput. However, measurements observed less that 2 Gbps throughput even at close range with 160 MHz channel width devices having 2x2 Wi-Fi 7. Additional throughput of the 2.4 GHz band radio could potentially get us over the hump in exceeding 2 Gbps speed tests. Measurements, however, did not confirm this. As shown in Figure 10, even at close range MLO of a Wi-Fi 7 2x2 station (STA) working in both, the 2 and 5 GHz bands never reached 2 Gbps.

However, despite failing to reach the magic 2 Gbps mark, connecting a 160 MHz Wi-Fi 7 STA to the fronthaul 2 and 5 GHz band radios while using the 6 GHz band of the Wi-Fi 7 extender connected to the main AP and the router is a very efficient use of the available capacity of a Wi-Fi 7 WLAN home network architecture. The STA cannot take advantage of the 320 MHz channel width available with Wi-Fi 7 technology and the spectrum available in the 6 GHz band. But the backhaul of a Wi-Fi 7 AP and extender can. This allows the phone to work at very close range to the extender using the full capability of the phone while only using a portion of the 6 GHz band AP radio for backhaul. The measurements shown in Figure 10 allowed the phone to work very close the then 2 and 5 GHz band radios of the extender while being far away in the house from the main AP.

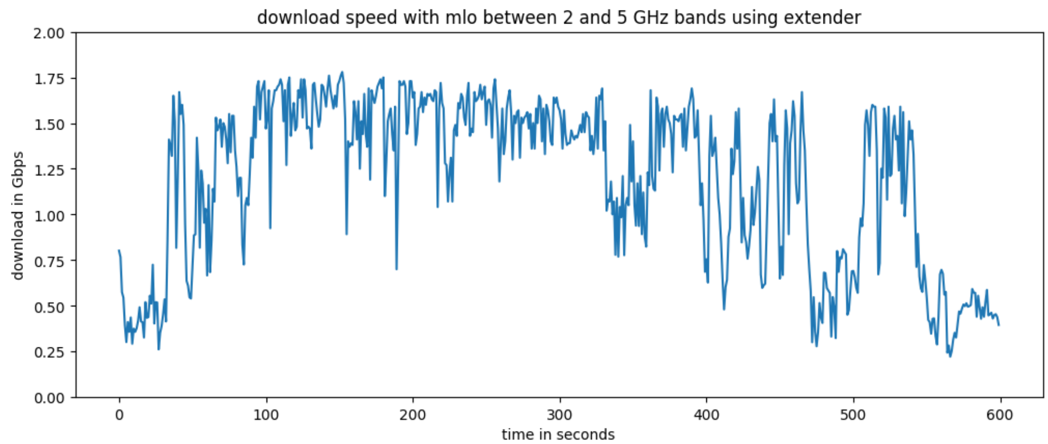

Figure 10 - Measured download speed of Wi-Fi 7 phone at close range MLO 2 and 5 GHz band

There are several types of early Wi-Fi 7 devices that have hit the market. Some computers have a Wi-Fi 7 network adapter that initially does not support MLO but does support 320 MHz channel width and 4K-QAM. In test mode with unsigned drivers these computers have been observed to support enhanced single link multiple radio (eMLSR) operation. Some phones with Wi-Fi 7 network adapters support both 320 MHz channel width operation and STR mode MLO. These phones have been observed to associate in either 2/5 bands or 2/6 bands and run traffic at times through two bands simultaneously. Other Wi-Fi 7 phones do not support 320 MHz channel operation and are limited to 160 MHz channel width operation in both the 5 and 6 GHz bands. The 160 MHz channel width Wi-Fi 7 phones have been observed to support both eMLSR and STR MLO operation. These phones are good candidates to run traffic in both the 2 and 5 GHz bands since they are limited to 160 MHz channel width operation.

For the AP the multilink operation active is set to true. The number of links is set to three. MLO is enabled. The multiple link device (MLD) medium access control (MAC) is set to the hardware address of the radio with the fastest PCIe connection, in this case the dual lane of PCIe gen 3 to the 6 GHz radio. The 6 GHz band radio is designated as link0. The 5 GHz band radio is designated as link1. The 2.4 GHz radio is designated as link2.

Android adds a new data structure class representing Wi-Fi Multi-Link Operation (MLO) that can be used only by Wi-Fi 7 capable devices.

An Android phone set to developer mode with verbose WLAN will indicate link0, link1, and link2. The client mode of the Android Wi-Fi 7 phone was STR, simultaneous transmit and receive. The associated link and the active link map will vary.

The best performance in terms of highest speed, lowest latency and jitter, and least impact on older devices results when the associated link is link0 the 6 GHz radio band with 320 MHz channel width and active link map of 1, indicating traffic will only flow over the 6 GHz band.

Caution must be taken in setting MLO parameters since some client behavior results in increased latency and jitter compared to single band operation in the 6 GHz band with 320 MHz channel width. A Wi-Fi 7 phone was observed to run traffic at times over both the 2.4 and 5 GHz band or both the 2.4 GHz and 6 GHz band. Even when running traffic over the 6 and 2.4 GHz bands, the channel width in the 6 GHz band was only 160 MHz channel width resulting in worse performance than single band 320 MHz channel width operation. The measured throughput of the Wi-Fi 7 phone with 320 MHz channel width capability in MLO mode running traffic on both the 2 and 5 GHz bands is shown in Figure 10.

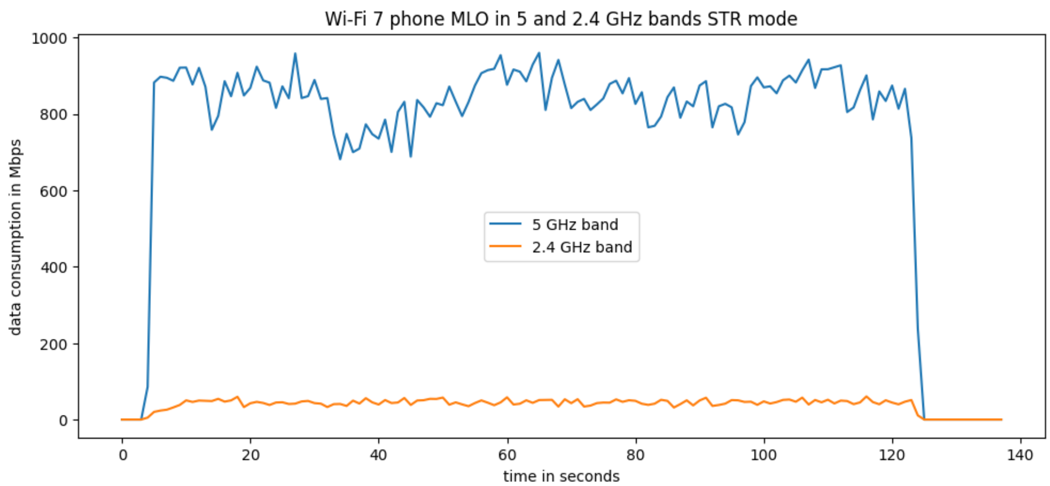

Figure 11 - Wi-Fi 7 phone using MLO to send traffic over 2 and 5 GHz bands at the same time.

The 320 MHz Wi-Fi 7 phone is connected to a Wi-Fi 7 AP with all three bands reports frequency, BSSID, Wi-Fi standard, RSSI, multilink device medium access control (mldMAC), and linkID. For example, in one case the phone reported a frequency of 5240 MHz for an AP set to channel 48 with 160 MHz channel width in the 5 GHz band. The BSSID reported was that of the AP 5 GHz band radio. The standard reported by the phone was Wi-Fi 7. The RSSI reported by the phone was between -54 dBm and -60 dBm. The reading changed over time even in the same location. The phone was close to the AP, on the same floor through one wall with about 3 dB attenuation, accounting for the strong reported RSSI level in the 5 GHz band. The phone reported the mldMAC the BSSID of the AP 6 GHz band radio. The AP set the mldMAC to the BSSID of the 6 GHz band radio since the 6 GHz band radio is fed with the fastest PCIe connection, dual lane PCIe gen3 at 16 GT/s. The phone reported linkID = 1 indicating that the phone is connected to the 5 GHz band radio of the AP with three links of MLO 2.4, 5, 6 GHz band.

The phone reports the list of Multi-Link Operation (MLO) affiliated links for Wi-Fi 7 access points. Affiliated links are the links supported by the Access Point Multi-Link Device (AP MLD). The Station Multi-Link Device (STA-MLD) gathers affiliated link information from scan results. Depending on the capability, it associates to all or a subset of affiliated links.

A Wi-Fi 7 2x2 phone with 320 MHz channel width capability in STR MLO mode will have four different MAC hardware addresses. There will be a higher layer MAC address shown on the Android phone as mldMAC and indicated in the AP console at MLD hardware address. Each of the three bands 2.4, 5, 6 GHz will have a different hardware address.

All three bands of the AP were included in the MLD configuration. For radios connected with PCIe gen 3 the radio with the most lanes, in this case two lanes of PCIe generation 3, was chosen for the main AP. The main AP BSSID is the mldMAC.

Speed test results measured 865 Mbps download and 41 Mbps upload with 18 ms ping latency and 45 ms jitter. Traffic flowed over both the 2.4 GHz and 5 GHz band radio during the speed test. This is clearly undesirable behavior since the 6 GHz band with 320 MHz channel width provides higher speeds and less latency and jitter than traffic flowing over both the 2.4 and 5 GHz bands. Additionally, as we have seen, older devices in the 2.4 GHz band running video streaming applications require more than half the 2.4 GHz band capacity. Unnecessarily using 2.4 GHz band capacity for a 6 GHz band 320 MHz channel width device reduces overall reliability.

MLD parameters can be observed on an Android phone when developer mode is enabled and Enable Wi-Fi Verbose Logging is toggled on. This feature is very helpful in understanding how MLO is working.

6. All About the Bandwidth (320 MHz channel width)

While using many of the first Wi-Fi 7 devices the observed advantage of Wi-Fi 7 over previous standards is clearly 320 MHz channel width.

Measurements were made with a Wi-Fi 6e phone using 160 MHz channel width and a Wi-Fi 7 phone using 320 MHz in the 6 GHz band. The intent was to quantify the advantages of 320 MHz channel width while keeping as many of the other variables as possible roughly the same.

standard	Channel width MHz	Download Gbps	STA RSSI dBm	AP RSSI dBm
6e	160	0.591	-62	-72
7	320	1.71	-70	-64

The macOS notebook computer network connection was Thunderbolt Ethernet Slot 0 with hardware speed 10Gbase-T full-duplex with standard 1500 MTU.

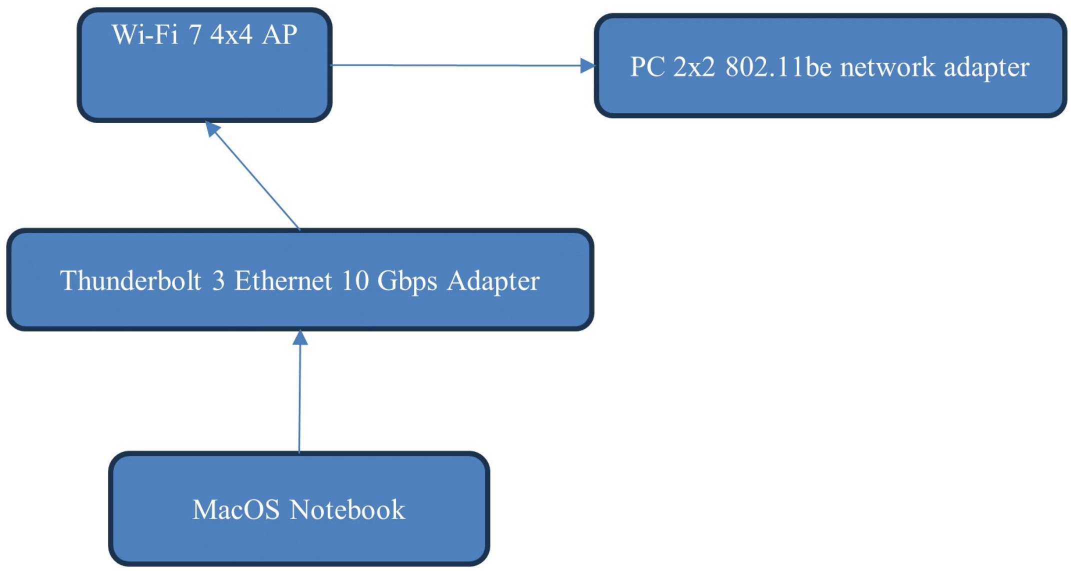

Figure 12 - Block Diagram of Capacity measurement of Wi-Fi 7 PC.

The AP AC power draw without driving traffic measured 15.2 watts.

The AP AC power draw measured 14.1 watts with a Raspberry Pi computer connected to the 1 Gbps Ethernet port of the wireless router. When the 10 Gbps Ethernet port of the wireless router is connected to the Thunderbolt 3 to 10 Gbps Ethernet adapter to the USB-C port of the notebook computer the AC power draw of the wireless router increases to 15.2 watts. Driving traffic over the 10 Gbps Ethernet power does not impact the power draw of the wireless router.

The throughput measured over a 30 second time period averaged 3.13 Gbps with PHY rate of 5764 Mbps.

10.9 GB were downloaded to the Windows 11 PC with Wi-Fi 7 network adapter in 30 seconds.

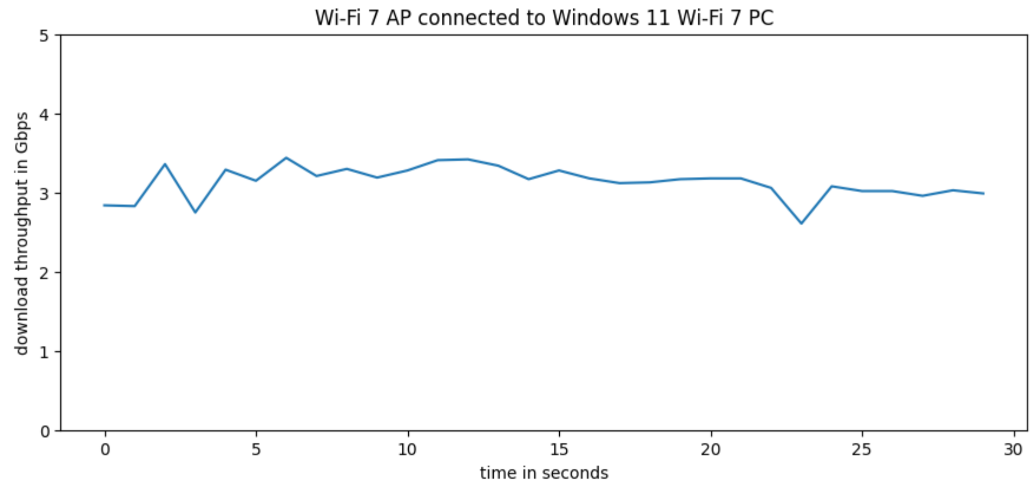

Figure 13 - Download speed from 10 Gbps LAN of AP to Windows 11 Wi-Fi 7 PC at close range.

99% of the packets were sent with MCS=13, Nss=2, BW=320MHz, 0.8 microsecond guard interval with 1% PER (packet error rate). The average AMPDU contained 56 MPDUs.

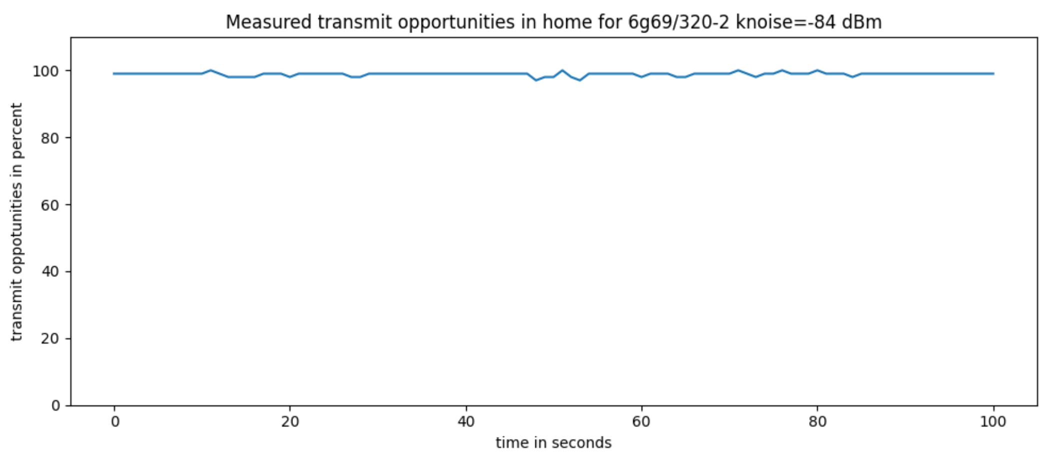

Figure 14 - Transmit opportunities measured mostly 99% in channel 6g69/320-2 during download test.

The AC power consumption increased to 20.7 watts with 5.7 Gbps PHY rate and over 3 Gbps throughput. The transmit chain power for the four chains of the 6 GHz band radio were set to +15 dBm per chain in order to keep the EVM good enough for MCS13. Since the AC power draw was 15.2 watts when traffic was not being driven through the 6 GHz band radio of the AP, the additional power draw from the four transmit chains at +15 dBm per chain was measured at 5.2 watts total, average 1.3 watts power consumption per transmit chain.

In an effort to gauge the impact of higher transmit power on AC power consumption, the per chain transmit power was set to +24 dBm per chain. The MCS dropped to 9 due to the nonlinear distortion at this power level. The AC power consumption increased to 24.2 watts indicating that the additional power drawn from the 6 GHz band transmitters was 7 watts corresponding to 1.75 watts per chain.

The Wi-Fi 7 notebook computer was placed 24 inches line of sight from the AP antennas, slightly above the AP antennas. The four AP antennas were half wave dipoles with at least 20 dB return loss in the frequency band of operation placed in a trapezoid pattern with 5/4 wavelength separation.

7. Spread the Love: Extending Reach at Full Speed with Mesh Nodes

Getting over 2 Gbps download and upload speed with Wi-Fi 7 AP and STA is quite easy. Doing so in the furthest rooms of the house and the backyard is impossible. However, 2 Gbps speed is possible at range with the use of a Wi-Fi 7 mesh nodes While the mechanism of wireless mesh node extension does not change with the introduction of Wi-Fi 7, two key features greatly enhance the efficacy of wireless mesh nodes. Multiple link Operation and 320 MHz channel width allow the traffic to flow flexibly, and 320 MHz channel width allows for much higher speeds through the mesh node.

The first principle of reliable network connectivity is ensuring the channel capacity far exceeds the demand. Optimizing channel capacity is trickier when the backhaul and fronthaul of a mesh network needs to be determined for a wide variety of customer devices.

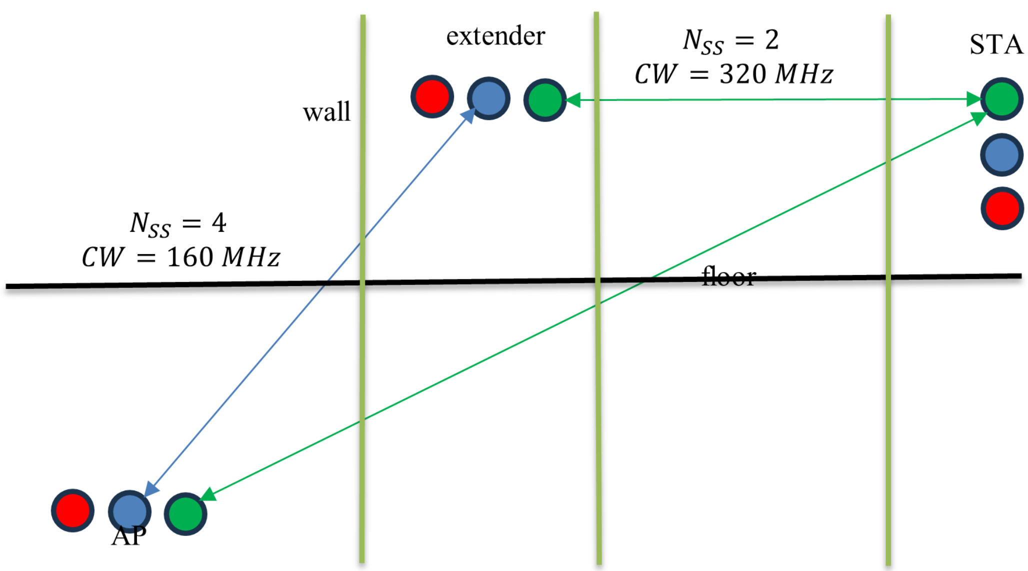

Figure 15 - Conceptual Diagram of 320 MHz Wi-Fi 7 STA, AP, Extender using 5 GHz backhaul

The conceptual diagram of a 320 MHz channel width STA connected to an extender front haul with backhaul between the AP and the extender is shown in Figure 15. The color of the dots represents the frequency band. The red dot represents the 2.4 GHz band with a maximum channel width of 20 MHz. The blue dot represents the 5 GHz band with a maximum channel width of 160 MHz. The green dot represents the 6 GHz band with channel width of 320 MHz.

The first principle of network reliability is providing capacity that exceeds demand. The maximum PHY rate of a Wi-Fi 7 2x2 320 MHz STA is 5.7 Gbps. Maximum LAN TCP throughput of a Windows 11 PC and an Android smart phone with Wi-Fi 7 network adapter at a 1-meter line of sight distance from a Wi-Fi 7 AP can exceed 3 Gbps. That is a lot of capacity. Certainly, sufficient to meet customer traffic demand.

However, the WLAN channel of a residential broadband customer's home is dynamic. Neighbors use of the shared unlicensed spectrum is dynamic. Devices and applications are always changing. The distance between the AP and any given STA varies along with the wall and floor attenuation, scattering objects and the movement of people and pets in the home. Thus, while the potential capacity of the WLAN channel can be quite high, the realized capacity at any given time can be quite low.

The STA that can download at 3 Gbps 1 meter from the AP will certainly not do so in the upper floor opposite corner from the AP. In fact, the throughput far away from the AP on another floor may be quite low, perhaps 50 Mbps. Or even lose connectivity in the 6 GHz band. Now, the traffic demand exceeds the channel capacity.

The use of wireless mesh nodes to extend coverage that employs a different band for backhaul and front haul traffic can restore the maximum capacity of the STA. Or at least close to it. The backhaul refers to the connection between the AP and the extender. The front haul refers to the connection from the extender to the STA. Which band should be used for backhaul and which band should be used for front haul? How does the optimum selection change based on the capabilities of the STA? The first rule of mesh optimization is to match the capabilities of the STA in the front haul. For an STA with 320 MHz channel width capability, the front haul should also have 320 MHz capability. This forces the front haul band to be 6 GHz since this is the only band with 320 MHz wide channels. If the 5 GHz band is used for front haul, then only half of the STA capability can be utilized.

The backhaul and front haul must use different bands. Otherwise, the front haul will be forced to cease use of the band during backhaul transmission, thus, preventing the full use of the capability of the STA. The backhaul can use the 5 GHz band but now we have another problem. The channel width is only 160 MHz. How can we get the full throughput of a 320 MHz wide front haul transported over the 160 MHz wide channel width backhaul?

MIMO spatial streams to the rescue. The STA is 2x2, meaning two transceivers, and thus is capable of two spatial streams of information. The backhaul connection is between 4x4 Wi-Fi 7 radios with capability of using 4 spatial streams. The maximum PHY rate of the 2x2 320 MHz channel width 6 GHz band STA is 5.7 Gbps. Likewise, the maximum PHY rate on the backhaul between two 4x4 160 MHz channel width 5 GHz band Wi-Fi 7 AP and extender is also 5.7 Gbps. Bingo, we have a match.

Neither the backhaul nor the front haul in practice will operate at the maximum PHY rate. Still, the roughly symmetrical capacity will hold as the distance between the AP and the extender increases and the distance between the extender and the STA increases. The set up illustrated in Figure 15 was implemented and measurement results are described below.

The AP 5 GHz band is set to channel 100 with a channel width of 160 MHz. The AP 5 GHz band radio is 4x4 with a maximum PHY rate of 5.7 Gbps. The AP reports a noise floor of -86 dBm and channel utilization of 7%. A noise floor of -86 dBm reported by the AP in a 160 MHz channel width indicates that the RF front end has a 3 dB noise figure and the AGC of the front end is not being forced by external interfering signals to raise the receiver noise floor to protect against high out of channel signals. (Urban, 2023)

The 4 receivers of the extender in the 5 GHz band report an RSSI level of -64, -67, -67, -69 dBm and a noise level of -86, -87, -88, -87 dBm. The Android STA reported -75 dBm RSSI level connected to the 6 GHz band radio of the extender. The four 6 GHz band receivers of the extender report RSSI levels of the STA at -70, -72, -74, -74 dBm and noise floor of -87, -87, -88, -87 dBm.

10.5 GB were downloaded from a computer connected to the 10 Gbps Ethernet LAN port of the wireless router to the STA in two minutes at an average rate of 752 Mbps with a window size of 6 Mbytes and 4 TCP streams.

While in theory speeds of over 2 Gbps throughput capacity should be able to be delivered over the 4x4 to 4x4 160 MHz backhaul and the 4x4 to 2x2 320 MHz fronthaul. Experimentation at closer ranges for both the fronthaul and backhaul never measured 2 Gbps throughput. Above 1 Gbps was easily reached and at times above 1.5 Gbps. It appeared that when the STA was close enough to the extender to receive levels commensurate with 2 Gbps throughput, the 5 GHz band of the backhaul may have been causing interference. The PHY rates of the fronthaul were not as high as when the STA was directly connected to the main AP for close range line of sight channel conditions.

When driving traffic over a 5 GHz backhaul and 6 GHz fronthaul to a Wi-Fi 7 phone and laptop, the throughput never measured 2 Gbps. The highest speed measured was around 1.8Gbps. The PHY rate of both the front haul and backhaul were more than sufficient for 2 Gbps throughput. Yet, 2 Gbps could not be measured. This could be due to fixable problems such as ensuring that traffic only uses hardware acceleration or buffer settings. Still, if the measured results are not improved, then use of 5 GHz backhaul and MLO in the backhaul is not justified since equal or better performance will work over a 6 GHz backhaul even for devices with 320 MHz channel width capability.

With a 5 GHz backhaul with 4x4 AP and extender primary channel 100 with 160 MHz channel width the throughput measured only 898 Mbps for a two-minute test.

Figure 16 shows a different mesh node scenario. This time the STA only supports 80 MHz maximum channel width in the 5 GHz band. The optimal backhaul is 6 GHz since the backhaul can take advantage of 320 MHz maximum channel width and up to 4 spatial streams. This has two benefits. One, the backhaul distance can be further away with greater wall and floor attenuation and still have more capacity than the fronthaul. Two, the backhaul can deliver the traffic demand to the fronthaul connected STA with very low duty cycle and thus having a small impact on other users of the main AP. This is even the case when the fronthaul capacity of the extender is heavily utilized by the application the STA is running. The fronthaul capacity of the extender can be heavily utilized without much impact on clients connected to the main AP. There are concerns about adjacent channel interference between AP and extender traffic in the same band.

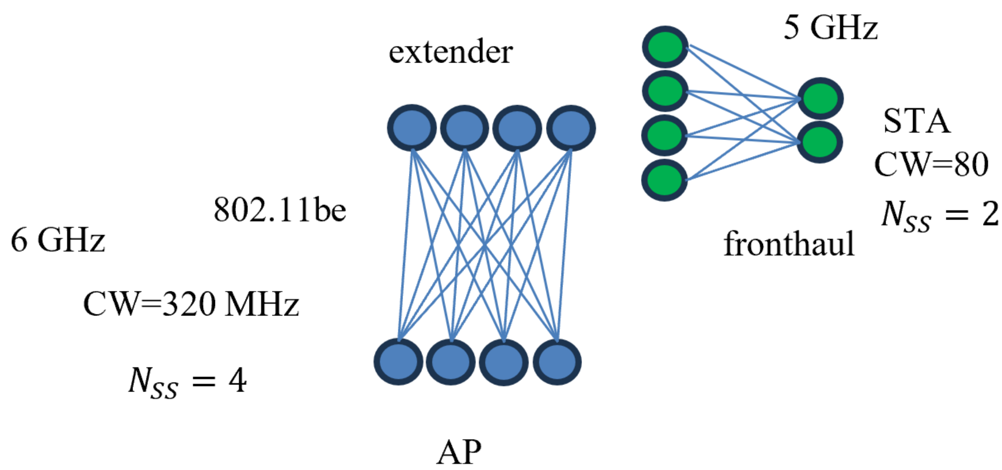

Figure 16 - Conceptual Diagram Wi-Fi 7 AP and Extender to Wi-Fi 6 STA with 6 GHz backhaul and 5 GHz fronthaul

An experiment was set up to show the benefits of using a 6 GHz backhaul when serving a mix of client devices. The main AP has a 4x4 160 MHz channel width radio in the 5 GHz band set to primary channel 48. The main AP has a 4x4 320 MHz channel width radio in the 6 GHz band set to channel primary channel 69 with a 320 MHz channel width using the three non-overlapping channels in the 6 GHz band offset higher in frequency, this is abbreviated as 6g69/320-2 (Urban, 2023). The extender has a 4x4 160 MHz channel width radio in the 5 GHz band set to primary channel 100. The extender has a 4x4 320 MHz channel width radio in the 6 GHz band set to channel 6g69/320-2 to match the main AP and establish the backhaul connection in the 6 GHz band. The main AP and extender also have 2.4 GHz band radios, but these have not been utilized in this experiment. Figure 17 shows an example. In this experiment a television set played a baseball game with the Wi-Fi connected to the front haul of the mesh node. The television Wi-Fi adapter was 802.11ac with a maximum channel width of 80 MHz. The backhaul channel utilization was very low due to the baseball game streaming.

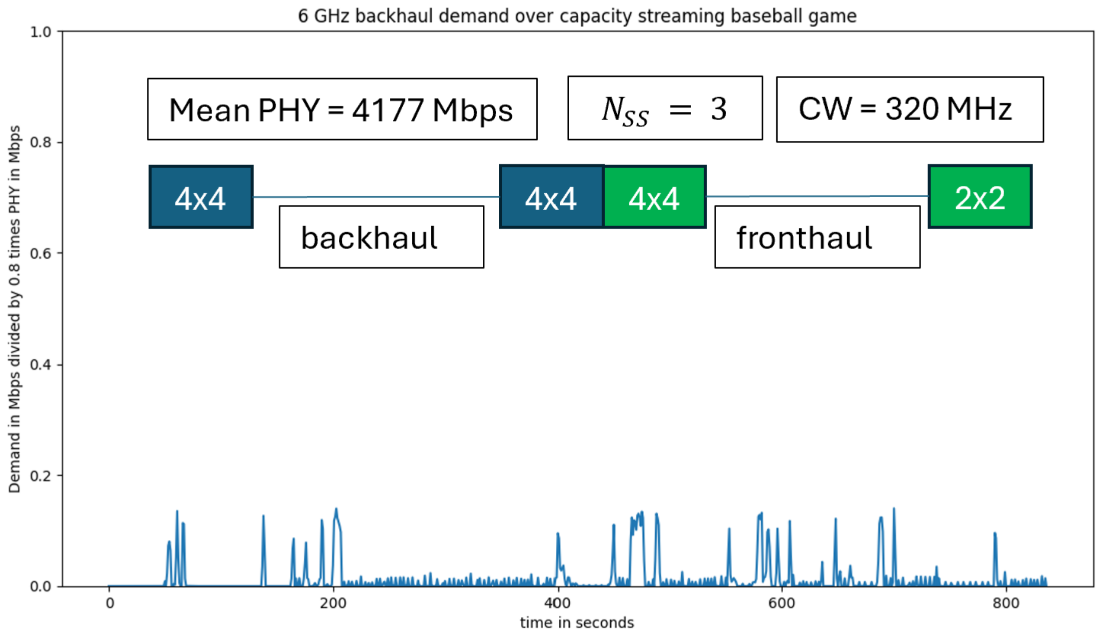

Figure 17 - Backhaul demand over capacity streaming baseball game.

Figure 18 shows a conceptual diagram of another experiment with many devices connected to various radios of the Wi-Fi 7 mesh node.

Fully utilizing the capability of the main AP and extender in the 5 and 6 GHz bands requires 6 STAs. Two of the STAs can have 320 MHz channel width capability while the other four only require 160 MHz channel width capability. All six STAs are 2x2. The 2x2 320 MHz devices were Wi-Fi 7. One of the 2x2 160 MHz STAs was Wi-Fi 6 802.11ax and the other three were Wi-Fi 6e 802.11ax.

In the experiment, download traffic was driven to all six devices at the same time.

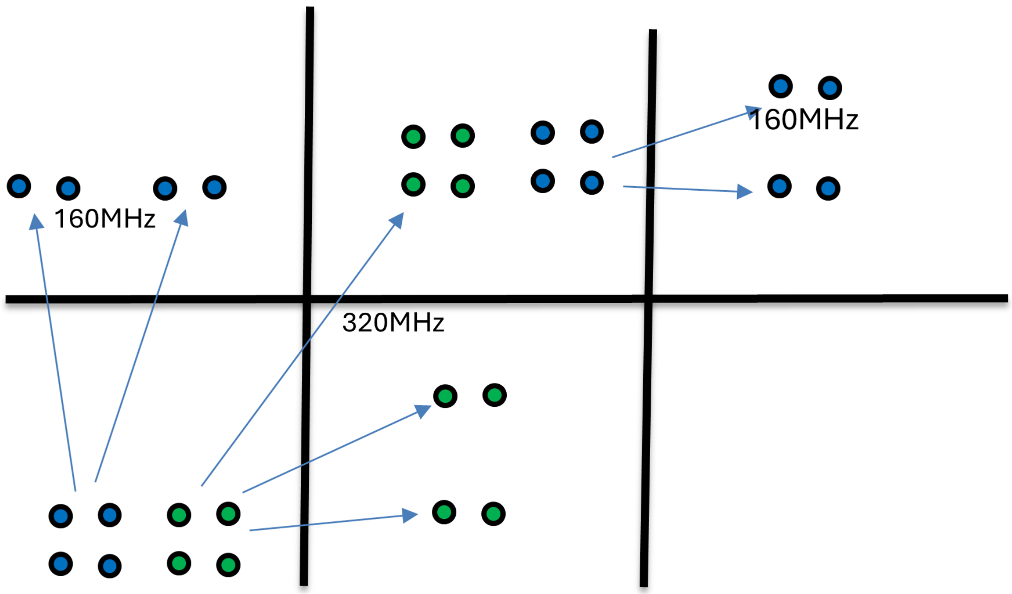

Figure 18 - Full speed ahead with many devices and a mesh node with 6 GHz backhaul and 5 GHz front haul.

The backhaul downlink traffic was 0% MU-MIMO. The backhaul downlink traffic had a maximum of 24% OFDMA. The mean of OFDMA traffic over the backhaul was only 2.7%. Almost all the backhaul traffic utilized 3 spatial streams. The MCS rate varied mostly between 5 and 6. The backhaul channel width was 320 MHz. The peak download throughput over the backhaul measured 1708 Mbps with a mean of 626 Mbps. The mean downlink PHY rate of the backhaul measured 3733 Mbps.

The extender was set to 6 GHz band backhaul and 5 GHz band fronthaul since the devices located in the far room upstairs without coverage from the main AP were 160 MHz channel width devices. The extender 5 GHz band radio front haul was 4x4 set to channel 100 at 160 MHz channel width. The devices located in the extender coverage area were one phone and one notebook computer both with Wi-Fi 6e network adapters having a maximum channel width of 160 MHz in the 5 GHz band.

The noise floor reported by the 6 GHz band radio was -86 dBm which for a 320 MHz channel width corresponds to a 3 dB noise figure receiver.

Figure 19 show the block diagram and the measured results of the simplest possible set up with just a Wi-Fi 7 AP and STA at a line-of-sight distance of 1 meter in the 6 GHz band with 320 MHz channel width. The notebook computer was able to download at 3.27 Gbps of TCP throughput. The wireless adapter was connected to the computer over PCIe single lane generation 2 which limited the throughput to 3.27 Gbps. This measured is included to show that the limitations of throughput observed over the mesh nodes were not due to the computer or wireless adapter or the AP.

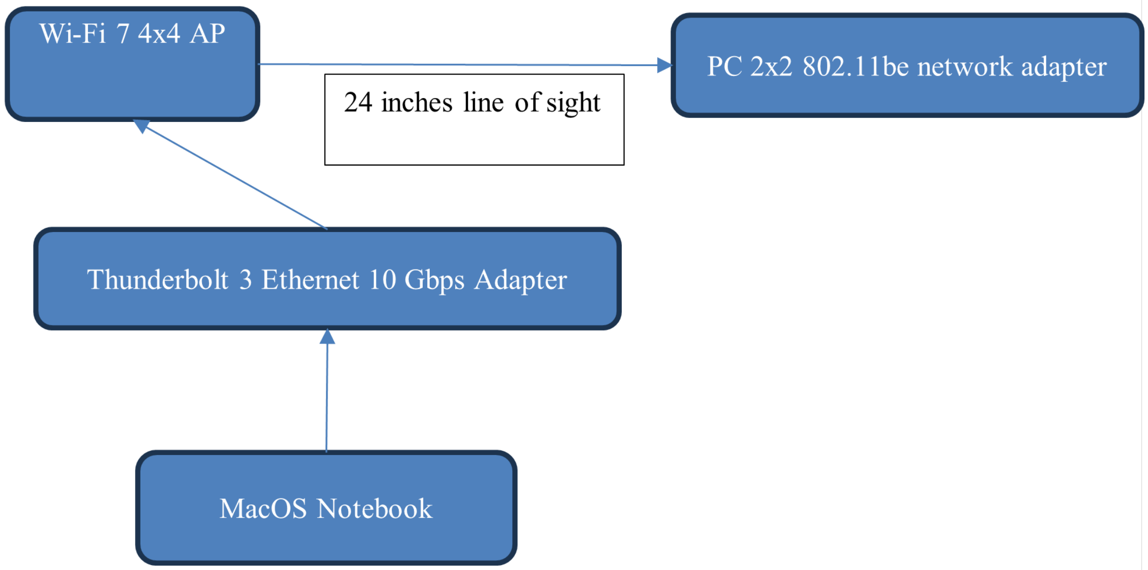

Figure 19 - 3.27 Gbps measured by Wi-Fi 7 client very close to main AP

The AP AC power draw without driving traffic measured 15.2 watts.

The AP AC power draw measured 14.1 watts with a Raspberry Pi computer connected to the 1 Gbps Ethernet port of the wireless router. When the 10 Gbps Ethernet port of the wireless router is connected to the Thunderbolt 3 to 10 Gbps Ethernet adapter to the USB-C port of the notebook computer the AC power draw of the wireless router increases to 15.2 watts. Driving traffic over the 10 Gbps Ethernet power does not impact the power draw of the wireless router.

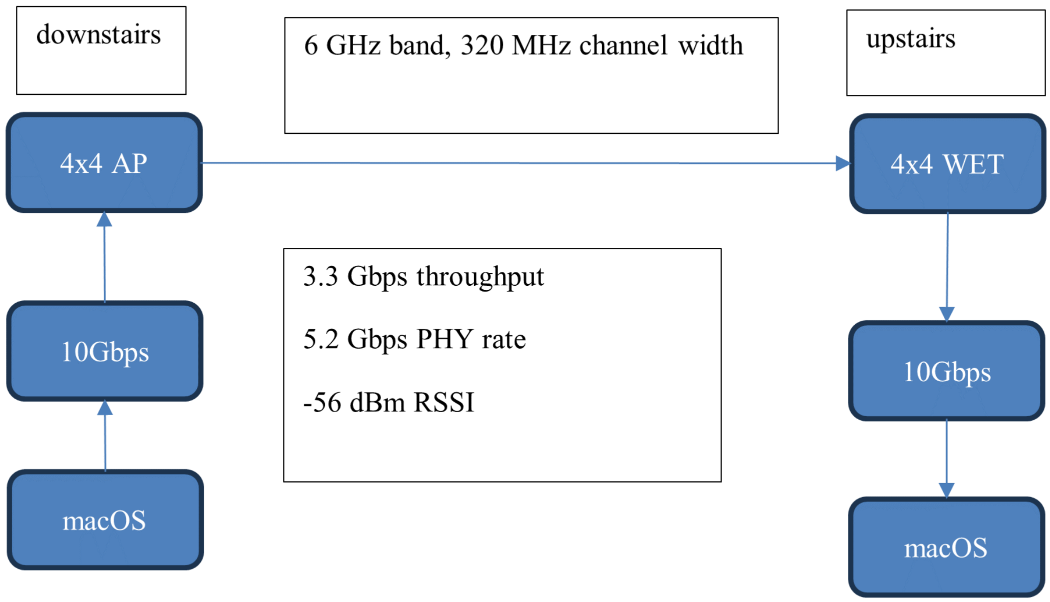

Figure 20 - Block diagram of 6 GHz backhaul measurement.

To understand the backhaul capacity, two computers were connected to the 10 Gbps Ethernet port of the AP and the extender. The wireless backhaul connection consisted of two 4x4 320 MHz channel width Wi-Fi 7 radios. The block diagram is shown in Figure 20.

The average download throughput over ten minutes measured 3.33 Gbps. The PHY rate measured 5188 Mbps. The MCS measured 6. The number of spatial streams measured 4. The channel width measured 320 MHz. The receive levels by the four chains of the AP measured -58, -56, -55, -57 dBm. The receiver levels measured by the four chains of the wireless ethernet (WET) extender were -56, -56, -58, -57 dBm.

At close range the throughput averaged 3.40 Gbps with PHY rate of 5760 Mbps between two macOS computers with 10 Gbps network adapters backhauled with two 4x4 320 MHz channel width radios. While this should be more, the extender needs to be far from the main AP to extend coverage. Thus, close range performance is not critical for practical application. It can, however, indicate problems that will show up over time and the poor close-range performance will be investigated.

At the same location as the wireless ethernet extender in an upstairs bedroom a download measurement was also made with the Wi-Fi 7 notebook computer. This gives us an idea of the difference between a 4x4 to 4x4. The 2x2 throughput measured less than 2 Gbps.

The use of a Wi-Fi 7 backhaul between a 4x4 AP and 4x4 WET in the 6 GHz band with 320 MHz channel width is an excellent method to get the most out of older devices with the least amount of impact on available network capacity. This is shown in Figure 21

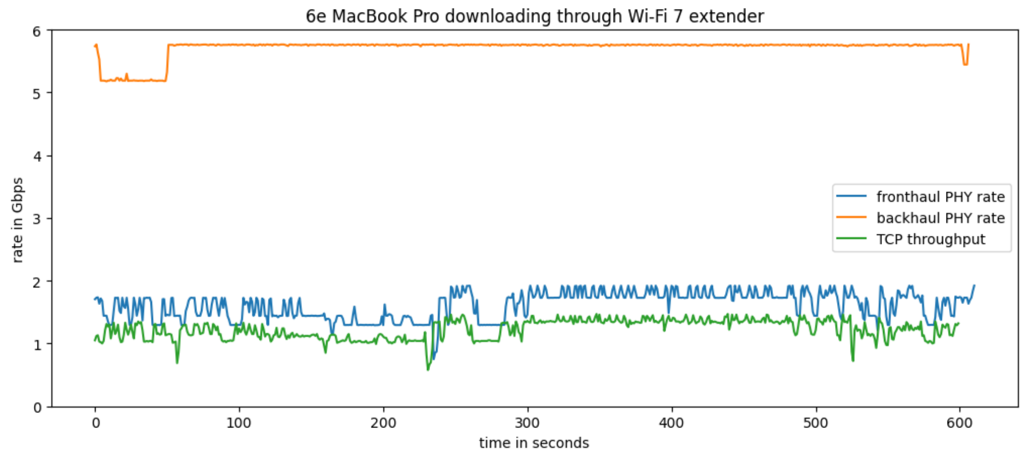

Figure 21 - Measured TCP throughput and front and back haul PHY rate

Latency is a critical factor in customer experience.

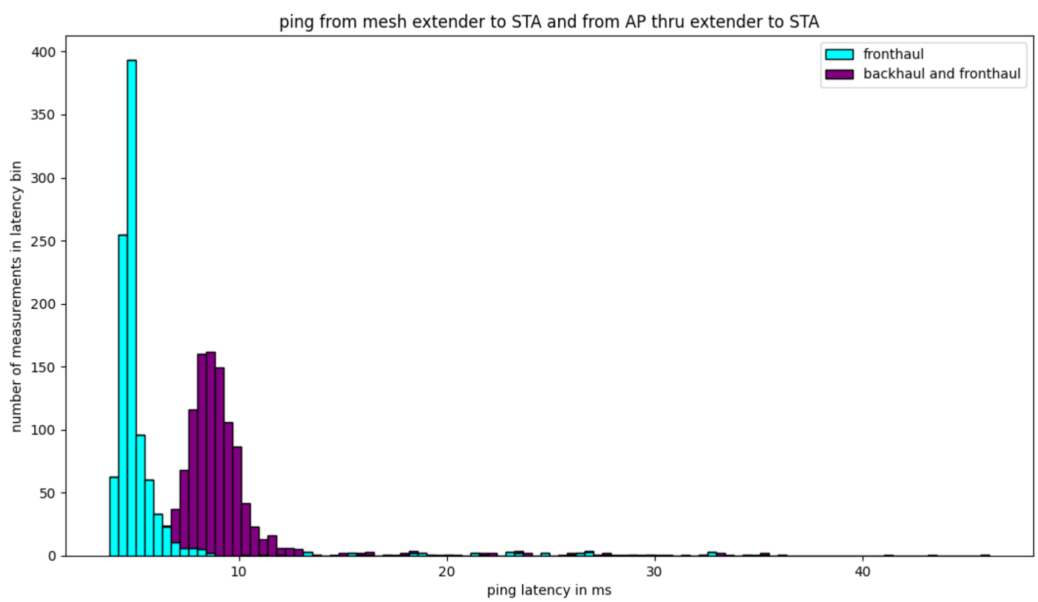

Figure 22 - Latency of fronthaul compared to latency over both backhaul and fronthaul.

Reducing latency and jitter is a key factor in reliability. The latency introduced over the backhaul of a mesh node is shown in Figure 22.

8. Conclusion

After working with the first available Wi-Fi 7 phones and computers with a Wi-Fi 7 AP, the conclusion is that the most important feature of Wi-Fi 7 is the capability to operate with 320 MHz channel width in the 6 GHz band. Wi-Fi 7 mesh nodes show great promise in extending the reach of greater than 1 Gbps coverage as well as serving older client devices even a far distance and heavy utilization without reducing the main AP capacity for Wi-Fi 7 clients.

Abbreviations

AC	alternating current
AP	access point
bps	bits per second
eMLSR	enhanced single link multiple radio
FDX	full-duplex
FEC	forward error correction
GB	gigabyte 10^9 bytes
HD	high definition
Hz	hertz
K	kelvin
MLD	multiple link device
mldMAC	multilink device medium access control
MLO	multiple link operation
MRC	maximum ratio combining
ms	milliseconds
PHY	physical layer interface
RSSI	received signal strength indicator
SCTE	Society of Cable Telecommunications Engineers
STA	station
STR	simultaneous transmit receive
TV	television set
US	United States
WAN	wide area network
wet	wireless ethernet

Bibliography & References

Urban, D. J. (2023). DOCSIS 4.0 and Wi-Fi 7 Perfect Together for Multiple Gigabit per second Service. *Cable Tec Expo 23.* Denver.