With 1.2GHz of spectrum are we moving to a channelized per room architecture for the home – enabled by Wi-Fi 7

A Technical Paper prepared for SCTE•ISBE by

Charles Cheevers
CTO Home Networks Solutions
CommScope
Charles.Cheevers@commscope.com

Ian Wheelock
Engineer Fellow
CommScope
Ian.Wheelock@commscope.com

Kurt Lumbatis
Distinguished Software Engineer
CommScope

Kurt.Lumbatis@commscope.com

Kamal Koshy, Charter Communications

Ahmed Bencheikh, Charter Communications

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1. Introduction

We are in a unique time in our history of Wi-Fi with three major changes happening in less than a 3 year period that fundamentally challenge us to look at our traditional view of Wi-Fi home architectures in the home. In particular how a Service Provider keeps pace with change and reaps the benefit of the increase in bandwidth, increase in coverage and decrease in latency while at the same time providing their customers with a clear and concise device and services roadmap.

The 3 fundamental changes are

(i) Wi-Fi 6 – just starting to deploy this year for most service providers in their primary Gateway or Access Point. Wi-Fi 6 extender solutions typically lagging behind the primary AP function.

(ii) Wi-Fi 6E and the addition of 6GHz spectrum. In particular in the US the allocation of 1.2GHz of new unlicensed spectrum has now fundamentally opened up a new approach to how Wi-Fi and all wireless services play out in the home. And provide a path to even higher bitrate immersive video services and lower latency services over Wi-Fi.

(iii) IEE802.11be and probably the next Wi-Fi 7 standard which takes the opportunity now of 6GHz spectrum and opens up single channel capabilities to support 320MHz channels from the present 160MHz channels supported today in Wi-Fi 6/6E.

Date	Standard	Wi-Fi	Frequency	Bandwidth MHz	MIMO	Bitrate
1997	802.11		2.4GHz	20	NO	2Mbps
1999	802.11b	1	2.4GHz	20	NO	11Mbps
1999	802.11a	2	5GHz	20	NO	54Mbps
2003	802.11g	3	2.4GHz	20	NO	54Mbps
2009	802.11n	4	2.4+5GHz	20/40	4x4	600Mbps
2013	802.11ac	5	5GHz	20/40/80/160	8x8	6.9Gbps
2019	802.11ax	6	2.4+5GHz	20/40/80/160	8x8	9.6Gbps
2021	802.11ax	6E	2.4+5+6GHz	20/40/80/160	8x8	9.6Gbps
2023/24	802.11be	7	2.4+5+6GHz	20/40/80/160/320	16x16	30-40Gbps

Figure 1 - The Wi-Fi Standards

While Wi-Fi took 20 years to finally revise its MAC for the creation of IEE802.11ax and subsequent Wi-Fi 6 standard we now have both 6E and Wi-Fi 7 happening over a 3 year period so need to now look ahead to the next 3 years and how the

- Transition from current home solutions of mixed mode g/n and ac to emerging Wi-Fi 6 AP and the start of third party Wi-Fi 6 clients
- Introduction of specific Wi-Fi 6 clients for Service Providers – typically first STB and Extenders
- Planning for use of 6GHz spectrum and the introduction of Wi-Fi 6E. Current discussions are around potential introduction by all new Tri-band Gateway or AP or with the introduction of a Wi-Fi 6E extender that supports augmentation for Wi-Fi 6 as well as first Wi-Fi 6E usage.

- Use of Low Power Indoor power levels for Wi-Fi 6E and the utilization of higher Standard power levels utilizing Automated Frequency Control mechanisms
- Exploitation of the 33-66Gbps of Wi-Fi spectrum available with 6GHz channels alone for the next generation home and services
- Use of 320MHz high capacity channel for high capacity client applications or use for backhaul to 10GbE capability in the home.
- Separation of 2.4GHz and 5GHz usage from 6GHz channels for legacy solutions as well as potential new usages for these legacy spectrum channels. 2.4GHz for example is now in stark relief for its limited capacity versus the other frequency levels but also may have a key role to play in the home for long range 'Narrow Band' Wi-Fi IoT functionality. Its current role for being primarily a reliable long range coverage channel when 5GHz is not usable or the device types are cheap and only support 2.4GHz radios.

This paper will discuss these areas in more detail in the following sections and hopes to offer a good discussion on the parameters and decision points to consider in the next 3 years of fast moving Wi-Fi technology changes. It should help the Cable Operator with the transition decision points of moving from Wi-Fi 5 through 6 and 6E as well as Wi-Fi 7.

	xBC	Speeds	Main Features	Comment
Mature Wi-Fi 5	Dual	1Gbps		160MHz channels were supported – but clients did not typically support
Current Wi-Fi 6	Dual and Triband	4x4 2.5Gbps	4x speed Lower latency OFDMA Better Battery Life	Wi-Fi 6 AP performs better for mixed Wi-Fi 4,5,6 clients than a Wi-Fi 5 AP. Typically **25% improvement** in mixed Wi-Fi client environment 160MHz channels supported Matched with 2.5GBe Ethernet support
2021/22 Wi-Fi 6E	Triband	4x4 4Gbps	Immediate use of Wi-Fi 6 features for the client	Wi-Fi 6E allows ONLY Wi-Fi 6 devices with 6GHz support to operate in the U-NII5 6GHz band. **Immediate** full use of the performance of Wi-Fi 6 with 160MHz channels and QAM1024 modulation Perfect solution for congestion (MDU) and low latency Wi-Fi services
2023 Wi-Fi 7	Triband	4x4 8Gbps	320MHz channels	Wi-Fi 7 (currently IEEE802.11be specification) is extending the channel width to 320MHz. Potential for 10Gbps like **wireless backbone** across the home

Figure 2 - The evolution of Wi-Fi from 5 to 7

So, from an availability for a Cable Operator to be able to deploy new Wi-Fi technology today we are in the Wi-Fi 6 era with Cable Operators expected to deploy Wi-Fi 6E solutions end of 2021 or early 2022. This is then followed in 2023 by the ability to upshift once more with the proposed availability of Wi-Fi 7 solutions in market in 2023 – potentially even trialing as early as 2022.

Cable Operators need to invest in their device strategy wisely and ensure as usual that

- They minimize SKU's for keep down inventory and operational cost overheads
- Return the investment in their investment in GW and Extenders deployed
- Not confuse their customers with too many Wi-Fi changes
- Associate Wi-Fi changes with other consumer friendly features and performance metrics that they understand
- Align their Wi-Fi 6, Wi-Fi 6E and Wi-Fi 7 upgrades with their DOCSIS 3.1 to DOCSIS 4.0 evolution and increasing PON speed solutions.

See below a potential evolution roadmap that highlights the introduction of both DOCSIS GW and Extenders to bring in the new Wi-Fi features. One potential alignment of Wi-Fi 7 now is DOCSIS 4.0 and these two technologies could be aligned for common introduction based on their current schedules. It highlights the probability of Wi-Fi 6 GW today lasting well into the introduction of 6E and the continued use of Wi-Fi 6E devices in the Wi-Fi 7 domain particularly. It also brings up questions about Extension of Wi-Fi which we will also touch on more in the paper.

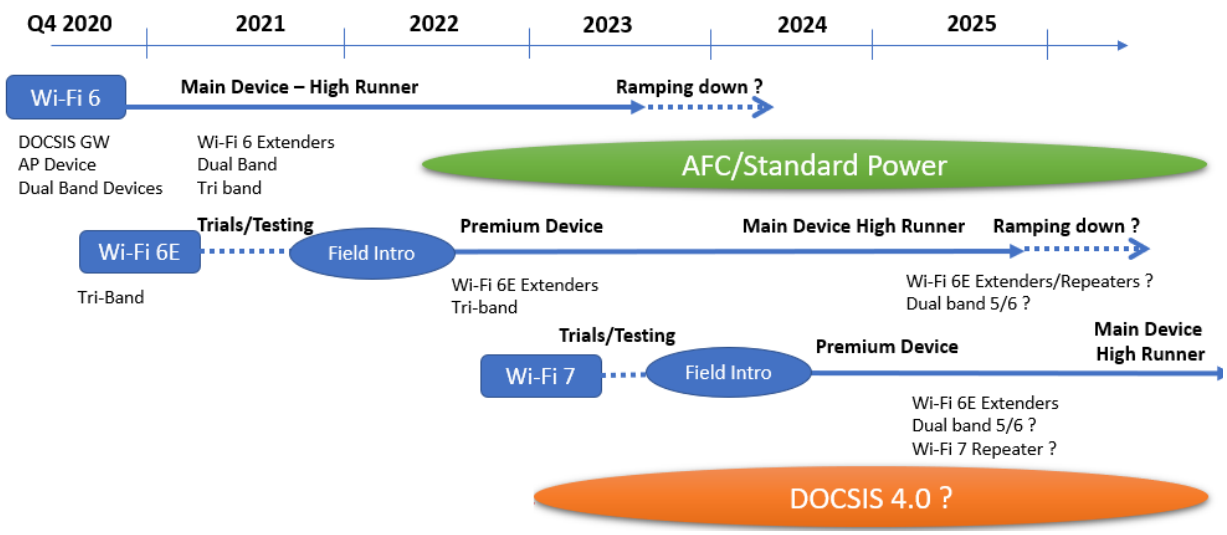


Figure 3 - Potential overlapping Wi-Fi DOCSIS GW solutions in the 2020-2025+ timeframe

Before we continue, we also want to outline some of the reasons why we need to make this investment in

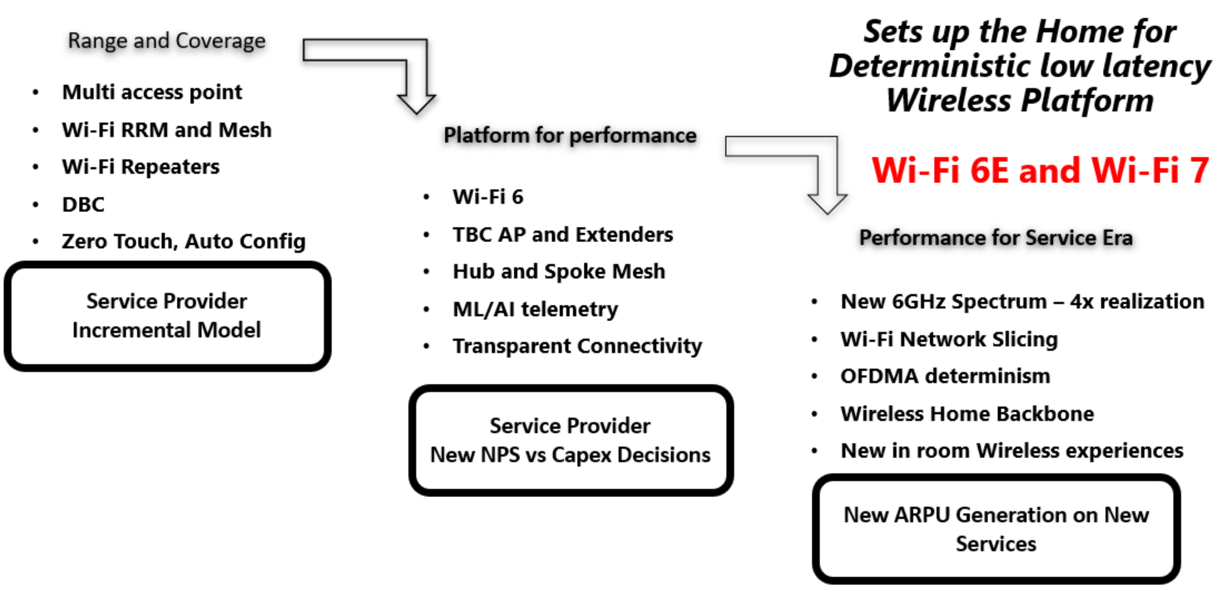


Figure 4 - The Wi-Fi Eras and where we are going

We have been focused over the last 20 years of Wi-Fi on

- 802.11 b/g - getting untethered from the ethernet cable
- 802.11 n – using 5GHz spectrum which formed the basis of being able to support streaming IP video
- 802.11ac – which got us to 1Gbps speeds on Wi-Fi

- 802.11ax – which redefined the MAC and added the foundation for added Spectrum for Wider Channels

We got to a point where we also

- Initially had one AP per home
- Added Repeaters for 'barely their capacity coverage'
- Improved with Wi-Fi Meshing solutions for better coverage
- Introduced new Wi-Fi 6 MAC and improved FEM technologies to be able to get more efficiencies in Mixed b/g/n/ac and ax client networks

But Wi-Fi still had difficulties getting 80MHz and 160MHz channels reliably enough, had high congestion issues in MDU's and could never really get the determinism to feel reliable to have it as a foundation for new wireless high capacity and low latency services in the home.

Now with 6GHz spectrum (1.2GHz in the US) we have the new Era of Wi-Fi – Deterministic, Low latency high capacity platform – to build new Wi-Fi home services.

2. Todays home – legacy g/n and ac devices and emerging Wi-Fi 6

If we could change everyone's Access Point to a Wi-Fi 6 device and every client to a Wi-Fi 6 device – we could take advantage of the improvements in features Wi-Fi 6 immediately. However, that is not possible for the Service Provider and even for the retail consumer. So, we currently have in everyone's home a mixed environment for Wi-Fi where there are variances in the primary Access Point

- 802.11n and 802.11ac access points still dominate the distribution for homes
- Over 90% of deployed Access Points are Dual Band Concurrent
- The majority of Wi-Fi extenders are really repeaters with the majority of those still running dual band 802.11n
- The breakdown of client devices (taken from various CommScope sources) are spread across
    - Pre AC (Wi-Fi 4) devices are > 43% of the current home devices (but in some regions of the world (are as high as 71%)
    - AC (Wi-Fi 5) devices are about 56% of the current home devices (in some regions of the world are as low as 27%)
    - Wi-Fi 6 devices still only number about 1% of the current home devices

Figure 5 - Wi-Fi Speed evolution

Within the client base there are also new devices like the popular Wyze cameras that only support 2.4GHz Wi-Fi 4 because of cost points and cost maturity of 2.4GHz only solutions for IoT and Camera applications.

From CommScope's analysis of the home 802.11b and 802.11g only devices have almost fully flushed through to later and better Wi-Fi solutions.

There are several significant device types in the home that have different replacement cycles for Wi-Fi but typically group into the following categories

- Wi-Fi Access Point or Primary Gateway – typically Service Provider supplied
    - Average time in the home – probably decreasing with technology acceleration but typically lasts for 5 years without change
    - Typically, not changed by the SP when new technology introduced if the household has no issues or requires a new service that requires a GW or AP upgrade
    - Wi-Fi upgrades may be tied to WAN access technology changes, such as DOCSIS 3.0 to DOCSIS 3.1 or GPON to XGS-PON
- Extenders – have a higher churn rate with consumers as they move through lower cost devices that underperform purchase improvement devices when necessary – probably a 3-4 year life cycle. Consumers have purchased retail repeaters themselves to remediate SP Wi-Fi issues. Some consumers have purchased their own meshing Wi-Fi solutions in recent times to bypass the primary service provider issued GW solution.
- Wi-Fi Client Devices
    - Static Clients
        - Wi-Fi Smart TV – TV's have a 5-7 year life but can be moved from Room to Room
        - Wi-Fi STB – churn faster than Smart TV but typically have 3-4 year lifecycle and higher for quality SP issued solutions or Apple TV devices
        - Wi-Fi printers – 5 year cycles
        - Wi-Fi based PC/iMac – 5+ year cycles
        - Smart Assistants – 5+ year cycles
        - Camera typically indoor but often edge of range outside the house – Doorbell or Security cameras
    - Mobile Clients
        - Smart Phones – depending on model and who supplies the phone but now tracking 2.5 to 2.88 years

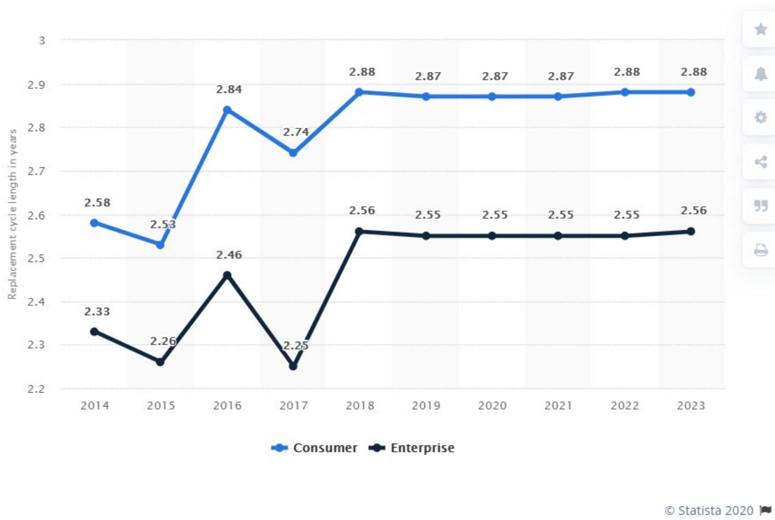


Figure 6 - Average time to replace Smartphone in the US

- Tablets – until they break or die
- Laptops – 4-5 years. Corporate Laptops churn faster at 3 year cycle

    - Apple Watch – churn time 3-4 years. Note even Apple Watch just uses 2.4GHz Wi-Fi.
  - Low cost IoT Wi-Fi devices (typically last a long time until they die)
    - Smart Power Switches
    - Smart Sensors

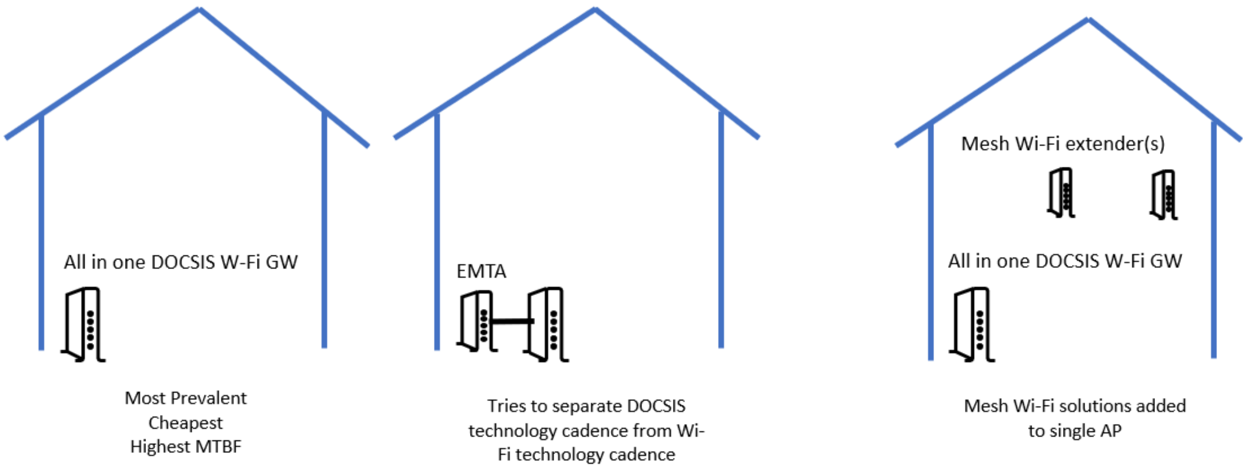


Figure 7 - Todays Wi-Fi architectures

There are 3 typical Wi-Fi architectures found in most Cable Homes.

1. **The most economical and the majority of households**

   Single all-in-one DOCSIS and Wi-Fi Gateway. Offers the lowest cost to the Cable Operator to provide both DOCSIS access and Wi-Fi services. Typically does a great job in homes less than 2.600sqft and offers also the highest MTBF because of single PSU. Highest Self install capability particularly in homes with existing DOCSIS modems as a replacement.

   Downsides of the all-in-one Gateway is that it tends to be located at an outside wall location close to Cable ingress point to the home rather than more centrally in the home to accommodate better whole home Wi-Fi coverage.

2. **The '2 box' solution where a separate eMTA and Wi-Fi AP are installed**

   Typically, both devices are connected by 3 feet of ethernet. Main driver for this architecture is to separate out the cadence of DOCSIS evolution and Wi-Fi evolution. The faster speed cadence of Wi-Fi technology and the consumer desire for the latest Wi-Fi solution has driven this solution. It does carry a higher initial CAPEX costs and probably over its lifetime, but the key metric is how often both the eMTA and AP are replaced vs one of them only. It also offers potential Operational improvements particularly for CSP's with multiple Access Networks like PON, DOCSIS, FWA where the same LAN based AP can be added to all access networks.

   This architecture is also the Cable Operators nemesis when customers add their own Access point and NAT out the Cable Operator services.

3. The Wi-Fi Mesh solution

We have now moved into the era of the Cable Operator deployed Mesh solution that extends Wi-Fi across the home, especially in larger homes. There are lots of discussions how best to extend coverage and the types of Wi-Fi extension

- Repeaters – trending away from these now to smart Repeaters
- Dual Band Smart Repeaters – employing some Wi-Fi Management RRM solution trying to maximize channel and band usage across the home
- Tri-Band extenders – with typically 5GHz backhaul solutions on a dedicated backhaul link that can also be used to attach clients under QoS mechanisms. Tri-band typically 2.4GHz+5GHz+5GHz – with U-NII1/2 and U-NII3 support one each radio.
- Other debates continue on how many streams and radios to use. Popular setups now are
    - 4x4 (2.4GHz) + 4x4 (5GHz) for the primary Wi-Fi AP when DBC
    - 4x4 (2.4GHz) + 4x4 (5GHz) + 4x4 (5GHz) for Wi-Fi AP when TBC
        - Similarly, for High End TBC extender
        - Lower end 4x4 (2.4GHz) + 4x4 (5GHz backhaul) + 2x2 (5GHz)
    - Low cost Smart Repeaters 2x2 (2.4GHz) + 2x2 (5GHz)

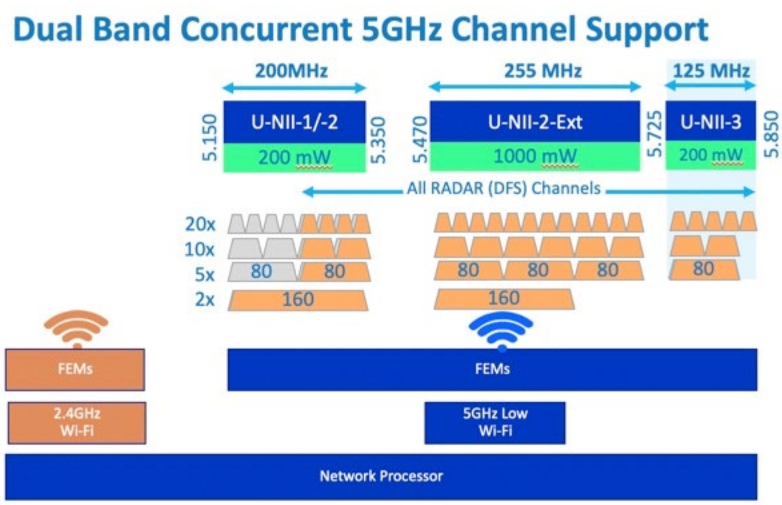


Figure 8 - Dual Band Concurrent AP (2.4+5GHz)

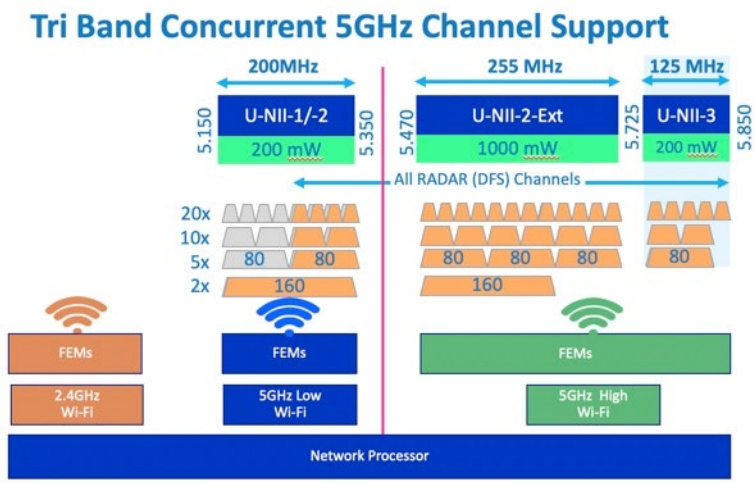


Figure 9 - Tri Band Concurrent (2.4+5GHz Low+5GHz High)

These have been introduced initially on Wi-Fi 5 architectures and within the constraints of 5GHz frequency availability in particular where 160MHz channel use has been almost non-existent because of (i) lack of client support during Wi-Fi 5 standard and (ii) no channels available with congestion and DFS requirements. Typically, most of the Wi-Fi transmissions in 5GHz are using 80MHz and 40MHz channels.

3. Service Providers and the introduction of Wi-Fi 6

Wi-Fi 6 introduces a significant number of new features for the operation of Wi-Fi, including a 4x average improvement per user in dense or congested environments (stadiums, etc.), a 4x improvement on network efficiency, and far better battery life for Wi-Fi 6 devices. Most importantly it offers a significant boost in performance over Wi-Fi 5 in terms of rate and range, promising about a 40% increase in data rate. The addition of 1024-QAM and 8 spatial streams as part of Wi-Fi 6 enables the highest speed of 9.6Gbps. From an AP technology perspective, it includes general signal handling improvements that not only benefit Wi-Fi 6 devices, but also previous generation devices, based on improvements with silicon process and front-end modules (FEMs).

Virtually all shipping Wi-Fi 6 APs are dual band concurrent, bringing these new benefits to both the 2.4 and 5GHz bands. Wi-Fi 5 did not address the 2.4GHz band, while Wi-Fi 6 has introduced improvements bringing beamforming and Multi User (MU) MIMO operation to 2.4GHz. Wi-fi 6 capability of using very narrow 2MHz frequency allocations to 2.4GHz clients enables a big increase in the range that is possible, as well as reducing power requirements for some IoT devices where they are not required to transmit across the entire minimum 20MHz channel as with previous versions of Wi-Fi. IoT devices can also benefit from Target Wakeup Time feature allowing them to spend more time “asleep” and save battery life.

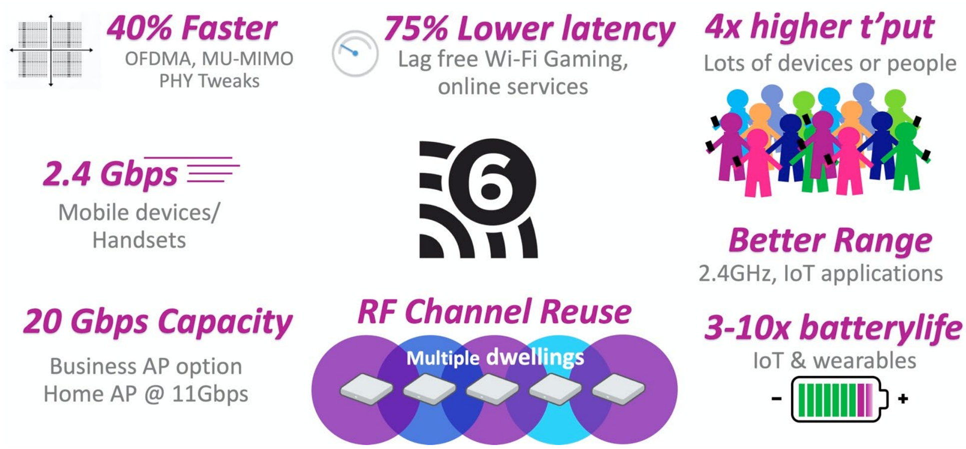


Figure 10 - The Primary Features of Wi-Fi 6

The addition of OFDMA in Wi-Fi 6 brings a lot more control over how the allocated channel spectrum is used by devices and can be used for both Downlink and Uplink communication. Traditional OFDM clients are allocated channel access on the basis of time only, where a single client is assigned a period of time to use a channel. OFDMA is a multi-user version of OFDM, enabling control over both time and frequency enabling multiple users to transmit at the same time, using different/unique ranges of frequencies allocated to them. Wi-Fi 6 has quadrupled the number of sub-carriers within a 20MHz channel to 256, by reducing the sub-carrier width from 312.5KHz down to 78.125KHz. These sub-carriers are grouped together into smaller groups spanning contiguous spectrum, known as Resource Units (RUs). Wi-Fi 6 OFDMA operation assigns different RUs to different clients to use at the same time. OFDMA enables a reduction in the time a client must wait to transmit data, improving performance and latency in Wi-Fi 6.

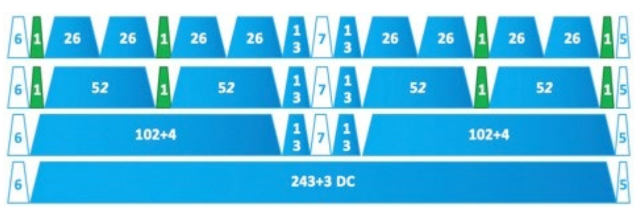
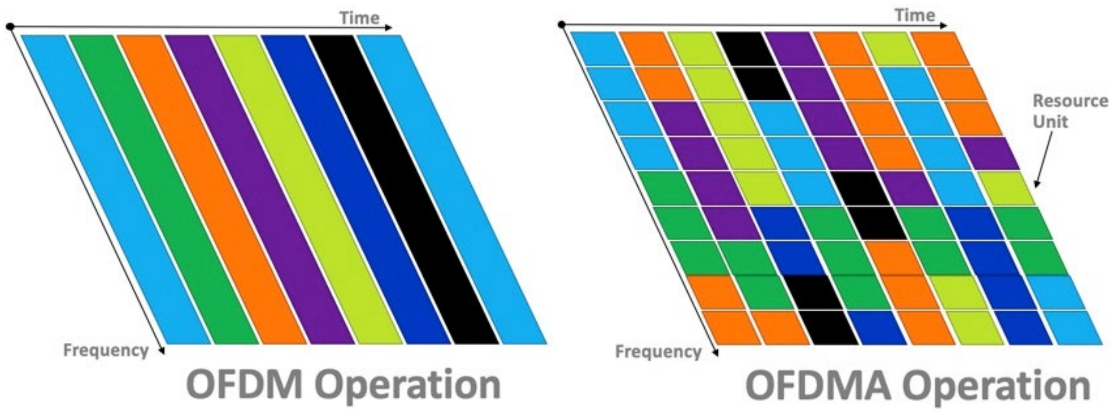


Figure 11 - 20MHz RU allocation mapping

Figure 12 - 40MHz RU allocation mapping

The ability to have parallel transmissions means that applications, such as audio or video streaming, that send chunks of data continuously can be served simultaneously. A 20MHz channel can support up to 9 concurrent clients, while a 160MHz channel can transmit to 74 clients in parallel. mixtures of RU allocations are also possible, providing more spectrum to some clients than others, depending on airtime demand and policies.

The AP is responsible for downlink OFDMA transmissions, coordinating the client to RU allocations. For uplink OFDMA transmissions, the AP coordinates the different associated clients and issues a trigger frame to get them to transmit at the same time. All clients using OFDMA must tune their power, frequency and timing to be able to join in the parallel transmission



As can be seen from the above diagram, the ability to send or receive traffic from different Wi-Fi users in the same time period has a significant improvement in link sharing and latency reduction. The "dark blue" user above gets services in the 3rd time period using OFDMA compared to the 7th time period with OFDM. There is a bit more signaling required for OFDMA in terms of link overhead, but the benefits, especially when user devices are sending short bursts of traffic (typical for interactive applications, or even voice/video conferencing), outweigh these significantly. Having parallel transmissions, as opposed to consecutive transmissions enables much lower latency which brings benefit to all services. A 75% reduction in latency is possible with Wi-Fi 6, due to OFDMA operating in both the DS and the US. Coexistence with Wi-Fi 5, where the traditional airtime access procedure (EDCA access) is present can be challenging, but through effective management of the EDCA minimum contention window (W_0) and maximum contention stage (m), controlled access between Wi-Fi 6 and Wi-Fi 5 devices can be achieved.

Wi-Fi 6 also supports up to 8 spatial streams, (Wi-Fi 5 offered it already but was rarely implemented) along with Multi User (MU)-MIMO. Most Wi-Fi clients include 1 or 2 spatial streams, so with an 8x8 AP, it will be possible to service 4 such clients at the same time using MU-MIMO, delivering gigabit speeds to each device. DL MU-MIMO is a mandatory feature of Wi-Fi 6 certification. Depending on the location of an AP relative to clients within a home, the use of MU-MIMO can really improve networking performance. Note that MU-MIMO is very effective at short to medium ranges, while OFDMA is effective at all ranges, short, medium and far. Also note that MU-MIMO is also available for 2.4GHz band, something that was not part of the Wi-Fi 5 standard. And finally note that it is possible to operate OFDMA and DL MU-MIMO together, identifying different users to different spatial streams while also using OFDMA to offer partial bandwidth to users on the same spatial streams.

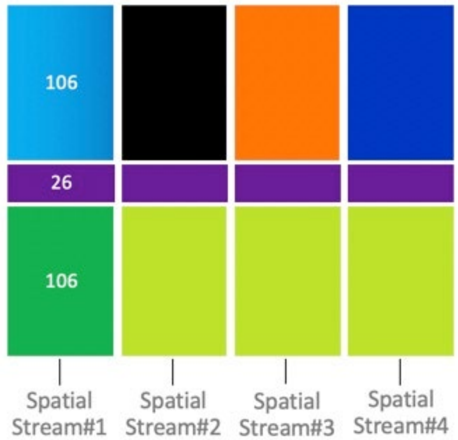


Figure 13 - DL MU-MIMO + OFDMA

The above figure shows how DL MU-MIMO and DL OFDMA can be put to good use, enabling 7 different users to receive data within the same transmission period. One user (in light green) received 3 separate RUs (106 sub-carriers each) from 3 different spatial streams, 5 other users got individual 106 sub-carrier RUs, while 1 user got 4 separate 26 sub-carrier RUs, one from each spatial stream. With increasing bandwidth to 160MHz, operating with a 4x4 setup, OFDMA+DL MU-MIMO will really improve network performance.

Decision points on Wi-Fi 6 introduction

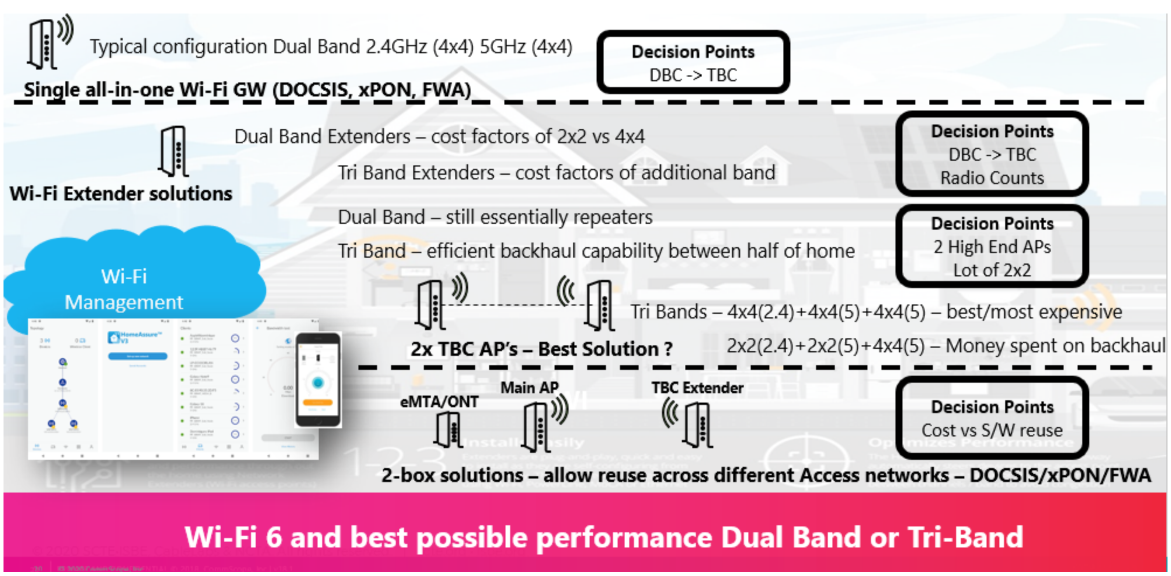


Figure 14 The decision points for Wi-Fi 6 introduction

From a service provider perspective, the introduction of a Wi-Fi 6 AP brings performance benefits even for previous Wi-Fi generations due to the hardware design improvements, including range and rate.

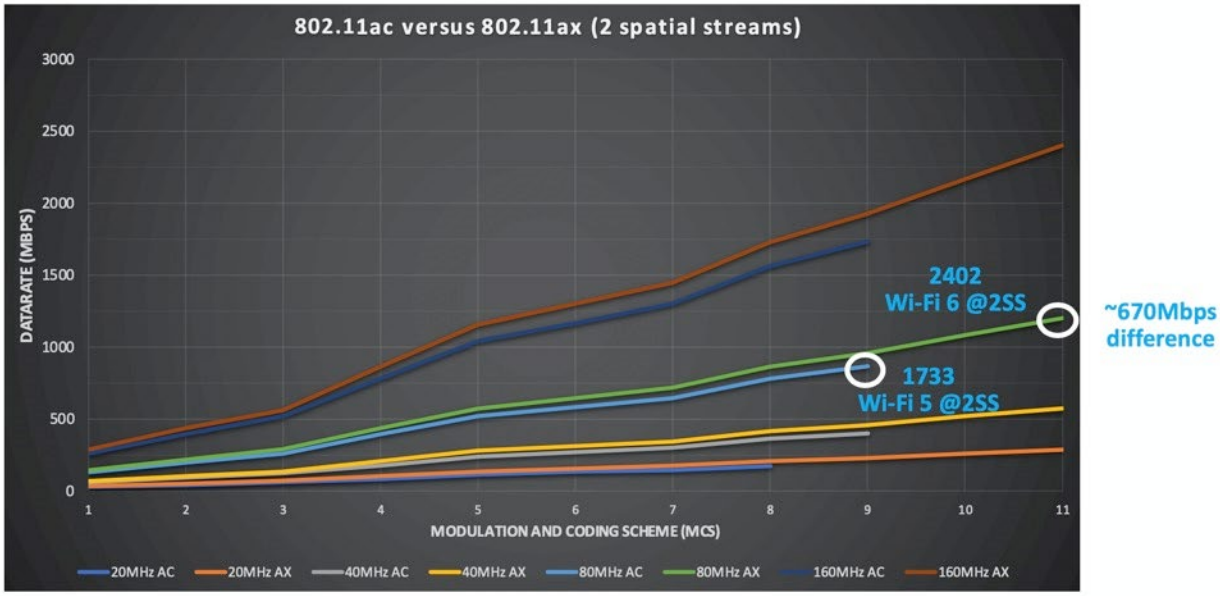


Figure 15 - Wi-Fi 5 vs Wi-Fi 6 2x2 Client Performance Capability (Mbps)

The real benefits are only realized when new Wi-Fi 6 non-AP STAs (devices) are added, such as service provider supplied STBs/SMDs and mesh extenders, or consumer owned mobile devices (phones, tablets) or media streamers (smart TVs, Amazon fire, etc.). The mix of Wi-Fi 6 APs matched with Wi-Fi 6 devices enables all the new technology features in Wi-Fi 6. See below the performance of

- AC only AP with an AX STB client – showing improved performance at range of the AX client with the AC AP
- AX AP against AC and AX STB – showing improved performance for both

CommScope recommends that future STB should use 2x2 instead of 4x4 to get the performance needed at lowest cost points and lowest thermals.

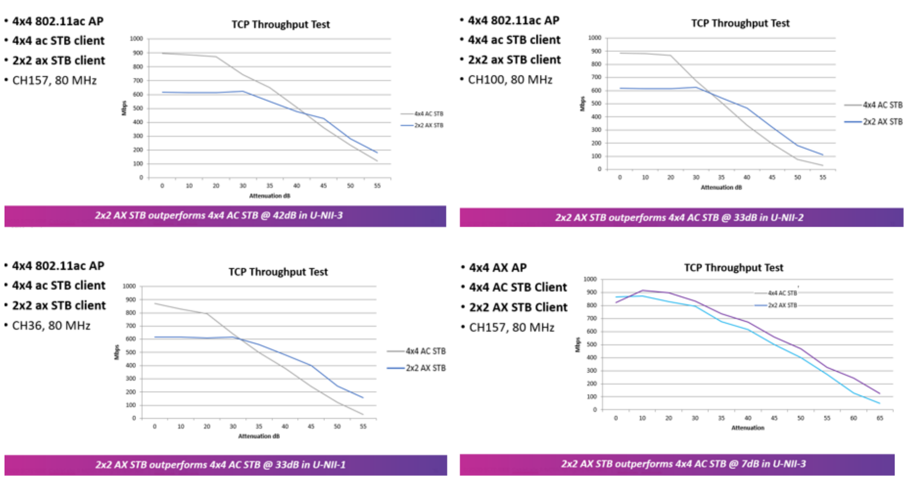


Figure 16 - STB client performance showing 2x2 Wi-Fi 6 outperforming AC 4x4

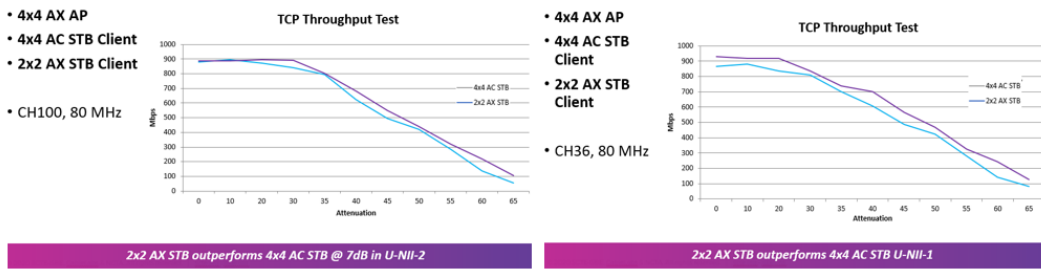


Figure 17 - STB client performance showing 2x2 Wi-Fi 6 outperforming AC 4x4

STB devices with Wi-Fi 6 will work extremely well with Wi-Fi 6 APs, bringing better overall experience to subscribers from greater range as well as more reliable service. Wi-Fi Extenders used to add coverage throughout a subscriber home will also benefit, especially due to the lower latency provided by Wi-Fi 6, which becomes very important when data has to bounce from the AP to the Extender, and then from an extender to a Wi-Fi device.

The ability to use OFDMA for serving AP connected devices and extenders in parallel cuts latency significantly when serving devices connected to extenders, as any queued traffic can be sent at the same time. Multiple hops back and forth through extenders all increase latency, which then has a knock on effect on the throughput devices can achieve – lower the latency and throughput increases, enabling adaptive streaming protocols like DASH/HLS/etc. used by STBs to operate at higher display resolutions, etc., giving a better quality of experience to the end subscriber.

4. Setting the stage for Wi-Fi 7 entrance – Wi-Fi 6E

The available spectrum used in Wi-Fi 6 is the same as Wi-Fi 5, and is limited to long standing 2.4 and 5GHz regulatory bands defined by the FCC, which covers about 400MHz of spectrum. Recent changes by the FCC, after many years of discussion between industry and regulatory stakeholders has led to the opening up of the 6GHz band offering up to 1.2GHz of additional spectrum for unlicensed usage, with Wi-Fi being one of the key benefactors of this spectrum. This effectively quadruples the spectrum available for Wi-Fi. To help differentiate the use of the 6GHz spectrum Wi-Fi Alliance have coined the term “Wi-Fi 6E” to identify Wi-Fi 6 devices capable of operating in this “Extended” 6GHz spectrum.

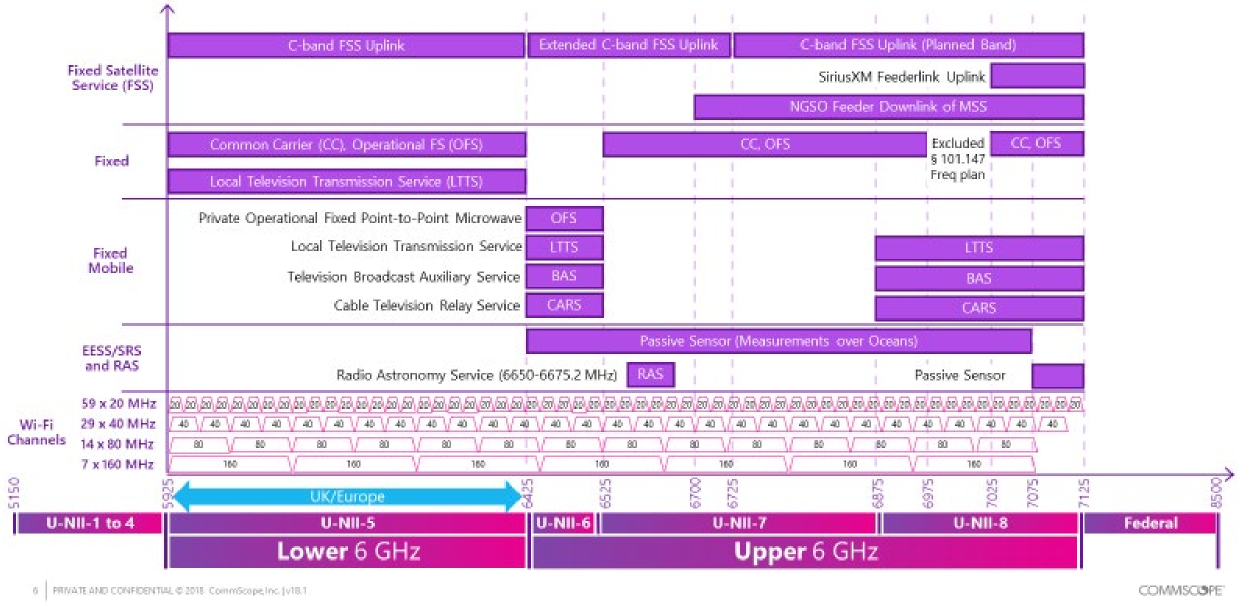


Figure 18 - US 6GHz spectrum and channel allocation to Wi-Fi

This extra spectrum will enable Wi-Fi innovation for decades to come, and some reports indicate it will add over $183B to the US economy by 2025, with Wi-Fi equipment sales being $1.54B of that figure. A key element of the use of 6GHz is the displacement of the need to adopt 5G cellular connections for high speed wireless access, leading to significant cost savings of over $54B by enterprise customers (note that this may be impacted by consequences of COVID-19). With the extra spectrum capacity, Wi-Fi has room to grow, and most users of Wi-Fi would likely stick with Wi-Fi than need to switch to a completely new 5G architecture, be it licensed or unlicensed.

One of the biggest drawbacks with Wi-Fi has been the lack of available spectrum to enable the HW capability of Wi-Fi 5 and Wi-Fi 6 APs that offered 80 and 160MHz channels. The existing spectrum enabled a maximum of two 160MHz channels, which typically required a TBC (Tri Band Concurrent) AP enabled with two 5GHz radio lineups. However constraints in the spectrum related to DFS/Radar access meant that it was often not possible to get that capacity, and APs were limited to using the available 80MHz wide channels (additional constraints relating to overlapping Wi-Fi APs in dense spaces also meant that 160MHz channels were difficult to operate due to interference).

	2.4 GHz	5 GHz	6 GHz
Available Spectrum	85 MHz	480 MHz	1,200 MHz
20 MHz	3	25	59
40 MHz	2	12	29
80 MHz	0	6	14
160 MHz	0	2	7
320 MHz	0	1	3

Figure 19 - Channel Availability over Spectrum

The 6GHz spectrum that the FCC has released has the capacity to support 7 additional 160MHz channels in addition to the existing roughly 400MHz of capacity in 2.4 and 5GHz. A single 160MHz Wi-Fi 6 channel can support up to 9.6Gbps (when using 8 spatial streams), meaning that the 6GHz band can offer over 67 Gbps (7 * 9.6 Gbps) of additional bandwidth.

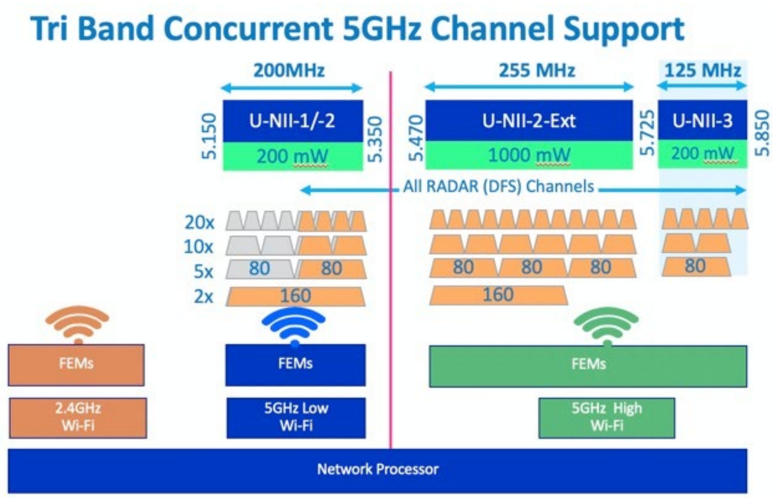


Figure 20 - TBC 2.4+5GHz AP

The 1.2GHz of spectrum in 6GHz was already categorized by the FCC into 4 separate bands, that were aligned to the various requirements of existing incumbent users. In order to operate in this new spectrum, APs either have to lower their operating power or work with a spectrum supervisory service

Wi-Fi 6e builds on top of Wi-Fi 6 to enable operation in the 6GHz spectrum, identifying the necessary controls around how the spectrum is channelized and various performance limits. Channel access details are also included to ensure a common set of rules around how 6GHz APs and devices can use the new spectrum. Wi-Fi 6e will be limited to the current performance outlined in the Wi-Fi 6 standard (which is 9.6Gbps).

The following diagram outlines the UDP rate over range/attenuation for a 4x4 AP to a 4x4 Client (typically a backhaul application on a 6E mesh solution). This is done at the current 5dBm/MHz PSD approved by the recent FCC Low Power Indoor specifications. **Note – all the Throughput/Attenuation plots in this paper assume perfect signal, with no noise and no co channel interference. They also show just Tx potential only and don't take into account factors like the Wi-Fi beacons which transmit in 20MHz channels and at 18dBm EIRP. So, the actual performance will be somewhat poorer than illustrated. Unless otherwise stated as a specific test for different client configurations assume all plots are just theoretical best case from AP for illustrative purposes.**

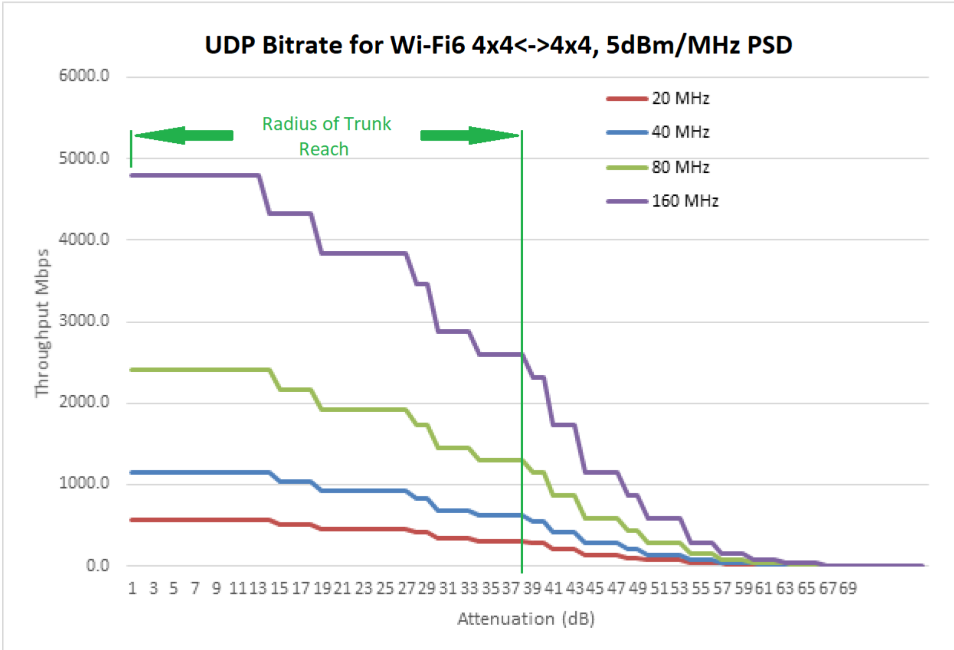


Figure 21 - 4x4 to 4x4 Wi-Fi 6E performance at 5dBm/PSD - LPI specification

In addition to the Wi-Fi Alliances efforts on enabling access to the 6E spectrum using Wi-Fi, one of the main questions affecting equipment vendors is how to create cost effective hardware that addresses the existing 2.4 and 5GHz landscape while also offering the benefits of 6GHz

Current TBC designs that operate two 5GHz radio lineups (5GHz Low (UNII-1 and UNII-2) and 5GHz High (UNII-2 Extended and UNII-3)) need additional filtering and power in order to provide the best performance. Operating two transceivers with just 160MHz of separation has required considerable isolation filtering to ensure that as one transceiver transmits at a high power that the other transceiver can receive signals from connected devices. The filtering adds cost to the standard design. Another constraint is that some Wi-Fi devices limited themselves to only operate in non-DFS channels, which is an 80MHz wide part of the 5GHz Low spectrum, meaning that this part of the spectrum must be supported.

Including a separate dedicated 6GHz only subsystem into an AP is possible from an engineering standpoint but adds additional cost to a product that may see limited initial 6GHz use while waiting for new devices to appear. Such a solution may also increase the industrial design/enclosure size beyond what would be acceptable for a home Wi-Fi AP format factor, as it is likely there would be 15 radios and associated antenna (3+4+4+4) for the 4 different bands to be supported. Such a unit is unlikely at this point in time. The simplest and likeliest deployment of 6GHz is to offer a tri-band that supports 2GHz+5GHz+6GHz. The tradeoff as discussed is the additional complexity of supporting U-NII1/2/3 in the 5GHz band and the initial relative little use of the 6GHz radio with the sparsity of 6E clients in the home.

Options are being considered as to what makes the best combination of low cost and flexibility for radio operation across the 5/6GHz space. Note that flexibility in terms of switching between filters and radio lineups unfortunately has a knock on effect on the total output power, as signal losses creep in as a result of passing signals through switch banks that enable such flexibility. Switching solutions overall also significantly increase the cost of the AP so for the moment its unlikely that Cable Operator devices will add 5/6 switching on the radio. Additionally, the decision as to when to switch a radio to use either 5GHz or 6GHz is also complex. Manually switched based on a consumer or Cable Operator policy or some algorithm based on some intermittent sampling of the 6GHz capabilities of the home 6GHz client arrivals. The following diagram illustrates the complexity of trying to support a Tri-band that can

- Switch between all U-NII1/2/3 bands on 2 chains
- Switch between 5GHz and 6GHz
- Support the Filtering required for 5/6GHz and within the 6GHz channel plan

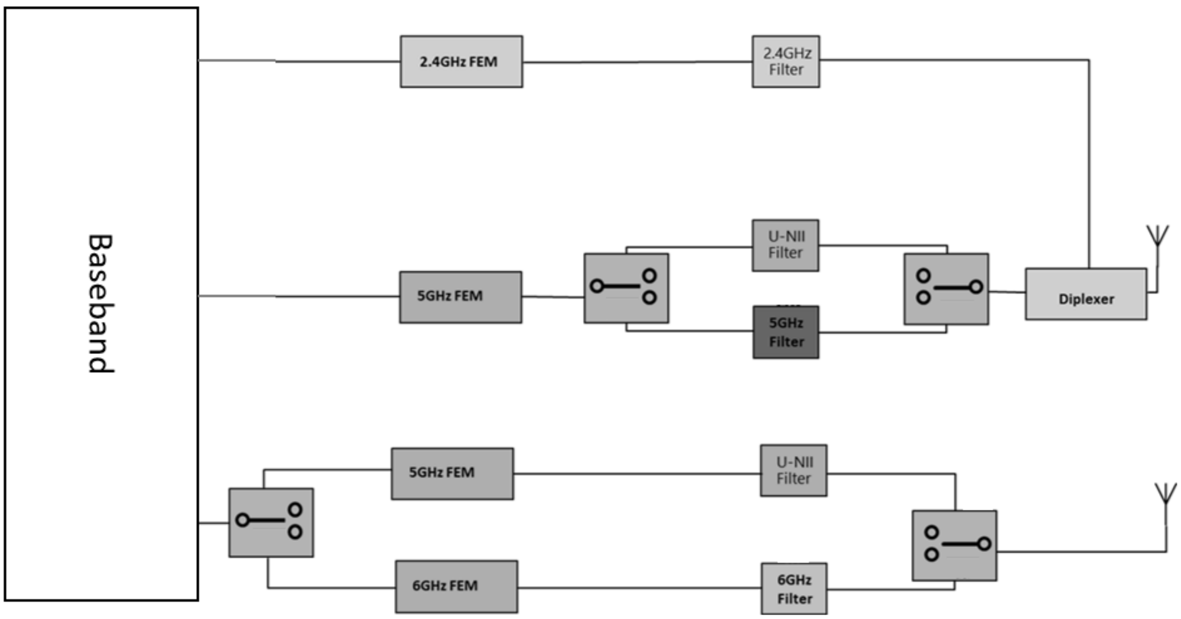
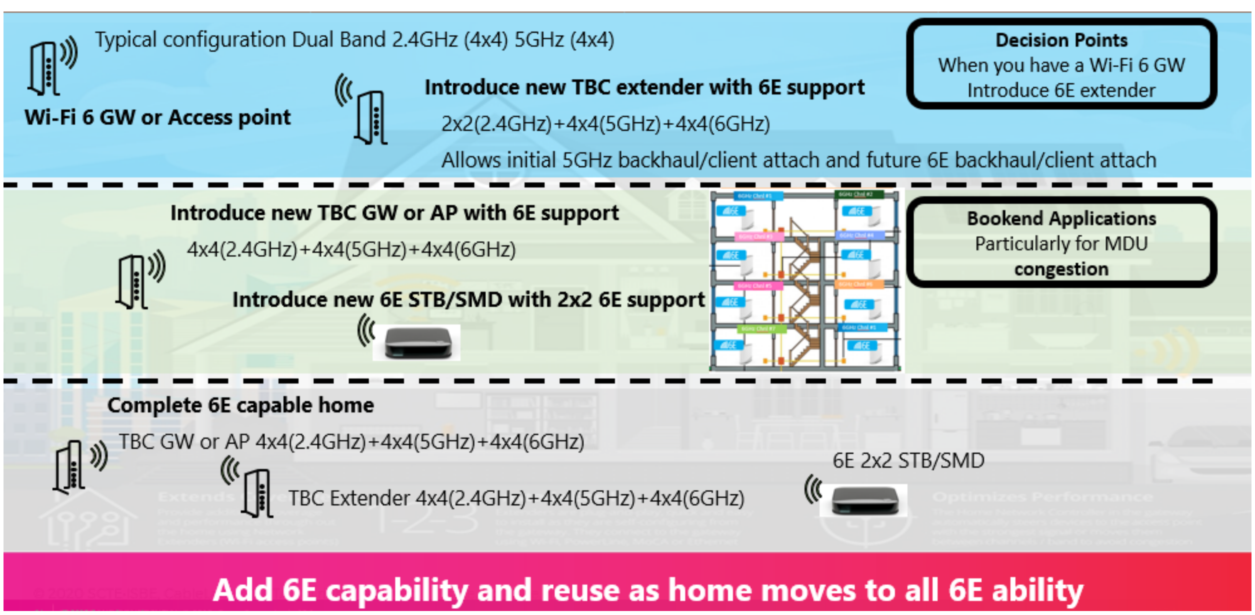


Figure 22 - Switchable 5/6 designs will bring in cost and complexity levels that may not be acceptable to Operator cost points



The 5GHz High spectrum is closest to the new 6GHz spectrum, so there is some interest in having a TBC AP design that continues to offer 2.4 and 5GHz Low and mixed 5GHz High and 6GHz support. This appears like a good tradeoff, but a key drawback with this approach is that the 5GHz High spectrum that is subject to DFS is also a part of the spectrum that enables greater radio output power (1W compared to 200mW in the other 5GHz Low spectrum). Using a mixed 5GHz/6GHz option means that once a single 6GHz device associates with the AP, the 5GHz High spectrum is no longer available as the AP has to switchover to 6GHz.

A lot of recent AP designs have incorporated Wi-Fi 6, and are either being deployed or going through the final stages of acceptance testing in service provider labs. Obviously, service providers want to keep in step with technology choices, but struggle with the economics and operational headaches of deploying a new Wi-Fi 6E AP so soon after launching their Wi-Fi 6 AP. To overcome this issue and enabling the adoption of 6GHz, one approach is to use 6GHz adapter devices. Ethernet (either 1Gbps or 2.5GBps) is used to connect to these new 6GHz adapters. Such an option is not unique, as pre-standard Wi-Fi 5 video bridge adapters were deployed by many operators in the past to provide whole home HD video streaming over Wi-Fi to ethernet connected IP STBs.

Figure 23 - ARRIS VAP2400 Wi-Fi Video Bridge

This approach relies on one adapter being connected to the main AP, configured to create a new 6GHz Wi-Fi network that other devices connect. These 6GHz adapters enable the adoption of 6GHz within the home, either to act as a 6GHz Wi-Fi backhaul to existing extenders in the home, or to enable subscriber devices take advantage of the high speed, low latency wireless connectivity over 6GHz back to the main AP. No change is required on the existing home devices, apart from using Ethernet to connect to the adapters. USB is also a possible interface (offering both a data/control path as well as bus powering).

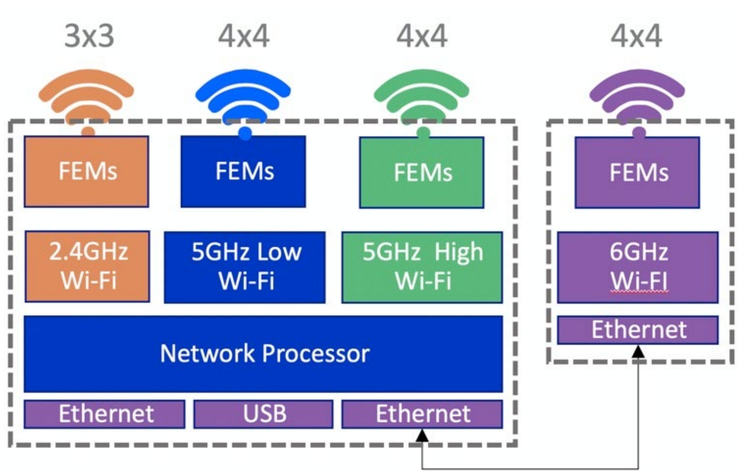


Figure 24 - External Wi-Fi 6E dongle for existing GW

This also brings up the question of the effective relevance of the 2.4GHz radio. With its primary purpose today as

- Supporting low cost devices like cameras and IoT devices
- Providing the comfort of connectivity at range particularly in single AP homes without meshing systems extending 5GHz particularly.

But given the sheer capacity of the spectrum shift now to 6GHz which has only 80MHz – 450-600Mbps vs 66Gbps capacity in the 6GHz band with 8 spatial streams and the Wi-Fi 7 standard even allowing for 16 spatial streams – what role does 2.4GHz have going forward in the home Wi-Fi ecosystem. Should we now look to

- Have a single point in the home for 2.4GHz AP for legacy devices and to support 2MHz channel IoT capabilities built in the Wi-Fi 6 standard for up to 4 times more range on narrow carriers.
- Focus a 5GHz and 6GHz solution on the high capacity single AP across the home or the multiple mesh APs – for maximized use of higher capacity bands and take every opportunity to reduce any effect on 5/6 designs that 2.4GHz drags in and see can we
    - Lower gate counts in silicon
    - Not having to trade off antenna placement for best 2.4GHz and 5GHz on the same antenna
    - lower costs and reduce thermals

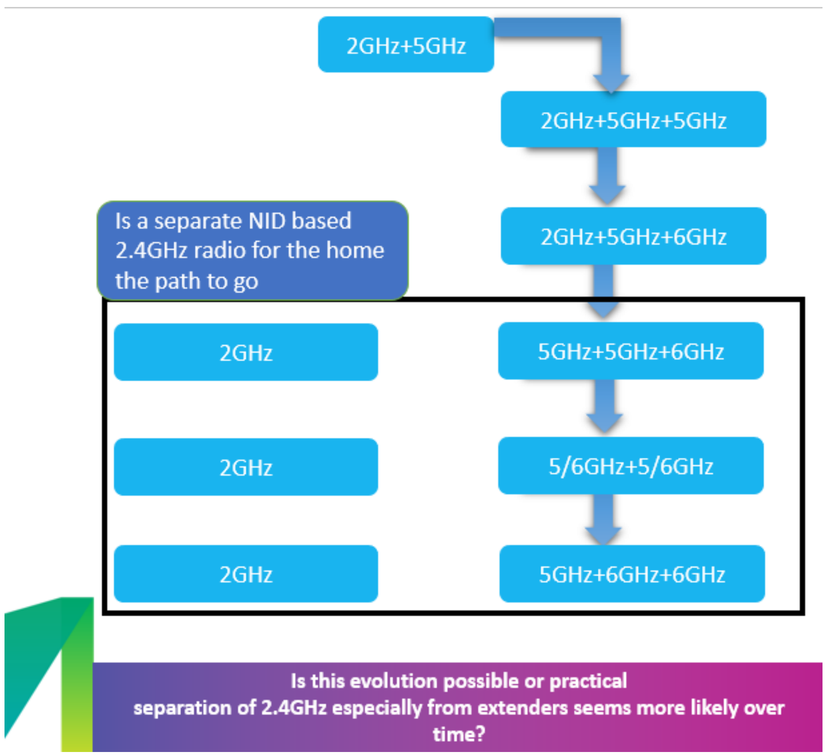


Figure 25 - Can 2.4GHz be separated from the Wi-Fi mesh 5/6/7 devices in some future architecture

It may take until Wi-Fi 7 is introduced to relook at the grouping of 2.4GHz the 5GHz U-NII-1/2/3 bands and the U-NII5/6/7/8 bands for optimal architectures in the home based on the evolution of FEM and

Filter technology to try and ensure the best possible designs to address the widest frequency range in the smallest form factor package.

This idea may not have a lot going for it, but in some ways the other 2.4GHz wireless systems, such as Bluetooth and Zigbee, putting all of these together into its own AP package may make sense for optimal coverage given that 2MHz use of 2.4GHz , Zigbee and BLE would have similar ranges from the same location of this 2.4GHz AP as illustrated below

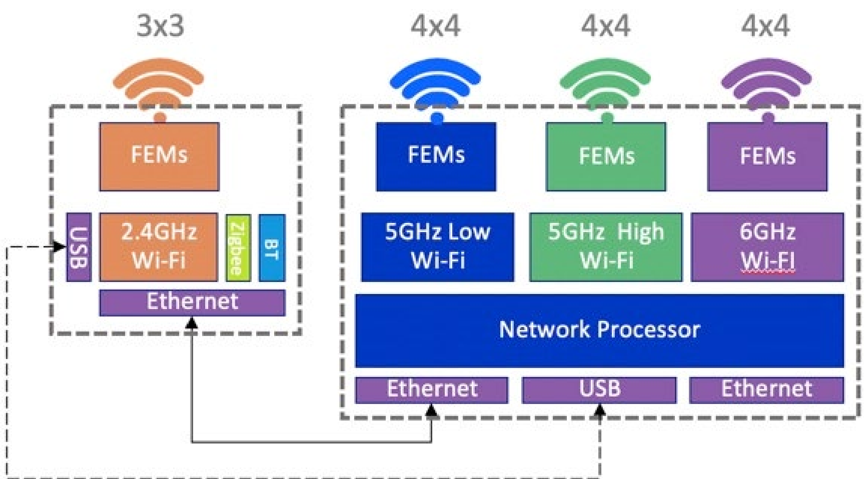


Figure 26 - Add 6GHz to AP, but extraction all 2.4GHz Radios

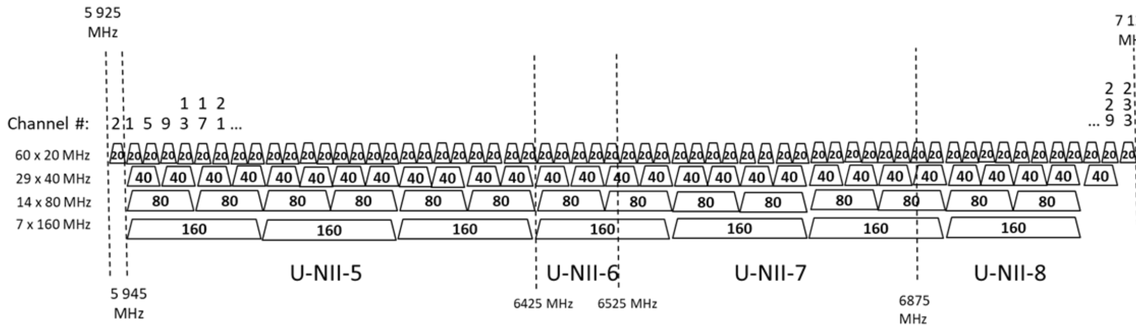
5. Low Power Indoor Mode to AFC controller Standard Power

Some of the FCC rules about 6GHz operation are specifically about power levels that APs can use when operating in the band. Serious consideration was given to the coexistence of future unlicensed operation of Wi-Fi devices and the incumbent 6GHz users (mostly Microwave links, Fixed Satellite Services (FSS), Cable TV relay and Broadcast services). This has led to various compromises about acceptable power limits across the different UNII bands.

A Low Power Indoor (LPI) only power level applies across the entire 6GHz band (from the bottom limit of UNII-5 to the upper edge of the UNII-8 band). This corresponds to a Power Spectral Density of 5dBm/MHz EIRP. For a 20MHz channel this is 18 dBm, while a 160MHz channel is allowed 27 dBM. Note that LPI APs can ***only*** operate indoors, and the FCC rules have very explicit limitations for such operation, as follows.

- Low-power APs can’t be weather resistant, preventing them from being installed outside permanently;
- Low-power APs can only have integrated antennas and it is prohibited to provide the capability of connecting other antennas to the devices;
- Low-power APs can’t be battery operated;
- Low-power APs must be clearly labelled with a notice that states that “FCC regulations restrict operation of this device to indoor use only.”

From a 6GHz regulatory perspective in the US the following is in play to try and number the potential channels in the 1.2GHz of 6GHz as well as define which channels and bands can be used for Standard Power under AFC control.



Operating Class	Channel width	Channel #s
131	20 MHz	1, 5, 9, ..., 221, 225, 229, 233 (as shown above)
132	40 MHz	3, 11, 19, ...
133	80 MHz	7, 23, 39, ...
134	160 MHz	15, 47, 79 ...
135	80 MHz (for 80+ operation)	7, 23, 39, ...
TBD	20 MHz (at 5925 MHz)	2 (only)

Figure 27 - Current potential channel numbering scheme for U-NII5 to U-NII8

Standard Power (SP) is a higher output power that APs can also use but under very strict conditions. Such power levels are only applicable to UNII-5 and UNII-7 bands (comprising 850MHz of the total of 1.2GHz of spectrum). SP operation is subject to a spectrum supervisory service called Automated Frequency Coordination (AFC). The AFC system relies on the AP reporting its geographical location to the AFC to identify any incumbent systems in the area, and what frequencies those systems may be using. The AFC will make a decision if Wi-Fi 6E operation is allowed by the AP, and if so, will identify the exact list of frequencies and power limits that apply. The AP must repeat this exchange with the AFC on a regular basis, as the data that the AFC relies upon may receive dynamic updates relating to existing or new 6GHz users that could impact the APs use of 6GHz. This approach will enable coexistence with the incumbent users of this spectrum. 320MHz channels are now part of the IEEE802.11be initiative and there is no final answer yet. The only 2x160MHz channels that fit in U-NII band is U-NII-5. There is also some opportunity to put 320MHz channel in U-NII-7 but as its mis-aligned in the current 160MHz allocation discussions are ongoing how this could be managed

Once an AP is enabled and compliant with the AFC system it is allowed operate outdoors as well as at the higher power level of 36 dBm EIRP for all channel bandwidths. This is a key enabler for outdoor APs, as well as potentially enabling higher indoor powers. As an industry we are still working through the architectures and process to be able to give location to an Indoor AP particularly and there are various mechanisms being considered that are trying to exclude the use of any additional GPS cost burdens on the AP. The frequency of the AP having to check with the AFC is also another part of the equation to try and create a cost efficient but friendly solution to incumbents. More on this area as the decisions unfold.

6. Wi-Fi 7 and the 320MHz channel what does it mean for the home

The current highest speed possible with 802.11ax on a 160MHz wide channel is 1.2Gbps per spatial stream. Using the typical allocation of 4 spatial streams ~4.8Gbps can be realized and with the maximum of 8 spatial streams in MIMO, this can enables a maximum data rate of just over 9.6Gbps, and this requires both the AP and client device to support 8x8 operation. The IEEE802.11be is now proposing to add the following features to the Wi-Fi 6E specification

- 320MHz and more efficient utilization of non-contiguous spectrum
- Multi-band/Multi-channel aggregation and operation
    - Multi-Link Operation - MLO. Arguably one of the most important features from a pure BW or latency perspective. MLO also ties together the important of 2.4GHz, 5GHz and 6 GHz frequencies and bands as you can utilize all or any combination of the bands
- 16 spatial streams and MIMO protocols enhancements
- Multi-AP coordination (e.g. Coordinated and Joint Transmission)
- Enhanced Link adaption and transmission protocol (e.g. HARQ)
- Adaptation to regulatory rules specific to 6GHz spectrum
- Refinement of 802.11ax features

If there are two clear 160MHz channels in 5GHz, and an AP supports 8x8 for both 5GHz Low and 5GHz High, the can allows for up to 19.2Gbps of capacity at just 8 spatial streams. In the next version of the Wi-Fi standard, 802.11be, the primary feature that is being added is the ability to use a 320MHz channel and to increase the spatial streams to 16 for the current 8 in Wi-Fi 6. This fundamentally then creates a unique platform to feed the new low latency and future high bit rate services. In the US with the entire 6GHz spectrum being 33-66Gbps of capacity it creates a fundamental platform for low latency and high capacity services. This paper is not going to outline these services but for example LighField TV at 8K levels comprising 43 or more planes of video at 8K rates can reach well above 2Gbps levels. If you look at products from Looking Glass (www.lookingglassfactory.com) you will see 'holographic' LightField TV solutions giving 'no glasses required' immersive viewing experience and showing real depth and volume. Solutions like Wi-Fi 7 and Wi-Fi 6E will enable these solutions to be un-tethered from Ethernet interfaces at 2.5GBE and even 10GBE.

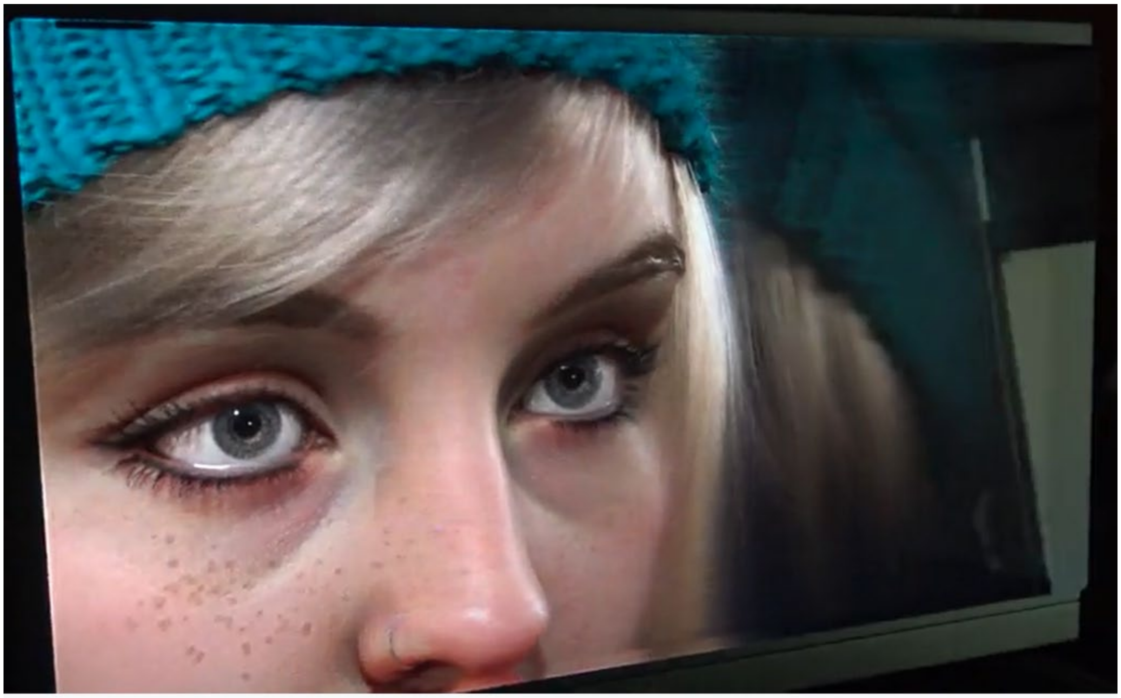


Figure 28 - Immersive display on the LightField Video Looking Glass display at 8K levels

If we look at the current FCC specification for 320MHz channel usage in the 6GHz band, the power level has been set to 30dBm for the 320MHz channel. With 30dBm at 5dBm/MHz the following performance levels can be expected. You can see below the performance of both 8x8 and 4x4 in the UNII-5 band with 30dBm. Performance levels are substantially improved with Airtime throughput over range and offer the potential of really good whole home coverage from a single GW/AP for all but the largest of homes in the US. Can we realize the following architecture for Wi-Fi 7 – with single high performance AP driving Gbps across the home. Up to 20Gbps could be realized with an 8x8 device with 8 spatial streams.

Figure 29 - Basic single 30dBm - 8x8 or 4x4 Cross Home Wi-Fi 7 Architecture

This single 1W 8x8 device with only 8 spatial streams providing cross home Gbps speeds driving opportunity again for single AP and no ethernet wire solutions for homes in the 2600sqft to 5,000sqft range. The rates range close to theoretic 20Gbps at the AP to maintaining a Gbps to 54dB of attenuation.

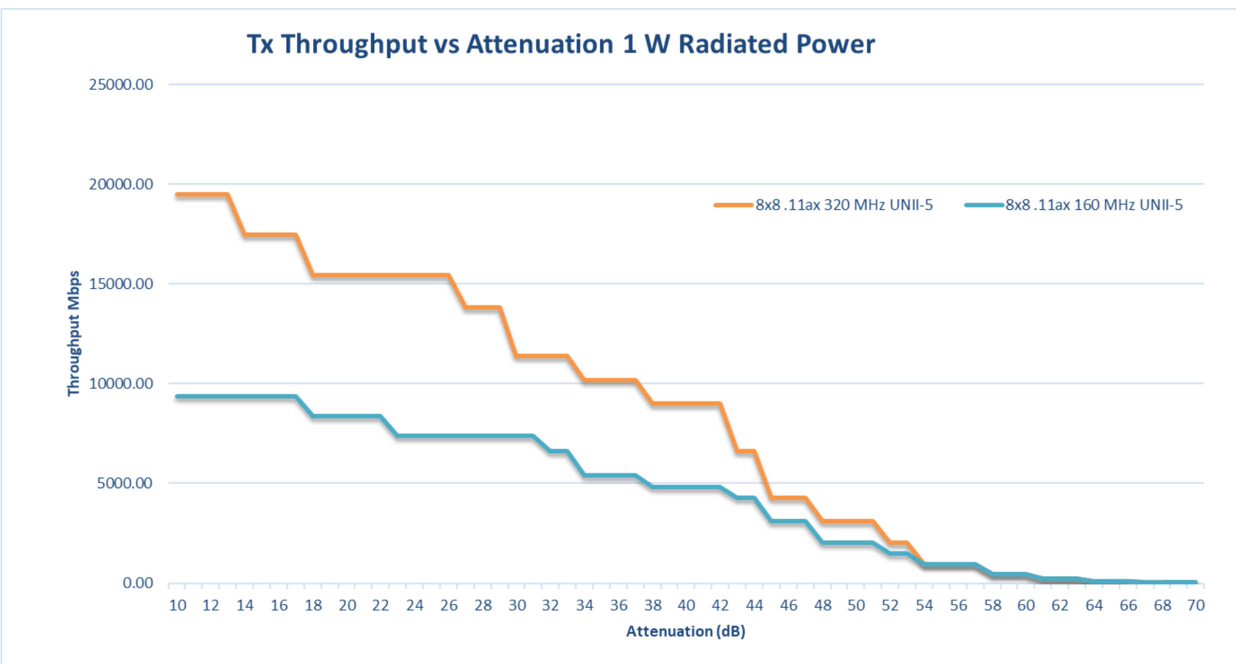


Figure 30 - 8x8 AP/GW at 30dBm in both 320MHz and 160MHz channels

Even for a 4x4 the potential for high performance across the home is high with a Gbps of throughput potential even at 55dB of loss and theoretically ~9Gbps at the Access point.

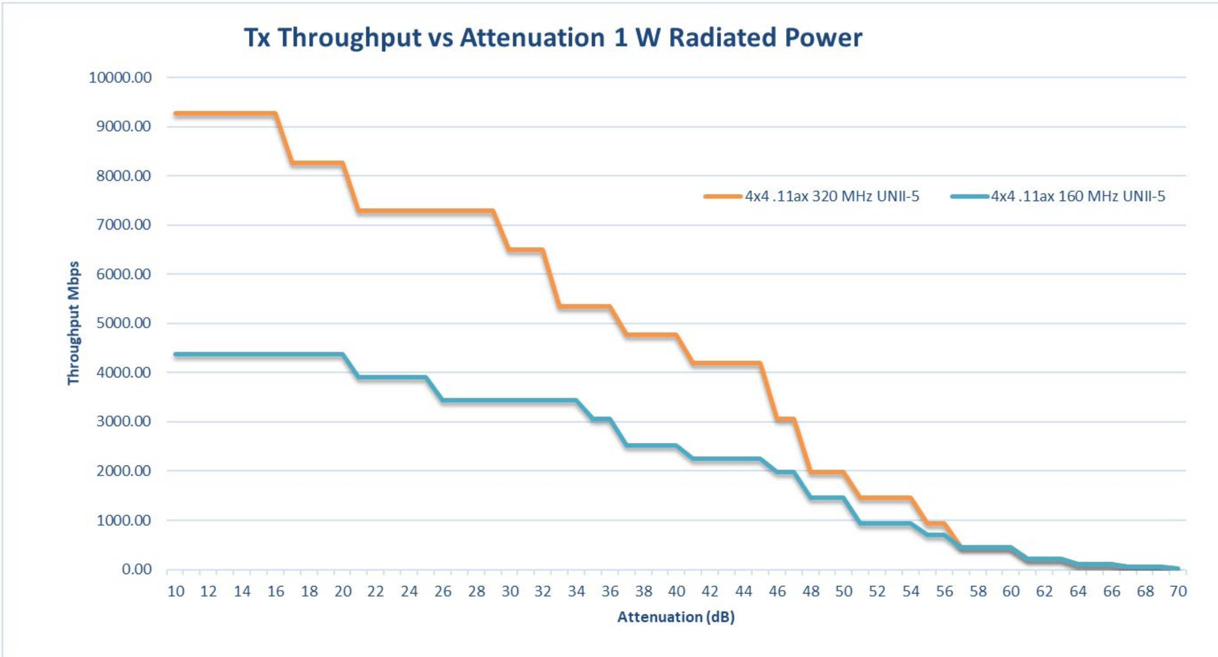


Figure 31 - 4x4 performance at 320MHz and 160MHz at 30dBm

As AFC standard power currently allows for higher power solutions outside – if we were to have approvals for 33dBm/2W Radiated power in a solution its performance over attenuation would improve as defined in following graphs.

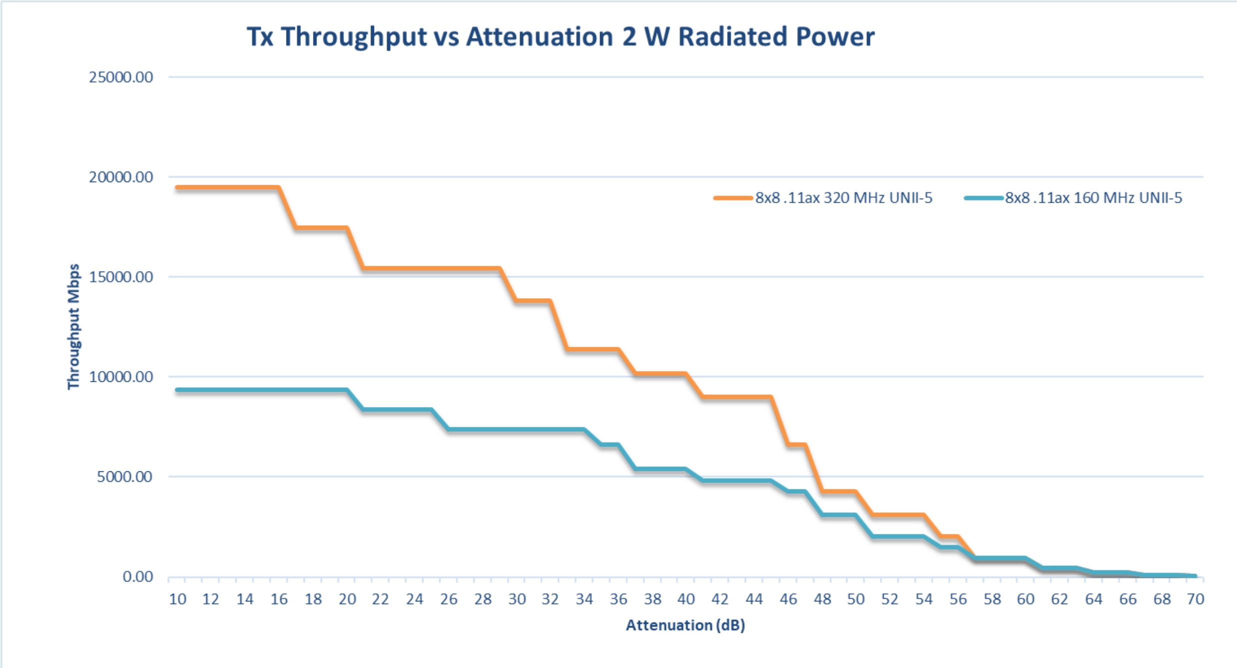


Figure 32 - 8x8 performance of 320MHz and 160MHz at 2W radiated Power

At 33dBm GBps speeds would be maintained to almost 54dB attenuation.

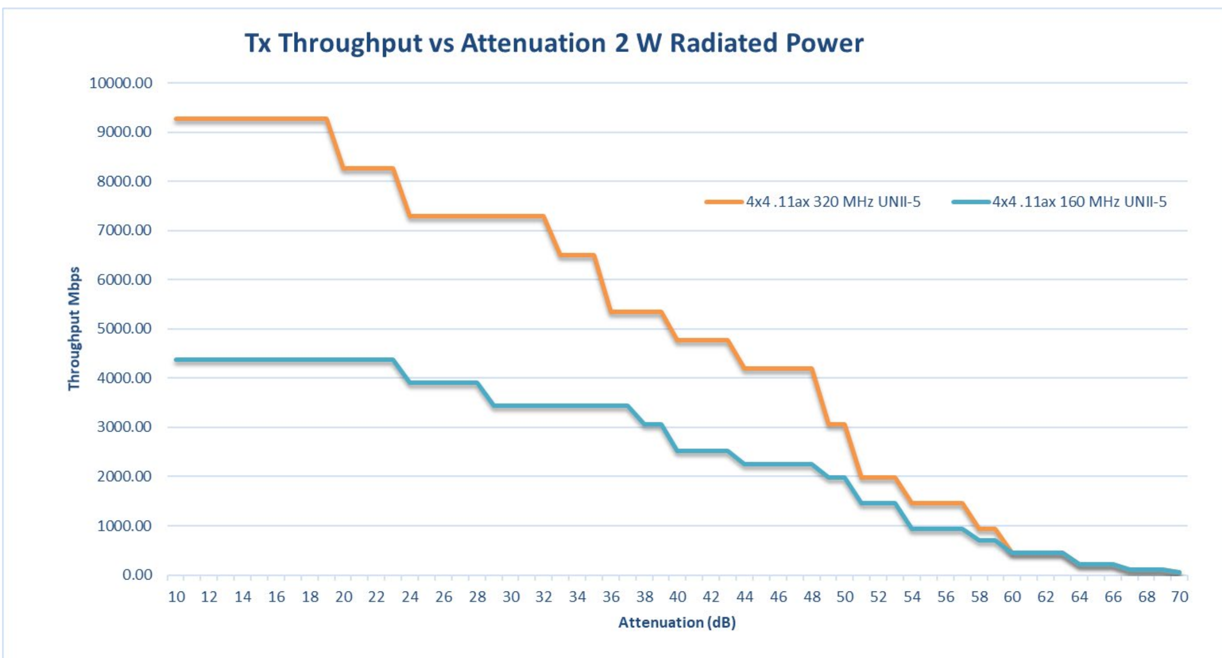


Figure 33 - 4x4 performance of 320Mhz and 160MHz at 2W radiated Power

Even 4x4 and 4 spatial streams would support Gbps speed to 53dBm attenuation.

However, there could be even more performance for Wi-Fi if we consider the room vs the home. With 6GHz spectrum we have the potential to create an intra room AP backbone using one 320MHz and an inter room 160MHz channel all using different spectrum and potentially to optimal single use levels particularly for larger homes.

If we assume, we want to bias more to 6GHz capable devices in some future scenario

- One primary home AP providing 320MHz cross home 8x8:8 (20Gbps) or 4x4 (10Gbps) at 30dBm.
    - Wi-Fi 6E/7 capable clients can attach to this AP, but its primary role is providing intra room Backhaul
    - The device could also offer 5GHz and 2.4GHz support as well
        - 4x4(2.4GHz) + 4x4 (5GHz) + 8x8 (6GHz) or 4x4(2.4GHz) + 4x4 (5GHz) + 4x4 (6GHz)
- In Room (potentially 4 other 160MHz channels that can be used – 4 rooms) that have a dual or triband
    - This device could be a triband 4x4 (5GHz inroom) + 4x4 (6GHz in room) + 4x4 (6GHz backhaul)
        - Could potentially even use 25mW VLPI mode for in Room LAN to create smaller form factor and lower thermals. Device could potentially adapt power to the room conditions and increase output power with appropriate PA designs.

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Figure 34 - Performance of VLPI in room potential low power solution

    - In room clients would also reduce uplink power to connect with these in room AP
    - The device could offer additional radios for 2.4GHz and 5GHz as well as 6GHz as backhaul

Figure 35 - Wi-Fi 7 backhaul - Wi-Fi 6E in room - Ultimate Home Wi-Fi ?

This is simply illustrated below with 3 in-room AP's using different in Room 160MHz channel to the 320MHz backbone channel across the home.

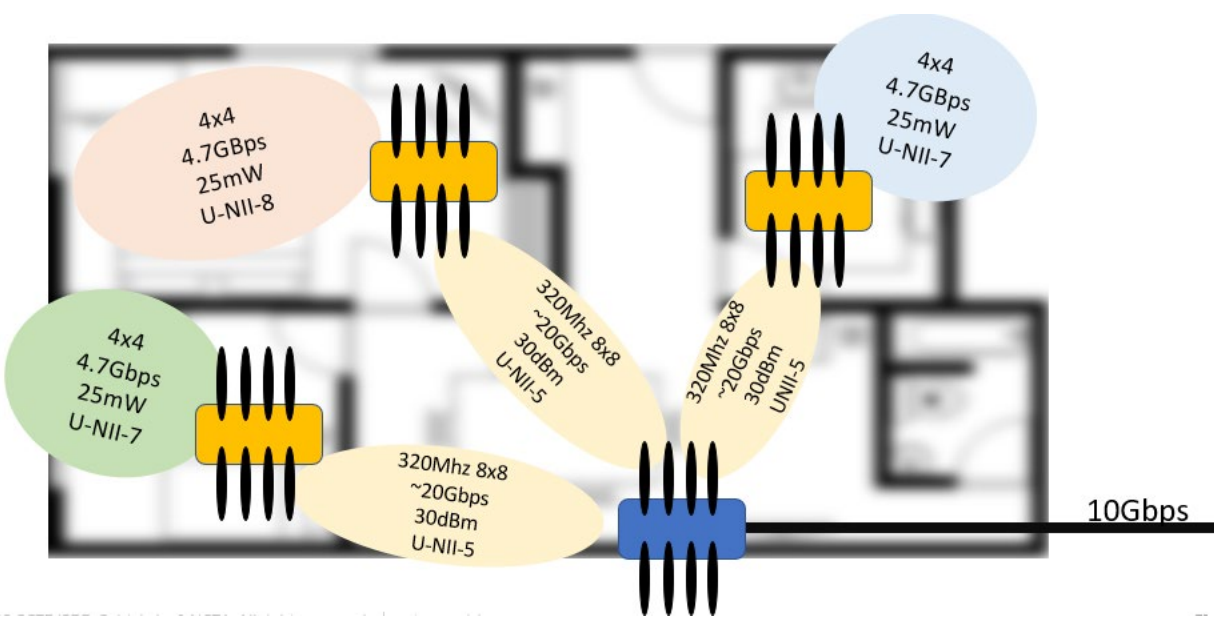


Figure 36 - use of Wi-Fi backbone and in room 4.7GBps networks

What would such an architecture be used for and what does 4.7GBps of in room clean Wi-Fi drive for new platform for applications and services. We are still trying to figure that out – but having this new bandwidth will accelerate more immersive video services and potentially drive applications like lower latency VR bandwidth to Wi-Fi 7 capable HMDs using lower power Wi-Fi to make the connection in room, increase battery life of HMD and reduce Heat in the device.

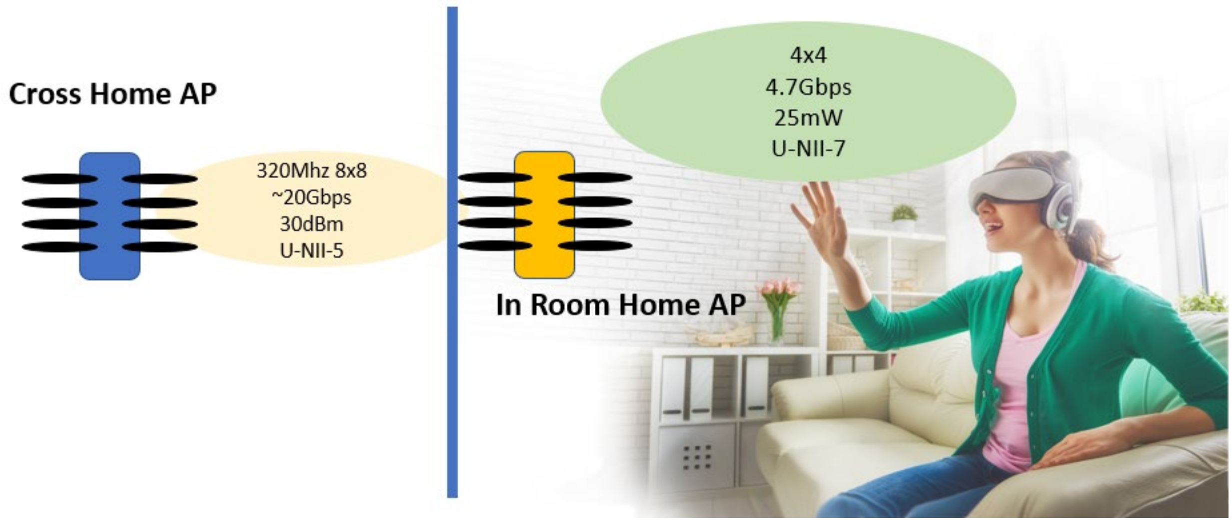


Figure 37 - Wi-Fi 7 and Wi-Fi 6E - driving high capacity low latency services

Additional services with lower decoding or encoding time for latency sensitive video could emerge and certainly the bandwidths supported in 6GHz allow for wireless HDMI services for the first time on Wi-Fi above 4K or even 8K levels with the full 16 spatial stream capabilities that 802.11be is driving.

The above architecture is a North start where we can take this new home Wi-Fi capacity. Challenges exist to continue to

- Make the solutions cost effective for the masses vs the minority of home budgets
- Keep the size and thermals in check – as the ergonomics of Wi-Fi AP's still has a big factor on any architecture.
- Keep latency over Wi-Fi at a minimum to ensure latency sensitive services are covered

The above requirements could see 320MHz solutions offered in a 2x2 solution play for 6GHz – given the math of getting to >4Gbps of airtime capacity on a 320Mhz channel. This would be in contrast to the higher more future proof capacity architectures at 8x8 and 4x4 illustrated above. So, there could be architectures that align more with keeping 4x4 for the 5GHz bands and legacy and using 2x2 for 320Mhz for 6GHz capable clients using Wi-Fi 7. Its not even clear if any initial Silicon directions would focus on a cost optimized 2x2 320Mhz solution for 6GHz.

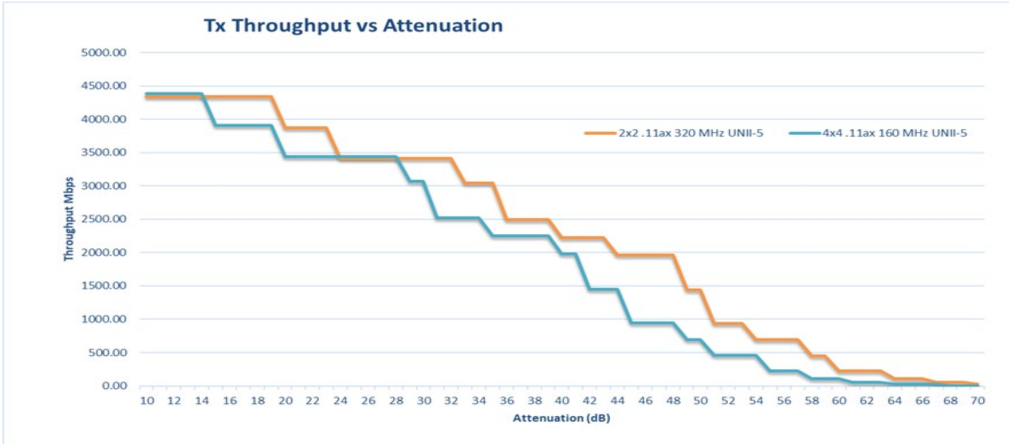


Figure 38 - 2x2 320MHz Wi-Fi 7 vs 4x4 160MHz Wi-Fi 6E

so, it will be interesting to see how single Wi-Fi 7 Wi-Fi Gateways and Access Points emerge to push into the highest performance levels vs keeping the cost economies for Cable Operators in particular. Who knows even Wi-Fi repeaters may make a comeback. Repeaters have always been problematic particularly for 2.4GHz low capacity or high congestion 5GHz networks as they receive and transmit the same packets on the same frequency typically halving the available airtime (typically more). With 6GHz channels however you have lots of capacity to half each time you repeat from 20Gbps in Wi-Fi 7 320Mhz channels to ~4.8Gbps in 160MHz 6GHz channels.

A single Wi-Fi 7 Gateway with 320MHz capability and Tri-band support will probably be the primary workhorse for the Cable Operator from 2024/25 onwards. However, as guaranteed Gbps applications in room emerge there may be the first in room high capacity APs that potentially focus specifically on driving applications only for 6GHz capable clients.

7. What do we do with 2.4GHz and 5GHz spectrum in the Wi-Fi 7 era

We have discussed a lot about the high capacity applications that can run in the 6GHz spectrum and why not with 66Gbps+ of capability there (increased spatial streams and modulation). Like any investment the focus should go where the growth will be so where does this leave the 2.4GHz spectrum and in particular the different performance/range ratio to 6GHz based devices. When 802.11ax was conceived one of the features added to it was to potentially complete the journey of 2.4GHz spectrum as the range work horse and the most likely to make a connection service, was a 2MHz channel that could be used for Narrow Band IoT services. This channel could carry the low bit rate IoT device services at ranges up to 4 times that today of 2.4GHz channels. This could then create a wider separation to the 6GHz access point role and would mean that a single 2.4GHz AP for NB-IOT functions in even the largest homes is feasible.

Wi-Fi 6 has brought fresh ideas to the 2.4GHz space, including the ability to deal with 2MHz wide channels for power sensitive IoT devices. Combining 2MHz, OFDMA, and Target Wakeup Time (TWT) together means that IoT devices are now capable of offering a significant competition to Zigbee, Z-Wave and BT devices. The 2MHz wide channel offers an 8 dB improvement on noise power, allowing the signal power to be 8 db lower enabling a greater coverage area for IoT devices. The TWT feature enables devices to remain in deep sleep mode for much longer than ever before, avoiding the constant need to listen to beacons transmitted by the AP, and allowing the conservation of the all important device battery life.

The flexible guard interval ranging from 0.8us (indoor) to 3.2us (outdoor) also makes the transmitted signals more robust, improving decoding ability at the receiver side. In addition to competing against existing LWPAN networks, Wi-Fi 6 also has the potential to avoid transmitting in the frequencies already used by these networks by not using OFDMA RUs that overlap the same frequencies. Another Wi-Fi 6 feature that helps IOT is the ability within OFDMA to repeat a device transmission in two different RUs, where a transmitted RU is repeated within the same time but on a different RU boundary.

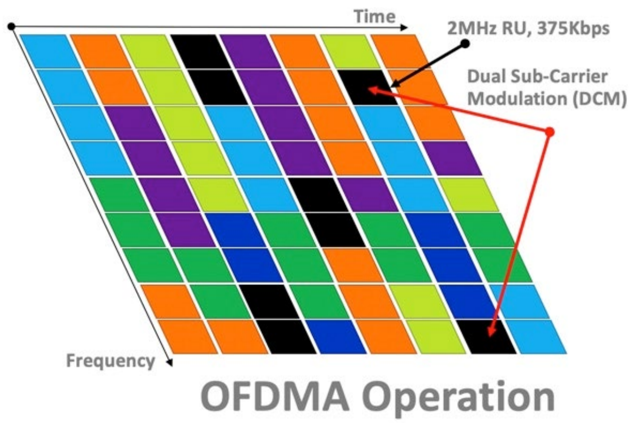


Figure 39 - OFDMA with 2MHz DCM

This Dual SubCarrier Modulation (DCM) feature helps the robustness of the IoT transmissions, increasing the chance of a successful data exchange. The use of OFDMA and 2MHz RUs (enabling 375Kbps) reduces the amount of bandwidth wasted by previous versions of Wi-Fi that had a minimum speed of about 6.5Mbps, and allows other active users to operate at the same time

Figure 40 - Improved Wi-Fi 6 IoT co-existence with ZB/BT

The 5GHz band is certainly getting close to capacity with existing Wi-Fi 4 and 5 devices, most of which are likely to remain in use for an extremely long time. While cellphones get replaced at some regularity, most other Wi-Fi devices, as long as they perform satisfactorily, are unlikely to be switched out. The gradual introduction of Wi-Fi 6 devices will show case the performance of OFDMA and DL MU-MIMO operation in the 5GHz band, and lead to a general appreciation of the benefits of using the newer standard. Initial releases of APs supporting the IEEE 802.11ax standard resulted in a mix of Wi-Fi 6 capable and not capable devices in the field. Some expected features like OFDMA were either not present or performed badly. Once a general adoption of Wi-Fi CERTIFIED 6 (per Wi-Fi Alliance standard) APs occur, these early teething issues will disappear. Additional advances in the mixing of Wi-Fi 5 and Wi-Fi 6 devices in 5GHz will occur, as well as more advanced and optimized OFDMA schedulers for Uplink and Downlink handling. It is important for silicon providers to allow scheduler interfaces to be exposed beyond todays interfaces as there will be requirements and opportunities to customize scheduling of packets and device transmissions based on lots of new innovative ideas, services and solutions.

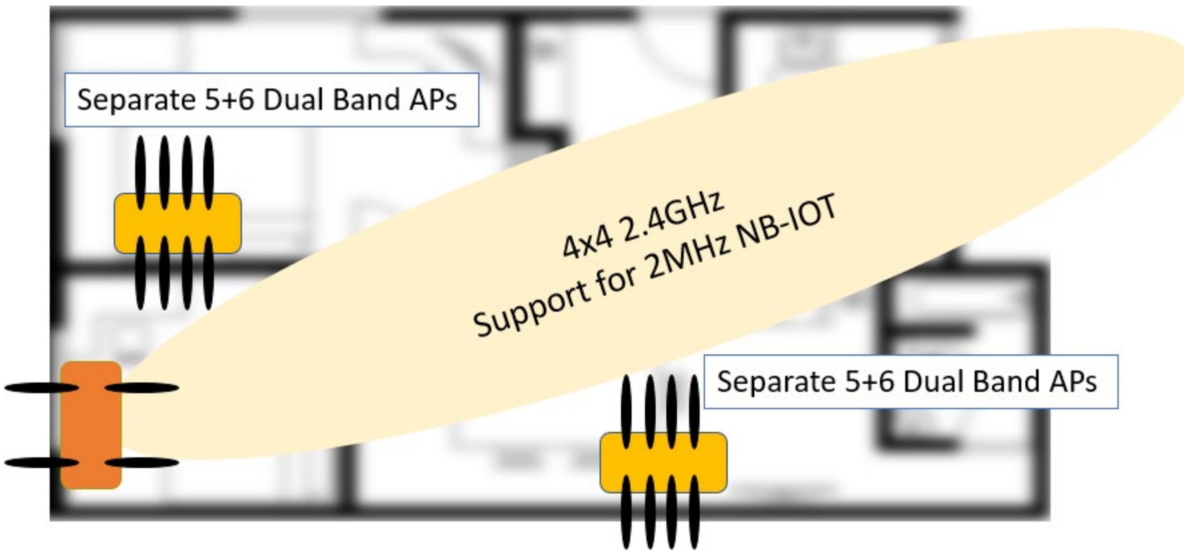


Figure 41 - Does 2.4GHz separate out from 5/6GHz in the home over time ?

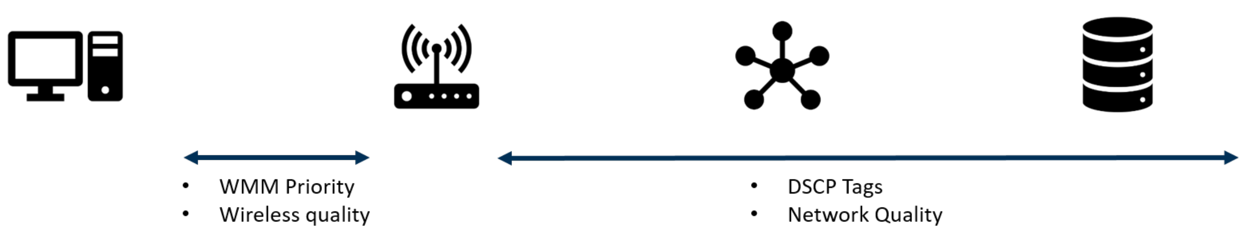
There are many options then for the future home Wi-Fi home that could emerge over the next 5+ years

8. Challenges and opportunities for Wi-Fi ecosystem

Wi-Fi ecosystem faces significant opportunities with new technologies as was described in previous section. This section describes some of the ecosystem challenges and potential solutions for Wi-Fi.

8.1. Enhanced quality of service for applications like VOIP, voice and gaming

Currently QoS implementation, enforcement and management for Wi-Fi is done an individual system level – at client level, router level or at network core level. Client devices like phone and laptops can prioritize traffic in devices using WMM, and DSCP. The implementation and the use of these tags is not uniform end to end. In addition, much of the traffic from devices does not have any priority assigned. Wi-Fi 6 has made significant improvements in prioritizing latency sensitive traffic with support from OFDMA scheduling. However, without accurate tagging from client devices, traffic from applications like VOIP, voice and gaming cannot be prioritized.



A few of the techniques that are proposed to improve QoS are given below.

- Future Wi-Fi standards that can address QoS end to end management

- Automatic classification of QoS for applications using known parameters including UDP/TCP size, frequency, IP address etc.

8.2. Onboarding of IoT devices in Wi-Fi networks

Onboarding of IoT devices into Wi-Fi networks can create potential issues for customers. Many of the Wi-Fi IoT devices including sensors, cameras etc. support only 2.4 GHz spectrum and this creates onboarding issues. IoT devices are onboarded using many techniques including key presses, connecting to Wi-Fi hotspot in mobile device and using other side channel mechanisms. Some mechanisms for device onboarding require both the IoT device and mobile device to be on the same band. Since mobile device may prefer 5 GHz when connecting to router, there are issues onboarding devices that support only 2.4 GHz.

An industry wide solution that encompasses the solutions from WFA including Easy Connect/Device provisioning protocol is needed to simplify customer experience.

8.3. Virtualization in Wi-Fi networks

Virtualization has been used in 3GPP networks starting with 5G networks. Virtualization brings many benefits including simplifying network costs, management of devices and improved network utilization and performance. With the advent of Wi-Fi extenders and mesh networks, virtualization of Wi-Fi networks can yield potential operational improvements for network providers. In multi-dwelling unit deployments, virtualization can simplify operational challenges and reduce the overall network deployment costs by enabling multiple units to share a common infrastructure. In addition, virtualization can be used to provide different quality of services to different classes of devices.

8.4. Operational improvements and network monitoring

Wi-Fi networks tend to have wide variability in quality of network connectivity, primarily due to deployment considerations. Wi-Fi channels may be overloaded due to interference from adjacent networks, use of other unlicensed technologies and due to router placement.

Having robust ability to understand network quality is important for an operator to maintain customer satisfaction with Wi-Fi networks. Network operators have a variety of tools at their disposal including ability to monitor device connection quality, interference in channel, signal strength of device transmissions etc. Some of the newer techniques can also be used that proactively flag network quality issues using anomaly detection techniques.

8.5. Devices supporting multiple networks

Many of the mobile devices support multiple networks including Wi-Fi, LTE/5G, CBRS and public/private versions of Wi-Fi. Traditional mechanisms that primarily default to Wi-Fi networks may not be ideal tradeoff of cost and quality of service. In some cases, operators have multiple networks that can be used by the mobile devices including simultaneous availability of Wi-Fi and LTE/5G/CBRS. Devices may get better network connectivity using LTE/CBRS when outside homes compared to Wi-Fi. A robust mechanism that enables devices to make the right selection is required. This requires collaboration between operators, operating system providers and device manufacturers. This also requires operators to collaborate to create robust mechanisms to share common network infrastructure.

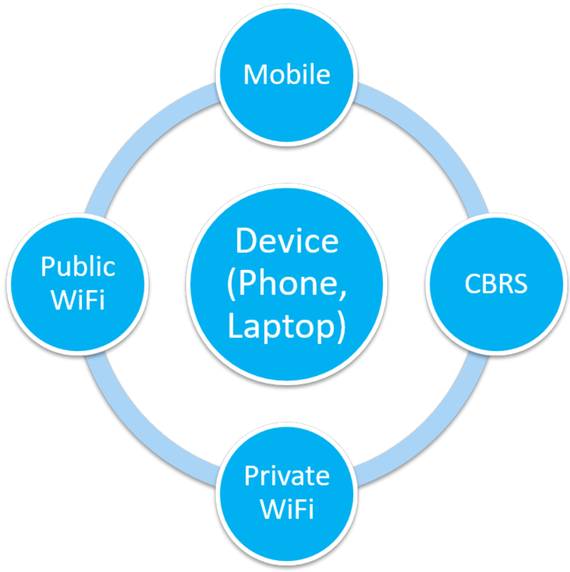


Figure 42 - Potential synergy between different Operator Wireless networks

9. Conclusion

Since the invention of Wi-Fi and the first packets sent wireless from an AP to a client there has never been a more exciting time for Wi-Fi than the current era of Wi-Fi 6, Wi-Fi 6E and Wi-Fi 7. It is unique in its Wi-Fi cadence and something that needs to be well understood by Cable Operators to plan a 5 year roadmap for their adoption of these technologies and fitting them into their overall customer experience plans. It is clear there will be overlapping SKU's of GW. AP and Extenders for Cable Operators to deploy for different levels of Wi-Fi performance. As Access speeds move to Gbps and beyond then 6GHz becomes the key spectrum to migrate to and to match the Access speeds with LAN performance. However, client upgrades to support 6E and 7 and customer satisfaction of increasing promises of performance will also have to be closely managed. Its clear that Cable Operators can exploit 6GHz immediately by leveraging it for high speed backhaul, cross home wireless backbones and most importantly high performance STB and SMD's as the quality of video increases to 4K and 8K (more driven now by better compression of AV2 and VVC). History has proven that applications will absorb the bandwidth available to leverage and the breach of the 5Gbps, 10Gbps and even 20Gbps over Wi-Fi with scheduled low latency will be quickly filled in by new immersive video and high capacity low latency applications. We typically don't see Cable Operators driving 'Build it and they will come' architectures but there will be fierce battles for consumers connectivity business over the next 5 years with 5G services also trying to leverage new spectrum and drive even Fixed Wireless Connections to overlay Cable Homes. So, the investment in getting 6GHz based services and capabilities into the consumer home to drive new video, immersive services may be the new direction for the Cable Operator and set them up for customer retention for the next 10 years of any new service that emerges. Did I hear someone say Wi-Fi 8?

Abbreviations

AP	access point
bps	bits per second
FEC	forward error correction
HFC	hybrid fiber-coax
HD	high definition
Hz	hertz
ISBE	International Society of Broadband Experts
SCTE	Society of Cable Telecommunications Engineers
HARQ	Hybrid Automatic Repeat Request (ARQ)
OFDMA	Orthogonal Frequency Division Multiple Access
SKU	Stock Keeping Unit
PON	Passive Optical Network
GW	Broadband Gateway device typically with Wi-Fi
STB	Set Top Box
MU-MIMO	Multi User Multiple In Multiple Out
LPI	Low Power Indoor mode
VLPI	Very Low Power Indoor mode
TWT	Target Wake Time
EIRP	Effective Isotropically Radiated Power
PSD	Power Spectral Density
dB	Decibel
dBm	Decibel-milliwatts
AV1	AOMedia Video 1 coding format
VVC	Versatile Video Codec
SMD	Smart Media Device
DASH	Dynamic Adaptive Streaming over HTTP

Bibliography & References

IEE8021.11: *802.11n, 802.11ac, 802.11ax , 802.11be*

