LESSONS FROM THE HISTORY OF Wi-Fi

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Introduction

On April 3, 1973, Marty Cooper made the world's first public cellphone call outside the Midtown Hilton in New York. After this dramatic beginning – he called a rival to declare victory – the cellular network became the predominant form of worldwide electronic communication. While the wired telecom network supported 11 million subscribers after its first 110 years of operation,[1] cellular went from zero to nine billion in 40 years.[2]

While cellular was taking off, regulators created a novel unlicensed spectrum regime,[3] chiefly suited for limited-distance networks such as Wi-Fi,[4] Bluetooth, and small IoT networks Zigbee and Z-Wave.[5] Wi-Fi alone connects to nearly 20 billion devices[6] in the homes and offices of the world's 1.4 billion fixed broadband subscribers.[7] Unlike the mobile networks that descended from Cooper's first call, Wi-Fi is quite limited in terms of coverage, capability, mobility, and security, even for public Wi-Fi applications.

Wireless networks chiefly depend on radio frequency (RF) spectrum; hence, the demand for this resource has increased as the numbers of users and devices have grown. The regulatory response to spectrum demand in the US has been peculiar.

Our FCC has granted four to seven times as much mid-band to unlicensed Wi-Fi as to our extremely efficient licensed networks.[8] In contrast, Japan allocates equal amounts of mid-band to licensed and unlicensed. Nation-by-nation, allocation strategies and usage patterns are quite diverse.

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[1] OECD, *OECD Communications Outlook 1999*, (OECD Publishing, 1999), http://www.oecd-ilibrary.org/science-and-technology/oecd-communications-outlook-1999_comms_outlook-1999-en.

[2] "Mobile Phone Subscriptions Worldwide 2023," Statista, accessed May 5, 2024, https://www.statista.com/statistics/262950/global-mobile-subscriptions-since-1993/.

[3] "Authorization of Spread Spectrum Systems Under Parts 15 and 90 of the FCC Rules and Regulations" (Federal Communications Commission, June 18, 1985), https://web.archive.org/web/20070928054826/http://www.marcus-spectrum.com/documents/81413RO.txt.

[4] In this paper, the term "Wi-Fi" is used in the common way, as a synonym for IEEE 802.11 wireless networks. The term is a registered trademark of the Wi-Fi Alliance, which organization excludes the original IEEE 802.11-1997 standard from the term's scope.

[5] "Comparing IoT Mesh Network Protocols: What's the Difference? | TechTarget," IoT Agenda, accessed May 5, 2024, https://www.techtarget.com/iotagenda/feature/Comparing-IoT-mesh-network-protocols-Whats-the-difference.

[6] "Wi-Fi® by the Numbers: Technology Momentum in 2023 | Wi-Fi Alliance," accessed May 5, 2024, https://www.wi-fi.org/beacon/the-beacon/wi-fi-by-the-numbers-technology-momentum-in-2023.

[7] Point Topic, "Global Broadband Subscriptions in Q1 2023: Fibre Glides Past Two Thirds," Point Topic, July 17, 2023, https://www.point-topic.com/post/global-broadband-subscriptions-q1-2023.

[8] Richard Bennett, "Industry Voices: When Wi-Fi Doesn't Save the Day," March 19, 2024, https://www.fierce-network.com/tech/op-ed-when-wi-fi-doesnt-save-day; Accenture, "Spectrum Allocation in the United States,"

While the typical Wi-Fi router is expected to cover a typical home, each 5G base station covers a neighborhood of about 100 to 250 homes.[9] The fastest-growing portion of the residential broadband market is Fixed Wireless Access provided over licensed networks, so the imbalance of licensed and unlicensed poses a threat to the viability of residential broadband itself: what good is an ultra-high-capacity network inside the home that can't connect to the Internet because wireless ISPs can't get the spectrum they need to connect those homes to the global network?[10]

This over-allocation of spectrum to Wi-Fi does not improve user experience for practical purposes. My performance testing of successive generations of Wi-Fi finds minimal correlation between throughput and channel size. This is informative because it shows us that simply shoveling spectrum into the unlicensed pool doesn't necessarily improve the lot of consumers. By the time Wi-Fi 4 (IEEE 802.11n) was ratified, the 5 GHz pool consisted of 555 MHz in the US. Today's combined pool of 5 and 6 GHz spectrum – 2000 MHz – represents a massive increase in the unlicensed spectrum budget with modest performance improvement over Wi-Fi 5 in realistic test scenarios.

It also poses another long-term risk to the Wi-Fi industry. When spectrum is free and the warehouse from which it comes is effectively infinite, what incentive does the industry have to make its services more efficient? Moreover, when the greatest barrier to more effective use of the unlicensed commons is the presence of obsolete devices, what incentive do users have to upgrade to more efficient standards?

Meanwhile, licensed networks face growing congestion. Wireless network congestion can be alleviated with more spectrum, adding additional sites or nodes, or by greater efficiency. In the face of limited spectrum, cellular service providers and equipment providers have learned to do more with less. It should come as no surprise that advances in radio engineering come almost exclusively from the R&D labs of the cellular equipment providers.[11]

This innovation has benefitted the Wi-Fi industry as well. Progress in Wi-Fi (and to an even greater extent, CBRS) mainly parallels, and in many cases depends on, the engine of innovation that comes from licensed spectrum network engineering.[12] But this kind of innovation can only do so much—ultimately, operators cannot engineer around severe spectrum scarcity. Additional small cells and greater efficiency can help on the margins, but are no replacement for additional spectrum.

The United States must rationalize its spectrum allocations in the mid-band to maintain leadership in both licensed and unlicensed technologies. That requires pivoting from over-allocating spectrum to Wi-Fi and instead making more spectrum available to support licensed, mobile networks that face growing congestion. The United States spectrum allocation apparatus—chiefly the FCC and its public clients and

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September 28, 2022, https://www.ctia.org/news/spectrum-allocation-in-the-united-states. Comparisons vary depending on what spectrum is considered mid-band.

[9] Mike Dano, "US Cell Towers and Small Cells: By the Numbers," *Light Reading*, accessed May 5, 2024, https://www.lightreading.com/digital-transformation/us-cell-towers-and-small-cells-by-the-numbers; "Number of U.S. Housing Units 1975-2022," Statista, accessed May 5, 2024, https://www.statista.com/statistics/240267/number-of-housing-units-in-the-united-states/.

[10] Bruce Leichtman, "About 3,500,000 Added Broadband From Top Providers in 2023," Leichtman Research Group, March 7, 2024, https://leichtmanresearch.com/about-3500000-added-broadband-from-top-providers-in-2023/.

[11] "New Developments and Applications in 5G Technologies - IEEE Future Networks," accessed May 5, 2024, https://futurenetworks.ieee.org/topics/new-developments-and-applications-in-5g-technologies.

[12] "2020: Beyond 4G Radio Evolution for the Gigabit Experience" (Nokia Siemens Networks, 2011).

NTIA and its government colleagues—must work together to find and assign an additional 1500 MHz of spectrum for auction to wireless operators who serve the general public.

This will correct the most egregious imbalance in our spectrum policy, but more work will be needed to determine the ideal balance. Residential Wi-Fi is an appendage to the residential broadband services that increasingly depend on Fixed Wireless Access. Making the body healthier and more competitive ultimately makes the appendage more useful even if wireline incumbents fear change.

The Analysis

My analysis presents performance data gathered from testing Wi-Fi generations four through seven in a typical suburban home office using the widely-used iPerf3 test tool. The analysis is far from comprehensive, but it is sufficient to quantify progress made across generations and to provide hints at the roles played by increasing the pool of raw spectrum versus increasing efficiency.

The most dramatic generational leap for Wi-Fi is evident in Wi-Fi 4 (802.11n). Wi-Fi 4 increased download bandwidth by 760% and upload by 588%. It accomplished this feat by operating on either the 2.4 GHz or 5 GHz bands, doubling channel width, and improving both the MAC and PHY protocols with frame aggregation and MIMO/OFDM, respectively. Subsequent channel doubling without significant work on efficiency produced much more modest gains.

I also examine the major modeling efforts used to persuade regulators to increase the pool of unlicensed spectrum. These simulations – Monte Carlo models – haven't been confirmed by real-world data because their parameters were deeply flawed. Their most questionable feature is failure to contrast optimal channel selection and power level algorithms with the decidedly sub-optimal features in widely used consumer-grade devices. They also suffer from unrealistic assessment of traffic loads and a refusal to consider the network-wide degradation caused by older devices.

Finally, I discuss regulatory challenges, the application context, ongoing work in the IEEE 802.11 standards group on reliability and alternatives to mid-band RF spectrum, and the need for better spectrum management.

The FCC assigned 1200 MHz of new unlicensed spectrum to Wi-Fi in the second quarter of 2020, the time of quarantines, an economy in collapse, and working from home. Naturally, conditions pushed the Commission to respond to the crisis in an extravagant but unsustainable way.

Before examining the present state of the ecosystem in detail, let's undertake a brief tour of Wi-Fi's history.

How Wi-Fi Became What It Is

The evolution and history of Wi-Fi is not well understood. The FCC's 1985 Spread Spectrum Order is often regarded as the precondition for wireless local area networks (WLAN), but the first WLAN on the market used unlicensed infrared (IR) spectrum.[13]

[13] "Authorization of Spread Spectrum Systems Under Parts 15 and 90 of the FCC Rules and Regulations."

The immediate radio-based predecessor to the IEEE Standards Association's 802.11 standards, now commonly known as Wi-Fi, was NCR's WaveLAN, released in 1990.[14] WaveLAN used the 900 MHz and 2.4 GHz ISM bands opened by the Spread Spectrum Order, delivering up to 2 Mbps with very modest power output.

A year before WaveLAN, the Photonics Corporation of Silicon Valley released what is arguably the first mass-market WLAN, an infrared extension of AppleTalk called PhotoLink. PhotoLink was the darling of the Macworld Exposition in 1989.[15]

NCR appreciated the value of the 802 standards; they had been active participants in the 802.3 1BASE5 Low-Cost LAN (StarLAN) task force chartered in 1984 that redesigned Ethernet to make it work on twisted-pair wiring.[16] Consequently, NCR was wise enough to petition 802 to create the wireless LAN subgroup that produced 802.11, chaired by its employee Vic Hayes and staffed by StarLAN veterans.[17] Standard operating procedure for 802 was to start with a commercial product such as WaveLAN and examine it for flaws and opportunities for improvement. It would then correct the flaws and add on enhancements before releasing a specification that would enable other companies to interoperate.[18]

802.11 spent seven years mulling over potential additions and alterations to WaveLAN before releasing the original standard named 802.11-1997.[19] The standard supported 1 – 2 Mbps operation over 2.4 GHz or infrared. By the time this standard was ratified, Photonics had raised its game to WaveLAN speed, garnering a competitor in the process, Spectrix. Infrared and RF were both included in the standard.

802.11-1997 failed to gain much traction, but it paved the way for the widely adopted higher-bandwidth 802.11b standard dubbed Wi-Fi by its promoters.[20]

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[14] "WaveLAN," in *Wikipedia*, April 25, 2024, https://en.wikipedia.org/w/index.php?title=WaveLAN&oldid=1220796250.

[15] Peter H. Lewis, "THE EXECUTIVE COMPUTER; Networking Without the Wires," *The New York Times*, August 20, 1989, sec. Business, https://www.nytimes.com/1989/08/20/business/the-executive-computer-networking-without-the-wires.html.

[16] *802.3-2022: IEEE Standard for Ethernet* (New York, NY: IEEE, 2022) ISBN 978-1-5044-8725-2. The author served as Vice-Chair of this task force.

[17] 802 chairs are scrupulously fair, so NCR didn't gain an advantage from placing an employee at the head of the committee; if anything, it worked the other way around as Hayes bent over backwards to ensure he wasn't seen to favor his employer's gear. The company did benefit from its involvement in the StarLAN committee, however. StarLAN changed the way 802 calculated interference and error rates, vital changes for wireless LANs, and established hub-and-spoke topology.

[18] In the case of the transition from Blue Book Ethernet (developed by Xerox, Intel, and DEC) to 802.3, the modification was limited to changing one field in the frame format from the upper layer protocol type to the frame length.[18] This change was ignored by the user community. 802 accepted the IBM Token Ring verbatim.

[19] IEEE Computer Society, *IEEE 802.11-1997*, IEEE Std. 802.11-2007 (New York, N.Y.: IEEE, 2007), http://standards.ieee.org/getieee802/download/802.11-2007.pdf.

[20] 802.11b's higher throughput was largely achieved by convincing the FCC that a more efficient implementation of the spread spectrum requirement in the enabling order for unlicensed spectrum wouldn't cause the end of the world. The relaxation of spread spectrum constraints allowed RF WLANs to outperform IR LANs, sending the latter to the sidelines.

802.11b was confined to the 2.4 GHz band believed by many to propagate better than the 5.8 GHz ISM band. In 1997, the FCC increased the allocation of 5 GHz unlicensed spectrum to 300 MHz in its "Unlicensed NII Devices in the 5 GHz Frequency Range" order even though nobody was using it.[21]

5 GHz became practical with the use of OFDM, a technique that converted multipath distortion from a negative to a positive.[22] After OFDM, the other improvements to Wi-Fi signaling were the adoption of MIMO[23] in 802.11n,[24] the incorporation of OFDMA in Wi-Fi 6,[25] and the appropriation of a version of carrier aggregation[26] known as Multi-Link Operation (MLO) in Wi-Fi 7.[27] The frame aggregation improvement in the Wi-Fi Medium Access Control (MAC) protocol in 802.11n also played a large part in enabling it to deliver a four- to eight-times performance increase over prior standards.[28]

Wi-Fi Performance Over Time

Examining the performance of various Wi-Fi protocols with different channel sizes, it's clear that at this stage additional unlicensed spectrum does not provide a practical benefit to Wi-Fi performance. It is only at very close ranges that additional spectrum actually improves performance. What's more, data rates achievable by existing versions of Wi-Fi are both already beyond those needed for realistic wireless applications and no longer a constraint to end-to-end throughput.

The FCC effectively created high-speed WLANs with its 1985 Spread Spectrum Order as revised and has continued to feed it with regular grants of additional unlicensed spectrum.[29] Wireless engineering contributes the means of using available spectrum as effectively and efficiently as possible. Application developers create demand, and consumers validate the whole process by literally buying in. The weak links in the chain are the device manufacturers who don't implement the standards correctly and the consumers who lack the technical expertise to even understand Wi-Fi's technical features, let alone to manage them.

While frame aggregation, OFDM, MIMO, OFDMA, and MLO produce substantial theoretical benefits in many scenarios, the most frequently exploited historical path to higher-speed Wi-Fi is simply using more

[21] Federal Communications Commission, "Unlicensed NII Devices in the 5 GHz Frequency Range" ([ET Docket No. 96–102; FCC 97–5], January 31, 1997), https://www.govinfo.gov/content/pkg/FR-1997-01-31/pdf/97-2007.pdf.
[22] EETimes, "OFDM Kills Multipath Distortion," *EE Times* (blog), April 15, 2002, https://www.eetimes.com/ofdm-kills-multipath-distortion/.
[23] J. Salz, "Digital Transmission over Cross-Coupled Linear Channels," *AT&T Technical Journal* 64, no. 6 (August 1985): 1147–59, https://doi.org/10.1002/j.1538-7305.1985.tb00269.x.
[24] Richard Van Nee et al., "The 802.11n MIMO-OFDM Standard for Wireless LAN and Beyond," *Wireless Personal Communications* 37, no. 3 (May 1, 2006): 445–53, https://doi.org/10.1007/s11277-006-9073-2.
[25] H. Yin and S. Alamouti, "OFDMA: A Broadband Wireless Access Technology," in *2006 IEEE Sarnoff Symposium*, 2006, 1–4, https://doi.org/10.1109/SARNOF.2006.4534773.
[26] O. Holland et al., "Management Architecture for Aggregation of Heterogeneous Systems and Spectrum Bands," *IEEE Communications Magazine* 54, no. 9 (September 2016): 112–18, https://doi.org/10.1109/MCOM.2016.7565257.
[27] "What Is Wi-Fi 7?," Intel, accessed May 9, 2024, https://www.intel.com/content/www/us/en/products/docs/wireless/wi-fi-7.html.
[28] One of the inventors of Wi-Fi's version of frame aggregation chairs the Wi-Fi Alliance today and another is the author of this paper.
[29] Richard Bennett, "Some History on Unlicensed Spectrum," *High Tech Forum* (blog), April 10, 2024, https://hightechforum.org/some-history-on-unlicensed-spectrum/.

spectrum in the form of wider ("fatter") channels. The original standard made three 20 MHz channels available in the 2.4 GHz band, a miniscule quantity by today's standards.

802.11n doubled the channel size to 40 MHz and incorporated 2.4 GHz and 5.8 GHz on an equal basis. Wi-Fi 5, 6, and 7 each doubled the channel size again, bringing it to the current 320 MHz maximum. MLO effectively doubles usable bandwidth yet again by permitting the simultaneous use of two such channels. With MLO, Wi-Fi can achieve an effective channel size of 480 MHz.[30]

Simply doubling the channel size has not led to anything close to a doubling of throughput, especially when the client device is more than 15 feet from the access point.

To determine how well channel doubling has worked through its four iterations, I tested each version of Wi-Fi from Wi-Fi 4 to Wi-Fi 7 in near (10 feet), typical (25 feet), and far (50 feet) configurations. I used iPerf3 v. 1.6 as the measurement tool along with a collection of three routers, four computers, three Wi-Fi 7 adapters, and two versions of Windows 11.[31] The testing was done in a suburban neighborhood with six external networks visible.

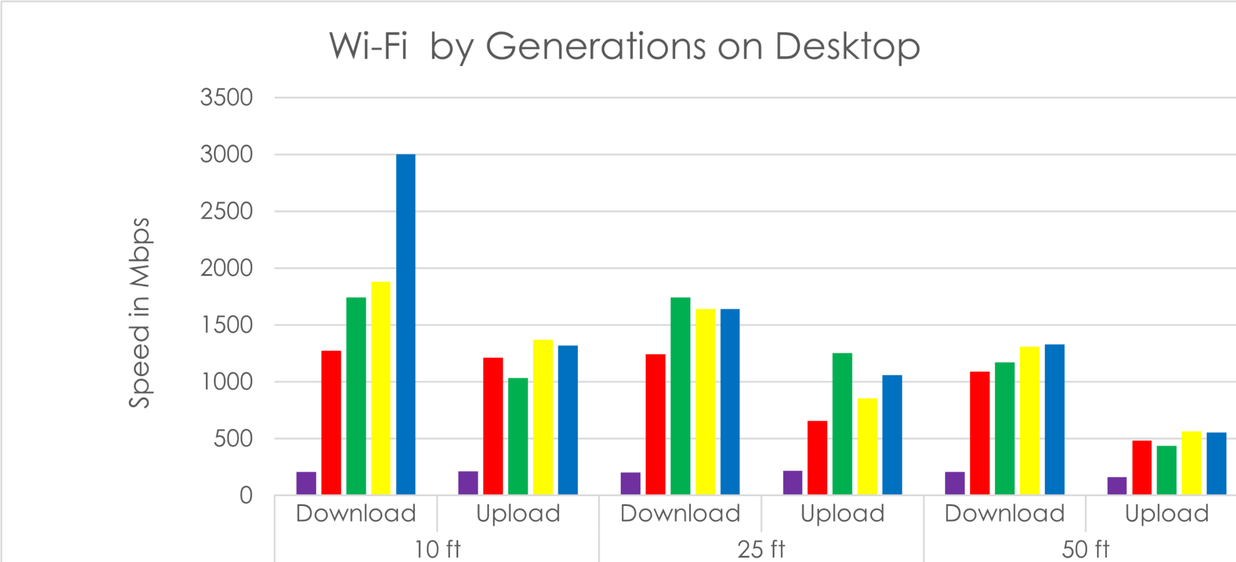
The following charts indicate the highest and lowest scores from various combinations of equipment across the generations of Wi-Fi. The variations in speed don't simply reflect the nature of Wi-Fi itself; some routers are faster than others simply because they have faster processors or more memory. Some interface chips are faster than others simply because their logic is better or software is more mature, and operating systems rarely do their best in the first release.

The best performance is achieved in the first chart, taken with a high-performance desktop computer.

Notable findings include:

- Wi-Fi 7 is capable of achieving incredibly high download throughput – 3 Gbps – when station and access point are separated by no more than 10 feet. When separated by 25 to 50 feet, throughput drops roughly in half.
- Prior generations of Wi-Fi also show degradation of throughput with distance, but much less dramatically. Wi-Fi 6 holds steady at 25 feet and declines 33% at 50 feet, while Wi-Fi 4 is essentially the same from 10 to 50 feet.
- At 50 feet, Wi-Fi 5 with an 80 MHz channel achieves 80% of the throughput of Wi-Fi 7 with its 320 MHz channel.
- It's hard to justify the additional expense of Wi-Fi 7 routers and access points over prior generations in terms of purchase price or spectrum opportunity cost. Wi-Fi 7 is clearly not spectrum-constrained within or between networks today.
- These findings also cast doubt on the need for additional unlicensed spectrum for the foreseeable future, and particularly undermine the calls for Wi-Fi spectrum in the lower 7 GHz band.

[30] This assumes that 160 MHz in the 5 GHz band is used simultaneously with 320 MHz in the 6 GHz band.
[31] Routers included TP-Link Deco BE85, ASUS GT-BE98, and ASUS RT-BE96. Computers included a laptop with an Intel Core Ultra 9 185H CPU and desktops with an Intel(R) Core (TM) i3-10100 CPU, an AMD Ryzen 9 7900 CPU, and an AMD Ryzen 9 3900X CPU. One adapter used an Intel BE200, another a Qualcomm FastConnect 7800 HBS, and a third employed the Intel Killer 1750x. Two desktops ran the pre-release 24H2 version of Windows 11 (with support for Wi-Fi 7 MLO), and the other two computers ran standard Windows, 23H2. The highest speeds came from pro-release Windows, Qualcomm, and ASUS RT-BE 96. The scores are roughly comparable to those recorded with prosumer-grade Ubiquiti U7 Pro and TP-Link Omada EAP773 ceiling-mounted access points.



	10 ft Download	10 ft Upload	25 ft Download	25 ft Upload	50 ft Download	50 ft Upload
11n 40 MHz ch	205	213	203	217	209	160
11ac 80 MHz ch	1270	1210	1240	657	1090	482
11ax 160 MHz ch	1740	1030	1740	1250	1170	436
11axe 160 MHz ch	1880	1370	1640	854	1310	561
11be 320 MHz ch	3000	1320	1640	1060	1330	551

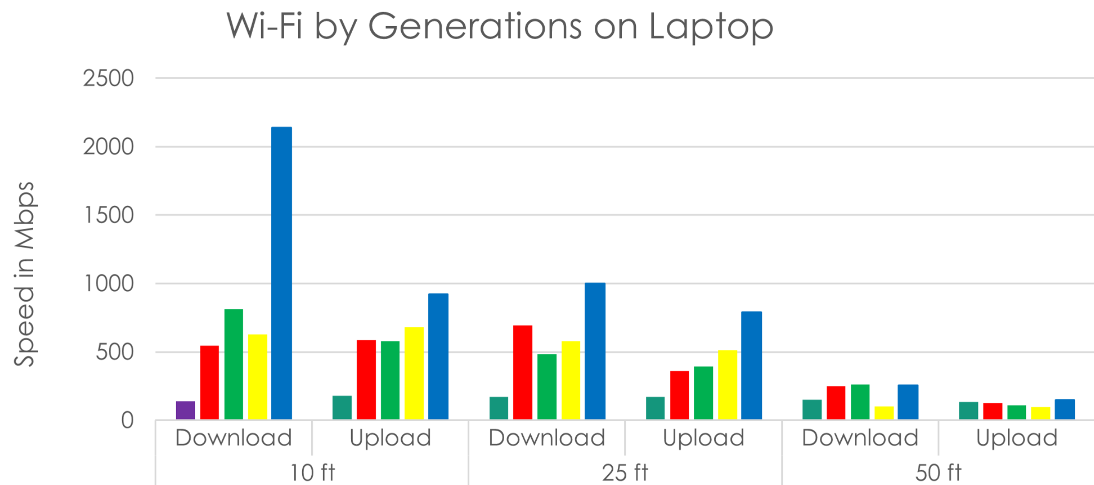
Figure 1: Optimal Wi-Fi performance by standard with high-performance configuration. Source: Author's testing, as described.

The lowest numbers come from a Wi-Fi 7 laptop purchased at Costco.[32] The laptop configuration displays roughly half the performance of the high-performance desktop equipment in the short-distance scenario and about a fifth in the long-distance scenario. At 25 feet, the performance variations are less extreme, from 60 – 85 percent. The top speed of Wi-Fi 7 in this configuration is the same at 10 feet as the desktop achieves at 25 feet. At 50 feet, Wi-Fi 6 is slightly faster than Wi-Fi 7, and Wi-Fi 6E is slower than Wi-Fi 4.

In laptops with built-in Wi-Fi, manufacturers typically build in antennas around the display. Depending on device orientation, such antennas are often more sensitive than the rabbit ear antennas included with Wi-Fi adapters for desktop machines. This particular laptop picks up stronger signals in the lateral direction than straight ahead. The antennas in this laptop are well-tuned for signals 25 feet away, but they're much less robust on 50-foot signals.

Regardless of the vagaries of measurement, Wi-Fi that delivers 1000 Mbps over 25 feet is a remarkable achievement in the eyes of those of us who remember the original 2 Mbps systems. Technical engineering innovation is an amazing thing.

[32] This laptop is an Acer Swift Go 16 Touchscreen Laptop with an Intel Core Ultra 9-185H Processor equipped with an Intel Killer 1750x Wi-Fi card and Windows 11 Pro 23H2. It comes standard with Windows Home, but I upgraded it to Windows Pro to enable remote access. The router in this configuration is a top-of-the-line ASUS ROG Rapture GT-BE98 router in access point mode. This router splits the 6 GHz band in half; hence, ASUS markets it as a quad-band device. Splitting the 6 GHz band reduces the number of available 320 MHz channels from three to two and degrades Wi-Fi 7 performance in the near-distance scenario.



	10 ft		25 ft		50 ft	
	Download	Upload	Download	Upload	Download	Upload
11n 40 MHz ch	140	180	172	172	150	133
11ac 80 MHz ch	547	585	694	361	248	125
11ax 160 MHz ch	813	579	482	393	261	110
11axe 160 MHz ch	627	683	578	512	101	99
11be 320 MHz ch	2140	924	1000	791	257	149

Figure 2: Typical Wi-Fi performance by standard with medium-performance configuration. Source: Author's testing, as described.

This is not a controlled experiment that accounts for interference and external traffic loads, nor is the sample size adequate for sweeping generalizations.[33] But it should represent a reasonable approximation of the relative progress across five generations of Wi-Fi.[34]

Relative Performance Improvement

Successive generations of Wi-Fi have not improved at a consistent, predictable rate. Comparing the bandwidth of each version from Wi-Fi 4 to Wi-Fi 7 to its predecessor produces some surprising results. Wi-Fi 4, generally considered a dinosaur today, represented the greatest relative improvement overall.

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[33] A preliminary test version used Speedtest, but it proved inadequate because short distance Wi-Fi 7 easily outperforms 1.2 Gbps DOCSIS 3 Internet service with PowerBoost. J. T. Ramsay, "What Is PowerBoost?," August 22, 2011, https://corporate.comcast.com/comcast-voices/what-is-powerboost.

[34] My performance findings are consistent with independent testing of Wi-Fi 5, 6, 6E, and 7 in lab settings with custom test tools; we all found about 3 Gbps download speeds over 10 feet with Wi-Fi 7. The following table summarizes performance reported by Intel, PC Magazine, Tom's Hardware, Dong Knows Tech, and the author. Note that the Intel test doesn't include Wi-Fi 7 while the PC Magazine tests are only Wi-Fi 7. Carlos Cordeiro, "Wi-Fi Unleashed: Wi-Fi 7, 6 GHz, and Beyond" (Intel Corporation, June 2022), https://www.intel.com/content/dam/www/central-libraries/us/en/documents/2022-06/wi-fi-tutorial-long.pdf; John R. Delaney, "Asus ROG Rapture GT-BE98 Pro Review," PCMAG, accessed May 15, 2024, https://www.pcmag.com/reviews/asus-rog-rapture-gt-be98-pro; Brandon Hill, "Asus ROG Rapture GT-BE98 Pro Wi-Fi 7 Router Review: Class-Leading Performance and Expandability," Tom's Hardware, May 15, 2024, https://www.tomshardware.com/networking/routers/asus-rog-rapture-gt-be98-pro-wi-fi-7-router-review; Dong Ngo, "Asus GT-BE98 Pro Review: An Excellent Wi-Fi 7 Router | Dong Knows Tech," February 26, 2024, https://dongknows.com/asus-rog-rapture-gt-be98-pro-wi-fi-7-review/.

Wi-Fi 5 also produced a significant improvement, especially on the downstream side. But it appears that Wi-Fi performance gains have tapered off since Wi-Fi 5.

Wi-Fi 6 was a disappointment, actually declining on the downstream side and only modestly improving on the upstream side. This probably indicates that 160 MHz channels are hard to find in the 5 GHz band in real life, while OFDMA worked as expected on the upstream side. Wi-Fi 6E benefitted from fresh spectrum in 6 GHz, but far underperformed the high expectations set by the industry for the new band in 50 ft measurements on ordinary computers.

Wi-Fi 7 performance is very implementation-dependent, showing good gains in laptop downloads and remarkable improvement on the desktop. The desktop outperformed the laptop as before, but its gains were less than expected with MLO. All other things being equal, desktop uploads and downloads should have gained 400% thanks to double the channel width and double the radios. Wi-Fi 7 is at a very primitive stage today, so its performance is likely to improve as radio engineers learn more about channel assignment trade-offs and the use of MLO. The increased complexity of Wi-Fi 7 means it is likely to ramp up more slowly than previous standards. Wi-Fi 6E is still struggling, so we don't know how long it will take to improve Wi-Fi 7 (or even if consumers will see much improvement).

As things stand, the best way to experience high-performance Wi-Fi is to sit very close to the access point behind the wheel of a desktop computer that can easily be wired to the access point. At ten feet, Wi-Fi 7 delivers blazing-fast 3 Gbps downloads, far more than cable modem Internet can handle. But at 50 feet, it's hard-pressed to keep up with a true fixed wireless ISP on the laptop.

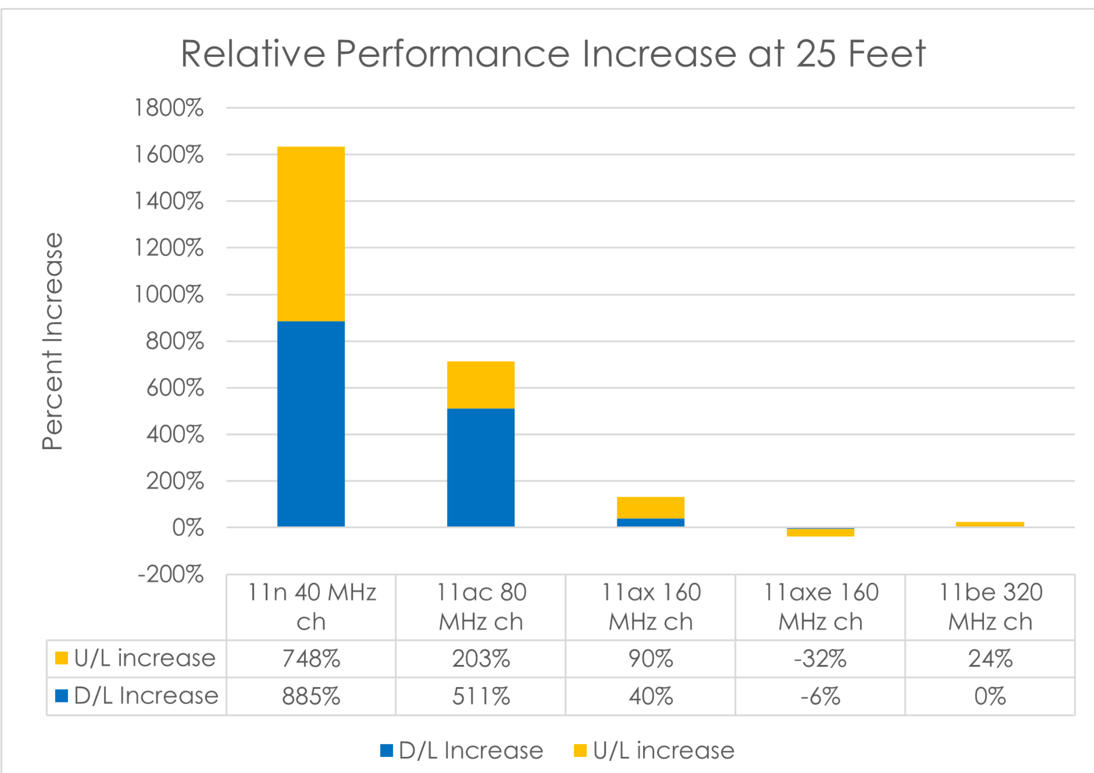

Figure 3: Relative near and far improvement from previous standard. Source: Author's testing, as described.

As noted, by far the most significant performance jump came with Wi-Fi 4, with a 760% download jump over its speediest predecessor, Wi-Fi 2 (data not shown), and 588% for uploads. By contrast, Wi-Fi 6E was only 20% better than Wi-Fi 6 for downloads and 30% for uploads.

Post-Wi-Fi 5, the mean improvement is 44% for downloads and 22% for uploads. In the case of Wi-Fi 7, increasing channel size by 160 MHz and adding dual radio MLO yields an average improvement of 28% for downloads and 142% for uploads. Given that all tested versions of Wi-Fi greatly exceed the upload capacity of DOCSIS 3, cable modem and vDSL users will not be able to detect these even faster speeds. Consequently, doubling channel size doesn't double throughput in fact or from the typical user's perspective.

The significant finding for regulators is the fact that Wi-Fi reached a plateau at Wi-Fi 5. Wider channels in Wi-Fi 6 delivered no significant performance benefit, but the use of dual simultaneous radios (MLO) in Wi-Fi 7 did move the needle. It is likely that the improvement in download speed in Wi-Fi 7 has more to do with parallelism than with wider channels.

It also appears that 80 MHz is the ideal channel size for Wi-Fi in the real world. Wider channels can move more data in quiet environments, but they're also more vulnerable to interference and noise because of lower power density. Some Wi-Fi advocates are now seeking additional spectrum rights in the 7 GHz band in order to increase the number of possible 320 MHz channels from three to four.[35] As the data show, this expansion is uncalled-for and unproductive. Adding more channels to a system that is already over-allocated is simply not the magic bullet advocates seem to think it to be.

Parallelism across the protocol stack was a key factor in the Wi-Fi 4 breakthrough. OFDM introduced the notion of subcarriers for 802.11a, and Wi-Fi 4's MIMO made subcarriers more effective by combining them with discrete spatial streams. Wi-Fi 7 takes parallelism to a new level by using two packages of spatial streams at the same time. Hence, a more productive approach to Wi-Fi performance may be to reduce the channel size and increase the number of MLO radios.

These findings raise questions about the value of larger unlicensed spectrum allocations. For Internet users, performance increases in the WLAN in excess of the performance of the ISP's wide area network (WAN) are academic. End users can still benefit from ultra-high performance WLANs, but only when running purely local applications such as file server access for software development or machine learning from pre-built databases.

For such applications, wired LANs are generally available with even higher performance than Wi-Fi can offer. Data centers employ 25, 40, 100, and even 400 Gbps Ethernets, so it's reasonable to suppose that they will remain wire-based.

Wi-Fi networks can only be as good as the broadband connection they depend on. Making Wi-Fi outperform Internet connections over short distances serves no evident or even discernable purpose. The primary goal for Wi-Fi performance is the level that common applications can actually use; in essence, we don't want the LAN to bottleneck end-to-end performance of applications. Regulators have

[35] Wi-Fi Forward, "The Case for Extending the Unlicensed 6 GHz Band into 7 GHz," accessed September 17, 2024, https://wififorward.org/resource/the-case-for-extending-the-unlicensed-6-ghz-band-into-7-ghz/.

long targeted 1 Gbps speeds on the assumption that this round number corresponds to user expectations of the Internet experience.

In reality, the bottleneck for Internet applications is the performance of web servers, which generally top out well below 100 Mbps.[36] Video streaming is even less demanding than web page loading, as it is inherently rate limited by the coding or resolution of the video program itself, approximately 8 - 40 Mbps for 4K video. YouTube recommends 35 Mbps for 4K/2160p at 60 frames/second.[37] Higher bit rate encoding consumes more space on server storage and imposes more load on server CPUs. Netflix 4K streams are compressed to as little as 1.6 Mbps.[38]

Simulations

Network standards bodies rely heavily on predictions generated from simulations. In my experience, simulations answer questions about the efficacy and efficiency of protocol features, traffic loads, security mechanisms, interference, and several other things. Once a task group is organized to set goals and directions for a new standard, advocates of competing approaches bring simulations to meetings to demonstrate the strengths and weaknesses of competing approaches.

The six major simulation studies conducted from 2013 to 2024 have come up with wildly varying estimates of spectrum needs – from 650 to 2000 MHz – despite conforming to IEEE 802.11ax templates for device density and usage patterns.[39] The low estimate came from Qualcomm's unpublished 2023 update to its 2016 study that included low power channels and Wi-Fi 7 320 MHz channels with MLO.

The high estimate, Plum's recently published study for the Wi-Fi Alliance, assumed extremely high device density, constant traffic, no enterprise scenario, and no Wi-Fi 7 features. The new Plum study mentions the 2023 Qualcomm update presented to the UK Spectrum Forum.

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[36] Richard Bennett, "You Get What You Measure: Internet Performance Measurement as a Policy Tool" (TPRC 45, Arlington, VA: Social Science Research Network, 2017), https://papers.ssrn.com/abstract=2944402.
[37] "Choose Live Encoder Settings, Bitrates and Resolutions - YouTube Help," accessed July 10, 2024, https://support.google.com/youtube/answer/2853702?hl=en-GB.
[38] Netflix Technology Blog, "Optimized Shot-Based Encodes for 4K: Now Streaming!," Medium, August 28, 2020, https://netflixtechblog.com/optimized-shot-based-encodes-for-4k-now-streaming-47b516b10bbb.
[39] IEEE Standards Association, "IEEE P802.11 Wireless LANs - TGax Simulation Scenarios" (IEEE Standards Association, November 16, 2015), https://mentor.ieee.org/802.11/dcn/14/11-14-0980-16-00ax-simulation-scenarios.docx.

	Offered traffic	Environment	Model	Conclusion
Plum (2013)		Apartment block, Terraced House, Office block, Transport hub	High-level	320 MHz additional spectrum by 2016
Qualcomm (2016)	1 Gbit/s per user in 99% of area	Residential, Enterprise	Detailed simulation (PHY)	Total 1280 MHz spectrum required
Quotient (2017)	4.5GB/person avg busy hour volume	Office, Residential, shopping mall	Detailed simulation (PHY)	Total 1120 MHz spectrum required
Qualcomm (2023)	1 Gbit/s per user in 99% of area	Residential, Enterprise	Detailed simulation (PHY)	Total 650 - 1250 MHz spectrum required
Intel (2023)	30 Mbit/s x 8 per AP + 100 Mbit/s x 8	One, two, or three rooms, each with a BSS. Requirement for 320 MHz channel assumed.	Detailed simulation (link-level)	Total 960 MHz spectrum required
Plum (2024)	1 Gbit/s per user in 99% of area	Dense Residential	Detailed simulation (PHY)	Total 2000 Mhz spectrum required

Table 1: Summary of major Wi-Fi spectrum usage simulations.[40]

In the regulatory realm, such predictions about spectrum needs developed in Monte Carlo simulations often inform decisions about licensing regimes. These simulations are less than perfect; hence, regulators in the US, Korea, and Canada have assigned 1,200 MHz of 6 GHz band spectrum to unlicensed, while the EU, UK, Japan, and others have allocated less than half that amount. While Brazil initially allocated 1200 megahertz to unlicensed in the 6 GHz band, it recently opened an ongoing consultation to unwind that decision and align with the growing international trend of allocating the upper portion of the band for licensed IMT systems.[41]

One point of convergence is the finding that three non-overlapping channels are generally needed to support Wi-Fi in any given band. This was the case for 802.11b, 802.11ax, and 802.11be. The standards differ with respect to channel size, but that relates more to desired performance than to interference mitigation.

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[40] Brian Williamson, Thomas Punton, and Paul Hansell, "Future Proofing Wi-Fi – the Case for More Spectrum" (Plum Consulting, 2013), https://community.cisco.com/t5/service-providers-knowledge-base/future-proofing-wi-fi-the-case-for-more-spectrum-report/ta-p/3642524?attachment-id=140992; Rolf de Vegt et al., "A Quantification of 5 GHz Unlicensed Band Spectrum Needs" (Qualcomm Technologies Inc, 2016), https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/quantification_5ghz_unlicensed_band_spectrum_needs_v3.pdf; Steve Methley and William Webb, "Wi-Fi Spectrum Needs Study" (Quotient Associates for Wi-Fi Alliance, 2017), https://vaunix.com/resources/wi-fi-spectrum-needs-study.pdf; Dmitry Akhmetov et al., "6 GHz Spectrum Needs for Wi-Fi 7," *IEEE Communications Standards Magazine* 6, no. 1 (March 2022): 5–7, https://doi.org/10.1109/MCOMSTD.2022.9762843; Richard Rudd, "Wi-Fi® Spectrum Requirements" (Plum Consulting, March 18, 2024), https://www.wi-fi.org/system/files/Plum%20%28Mar%202024%29%20-%20Wi-Fi%20Spectrum%20Requirements.pdf.

[41] *See* Global Validity, "On April 28th, ANATEL initiated Public Consultation No. 29/2024 which focused on limiting the operational frequency band of WiFi 6 GHz in Brazil" (June, 2024), https://globalvalidity.com/brazil-anatels-public-consultation-on-wifi-6-ghz-frequency-band-update/.

For the last ten years, standards bodies and regulators have desired to make WLANs capable of achieving 1 Gbps of sustained performance for the client-facing side of each access point.[42] This is a dubious target that serves to inflate spectrum needs. High-end smartphones such as the iPhone 15 Pro Max can reach gigabit levels over Wi-Fi 6E, but fairly recent iPad Pros cannot. As noted, gigabit speeds aren't useful for video streaming, nor are they needed for conferencing. But the gigabit goal marks standards-makers and regulators as forward-looking, so we're stuck with it.

The chief question for regulators is how much spectrum to allocate to Wi-Fi in the general neighborhood of 5 – 6 GHz. Using IEEE TGax templates for coverage simulation, Qualcomm found in 2016 that 1280 MHz around the 5 GHz band would support 500 Mbps traffic loads on 80 MHz channels in the most common scenarios:

> *To enable future WLAN-type application and usage scenarios, regulators should plan for around 1280 MHz of unlicensed spectrum centered around the 5 GHz band for use by unlicensed technologies, to enable common deployment scenarios such a single access points for apartments (Configuration A) and 2 antenna client devices in dense enterprise settings (Configuration E).*[43]

This quantity of spectrum can be provided by adding part of the lower 6 GHz band to existing allocations in the 5 GHz band, consistent with European and Japanese practice and the design of Wi-Fi 7 routers from major manufacturers such as ASUS, TP-Link, and Netgear that split the 6 GHz band. Considering that Wi-Fi is mostly deployed in the home/office or in buildings and gathering places, the perceived need for any additional spectrum, if any, should be limited to small geographic locations. Providing additional mid-band spectrum will be vitally needed for wide area coverage and capacity for 5G and beyond. Furthermore, in the UK's Office of Communications (Ofcom), the regulator is studying the possibilities of allocating 6 GHz spectrum for both licensed wireless outdoors and Wi-Fi indoors, as well as another 'hybrid' configuration.[44]

In a paper commissioned by the Wi-Fi Alliance and released this year, Plum Consulting relies on a "full buffer" traffic model to justify a 2.5x increase in 6 GHz unlicensed spectrum. While this type of model follows IEEE convention, continuous traffic is a dubious assumption, as it is not readily observed in the wild.[45] In LAN traffic capacity studies dating back to the 1970s, the conventional estimator for traffic is a stochastic model such as Poisson Distribution, which is a better reflection of real-life bursty traffic.[46]

Moreover, Plum is aware that MLO is part of Wi-Fi 7, but it doesn't include it in its model. With these assumptions and omissions, Plum concludes that the status quo allocation of 5 and 6 GHz spectrum in Europe will only support relentless 1 Gbps in 50 – 60% of dense apartment buildings:

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[42] de Vegt et al., "A Quantification of 5 GHz Unlicensed Band Spectrum Needs"; Akhmetov et al., "6 GHz Spectrum Needs for Wi-Fi 7"; Rudd, "Wi-Fi® Spectrum Requirements."
[43] de Vegt et al., "A Quantification of 5 GHz Unlicensed Band Spectrum Needs."
[44] https://www.ofcom.org.uk/spectrum/innovative-use-of-spectrum/vision-for-sharing-upper-6-ghz-spectrum-between-wi-fi-and-mobile/
[45] IEEE Standards Association, "IEEE P802.11 Wireless LANs - TGax Simulation Scenarios."
[46] "Poisson Distribution," in *Wikipedia*, June 21, 2024, https://en.wikipedia.org/w/index.php?title=Poisson_distribution&oldid=1230289460.

> *The currently available EU spectrum allows coverage of around 50-60% of a dense-residential building at gigabit speeds, using either eleven 80 megahertz or five 160 megahertz channels. Should the upper 6 GHz band be made available, this would give 99% coverage (using nineteen 80 megahertz channels) or 86% coverage (nine 160 megahertz channels).*[47]

The Plum study doesn't address enterprise scenarios at all. If we take the Plum findings at face value and assume that the European status quo needs doubling to achieve sustained gigabit performance, MLO does the trick all by itself. This conclusion is supported by my testing showing 1.5 Gbps throughput at 25 feet.

The IEEE-standard simulations are simply biased toward a spectrum footprint at least twice as large as the real-world footprint by their omission of parallel radio operation and an utterly unrealistic traffic usage model. When simulations cannot be confirmed by empirical testing of final products, their value is quite limited.

This analysis suggests that the US likely went overboard in allocating the entire 6 GHz band to unlicensed, but in any event, adding to that largesse for the sake of an additional, inefficient 320 megahertz channel is uncalled for.

Lessons Learned, Lessons to Come

Advances in Wi-Fi performance enabled by new standards are always blunted by the older Wi-Fi devices currently in the field. While mobile operators are able to repurpose existing spectrum to a new standard by dynamic spectrum management and retiring down-level devices, Wi-Fi simply has to wait for users to upgrade their installed base. The appetite for new bands for new standards is generated by obsolete devices.

New standards rarely play well with old devices. For some users, an MLO Wi-Fi 7 router will be a step backward. TP-Link addresses this problem in their support forum:

> *For instance, through comparative testing, it is observed that when some client devices connect to a Deco MLO Network, their actual throughput may not be significantly improved in comparison to a non-MLO network connection, since the clients don't fully support MLO or have limited compatibility with the feature. Under these circumstances, and in certain scenarios, the performance of the MLO network connection may even be inferior to that of a standard, single-band Wi-Fi connection between the client device and the Deco.*[48]

To simplify, MLO achieves performance gains by doubling the number of radio transceivers in Wi-Fi devices and operating them in parallel. This is more accurately described as parallelism than simple aggregation.

[47] Rudd, "Wi-Fi® Spectrum Requirements."
[48] "Why Is My MLO Network Performance Not as Good as Expected? | TP-Link," accessed May 10, 2024, https://www.tp-link.com/us/support/faq/3911/.

The design of newer Wi-Fi 7 router and access point products suggest that many vendors no longer see great value in the 6 GHz band. The newest Wi-Fi 7 routers from Netgear,[49] ASUS,[50] and TP-Link[51] split the 6 GHz band into two sub-bands, assigning one to the consumer-facing fronthaul side and reserving the other for mesh network backhaul.[52]

In this configuration, the user has only two 320 MHz channels at their disposal rather than the three contemplated by the FCC. The vendors would rather rely on the 5 GHz band for the heavy lifting, treating 6 GHz as a luxury band whose appeal is mainly for Speedtest buffs. Among other things, splitting the 6 GHz band allows vendors to serve the US and EU markets with a single product by turning off U-NII 7 and 8. This is a typical marketing reaction to low-demand features, and again undermines any support for additional unlicensed allocation in the 7 GHz band. If companies are dividing the band because of lack of international consensus and effectively giving up on the upper 6 GHz band, then there is no advantage to making lower 7 unlicensed, even if more spectrum mattered.

Entry-level Wi-Fi 7 products from TP-Link (Archer BE230), Xiaomi (BE7000), and ASUS (RT-BE88U) don't support the 6 GHz band at all, and broadband providers typically offer Wi-Fi 7 routers only to those who ask for them. In some cases, rental fees are higher for 6 GHz gear.

Wi-Fi's Original Sin

Wi-Fi's biggest challenge is uncoordinated sharing, a dilemma that isn't solved by even more spectrum. Its fundamental constraint isn't a shortage of data streams; it's the reliance on uncoordinated Carrier Sense Multiple Access (CSMA) operation across neighborhoods and within individual networks. This is the reason for OFDMA, the scheduling protocol introduced in Wi-Fi 6 and upgraded in Wi-Fi 7, as well as the MLO Discovery feature.

CSMA was a common feature in first-generation LANs of all types, but wired network engineers discovered it doesn't scale a long time ago. 10BASE-T brought full duplex, collision-free networking to 802.3 Ethernet in 1990 in the 802.3i amendment.[53] Some proposals for the initial 802.11 MAC protocol relied on scheduling over contention for permission to transmit.

One such proposal, Point Coordination Function (PCF), lives on as an option in 802.11, but its utility is limited to individual networks due to Wi-Fi's lack of cross-domain coordination.[54] Cross-domain is an issue for wireless networks because signals can't always be guaranteed to stay within the organizational units that manage networks. Wired networks don't have this problem, of course.

The Wi-Fi community finally recognized the need for scheduling by adopting OFDMA in Wi-Fi 6, but its implementation left much to be desired. Fortunately, Wi-Fi 7 signals a desire to move beyond CSMA to

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[49] Brandon Hill, "Wi-Fi 7 Is Here for Early Adopters: What You Need to Know," Tom's Hardware, October 6, 2023, https://www.tomshardware.com/news/wi-fi-7-faq.
[50] Ngo, "Asus GT-BE98 Pro Review."
[51] Dong Ngo, "Deco BE95 Review (vs Deco BE85): That Useless 6GHz-2 Band | Dong Knows Tech," February 21, 2024, https://dongknows.com/tp-link-deco-be95-wi-fi-7-mesh-system-review/.
[52] ASUS allows both 6 GHz sub-bands to used for fronthaul, but the process of overriding the default setting is complicated and poorly documented.
[53] *802.3-2022*.
[54] "Point Coordination Function," in *Wikipedia*, accessed June 27, 2012, http://en.wikipedia.org/wiki/Point_coordination_function.

inter-access point coordination, scheduled OFDMA, and spatial multiplexing. All that needs to happen is turnover from legacy devices to those that fully support Wi-Fi 7, a process that will take a decade at least.

Wi-Fi's Next Steps

When the Wi-Fi 7 standards activity was accepted by 802.11, its chief goal was to increase throughput to 30 Gbps; the final standard achieves a theoretical throughput of 47 Gbps.[55] The short title of the charter was "Enhancements for Extremely High Throughput (EHT)."[56]

In today's world, 47 Gbps can serve 5G to hundreds of residences, so we have to wonder how valuable it is to consumers as a whole to assume that multiple Gbps are needed inside each residence. Wired 2.5 Gbps Ethernet is just beginning to appear in residential and industrial scenarios, after all.[57] But this is just theoretical throughput, a feature of the standard rather than of any actual implementation. It's unlikely that ordinary Internet users are going to need a neighborhood's-worth of capacity in each individual home.

Theoretical throughput assumes a quiet radio environment and the maximum number of antennas, radios, streams, links, RF chains, subcarriers, etc. No 802.11 theoretical throughput claim has ever been observed in an actual product. But Wi-Fi 7 will reach 3-5 Gbps over 25 feet in some implementations in the near future. Given the inherent consumer-facing focus of Wi-Fi, these speeds already will exceed any reasonably expected consumer need, and even typical Internet connection speeds, by a very large margin.

We're just now seeing 2.5 Gbps ports in high-end cable modems, meant to support 1-2 Gbps Internet connections. There is demand for higher-than-Internet speeds inside data centers, offices, and factories to support access to the cloud and to local Network Attached Storage (NAS) at 10-40 Gbps, but such uses are likely to remain wired.[58]

The best that wireless can do is to boost the speed of *access to the access to* the Internet and the cloud. When organizations such as NCTA claim: *Wi-Fi, and not licensed mobile, is the workhorse of wireless services, carrying over 85% of mobile data traffic*, they're addressing the 25 feet or so from nomadic and mobile devices to the residential or enterprise network.[59]

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[55] Cheng Chen et al., "Overview and Performance Evaluation of Wi-Fi 7," *IEEE Communications Standards Magazine* 6, no. 2 (June 2022): 12–18, https://doi.org/10.1109/MCOMSTD.0001.2100082.
[56] Jon Rosdahl, "Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment: Enhancements for Extremely High Throughput (EHT)" (IEEE Standards Association, January 18, 2019), https://www.ieee802.org/11/PARs/P802_11be_PAR_Detail.pdf.
[57] "Industrial Ethernet Market Trends 2023-2032 | Share Report," Global Market Insights Inc., accessed May 12, 2024, https://www.gminsights.com/industry-analysis/industrial-ethernet-market.
[58] "Ethernet Innovation Inside The Datacenter," accessed May 12, 2024, https://www.networkcomputing.com/data-center-networking/ethernet-innovation-inside-the-datacenter.
[59] "Setting the Record Straight on Spectrum Priorities | NCTA — The Internet & Television Association," May 14, 2024, https://www.ncta.com/whats-new/setting-the-record-straight-on-spectrum-priorities.

This claim conflates mobile and nomadic devices (such as laptop computers) and ignores the 99% of the Internet that is wired. "Access" is a tricky word.

But it's important to realize that network standards bodies don't simply target current needs, they produce specifications for decades. This is true of Wi-Fi, 3GPP, Ethernet, and all the others. The logic is "if you build it, they will come," expecting new applications to emerge that can only be used on super-advanced networks. Sometimes these applications emerge within the lifetime of a given standard and sometimes they don't. Standards setting is forecasting, and past performance doesn't guarantee future results. We've had gigabit Ethernet since the '90s, but there still aren't popular apps that depend on it.

Even though Wi-Fi 7 is likely to become a commercial success at some point, it's entirely possible that we won't see clear evidence for at least five years. The winning configuration is likely to be OFDMA/MU-MIMO over MLO in the 5 GHz and lower 6 GHz bands with 80 – 160 MHz channels.

Short and Long Range

At distances of 40 feet or more, there is no measured performance benefit from channels fatter than 80 MHz. The Wi-Fi PHY enhancements developed since Wi-Fi 5 produce short-distance improvements that begin to evaporate at 4 meters.

802.11 seems to have accepted that it has pushed short-range Wi-Fi performance to or beyond reasonable limits. The next amendment of the standard, 802.11bn (Wi-Fi 8), focuses on ultra-high reliability (UHR), Quality of Service, and performance in more realistic scenarios:

> *Wi-Fi 8 is set to prioritize UHR as its key characteristic,[60] as opposed to previous standards which focused on increasing peak throughput. Indeed, delivering ultra-low deterministic latency is a key challenge for next generation Wi-Fi technologies.[61] As detailed in Fig. 4, Wi-Fi 8 has a target standardization cycle ending in 2028, with the UHR Study Group already established in July 2022 focusing on defining the protocol functionalities for future products.[62] The four key areas of focus include (i) improved throughput at lower Signal-to-Interference-plus-Noise (SINR) ratios, (ii) reducing tail latency and jitter, (iii) enhanced spectral reuse, (iv) greater power savings and peer-to-peer operations.[63]*

Realistically, we can expect that peak Wi-Fi speeds will hover around the 1 Gbps range in short-distance scenarios, with likely improvement in the drop-off rate with distance. It is unlikely that a dramatic improvement will take place even if Wi-Fi 8 is as successful as proponents expect. If this is the case, and

[60] Lorenzo Galati Giordano et al., "What Will Wi-Fi 8 Be? A Primer on IEEE 802.11bn Ultra High Reliability," 2023, https://doi.org/10.48550/ARXIV.2303.10442.
[61] Dave Cavalcanti et al., "WiFi TSN: Enabling Deterministic Wireless Connectivity over 802.11," *IEEE Communications Standards Magazine* 6, no. 4 (December 2022): 22–29, https://doi.org/10.1109/MCOMSTD.0002.2200039.
[62] IEEE Standards Association, "P802. 11bn," *Institute of Electrical and Electronics Engineers (IEEE) Standards Association, Piscataway, NJ, USA*, 2023.
[63] Ehud Reshef and Carlos Cordeiro, "Future Directions for Wi-Fi 8 and Beyond," *IEEE Communications Magazine* 60, no. 10 (October 2022): 50–55, https://doi.org/10.1109/MCOM.003.2200037; Giordano et al., "What Will Wi-Fi 8 Be?"

new applications require gigabit performance, we can expect enterprises and ordinary users to deploy additional access points in mesh network configurations.

One promising undertaking is a Study Group within 802.11, the Integrated Millimeter Wave (IMMW) SG.[64] In the 802 process, the first step toward developing a standard is a Study Group that defines the scope of the standard.

Study Groups prepare draft Project Authorization Requests (PAR). If the IMMW PAR is approved, a task force will be chartered to develop a standard.

On March 13, the study group took a straw poll on a PAR that garnered 67 ayes, 16 nays, and 25 abstentions. This indicates good progress but not success. The draft PAR proposes an expansion of Wi-Fi 7 multi-link operation in mmWave bands because the mid-band is tapped out:

> *This amendment defines standardized modifications to both the IEEE Std 802.11 physical layer (PHY) and the IEEE Std 802.11 Medium Access Control (MAC) that allows Wireless Local Area Network (WLAN) non-standalone operation in unlicensed bands between 42 GHz and 71 GHz using single-user (SU) OFDM based transmissions. The amendment requires that an 802.11 device supporting this amendment also supports at least one of the 2.4 GHz to 7.25 GHz (sub-7 GHz) unlicensed bands. The amendment expands the multi-link operation defined in the sub-7 GHz band specifications to support non-standalone operation in the unlicensed bands between 42 GHz and 71 GHz.*

The Study Group has a long way to go, but it's off to a good start. It has heard presentations on the use of light wave as well as millimeter wave transceivers at speeds of 3 – 20+ Gbps. The requirement for support of at least one form of sub-7 GHz RF is a testimony to the highly political nature of 802. The upstarts can't be seen as throwing shade on the work of the establishment.

The advent of Wi-Fi 7 indicates a desire on the part of 802.11 to enter the gigabit zone with highly reliable systems. It now has on the table three ways to get there: sub-7 GHz RF, millimeter wave RF, and optical. It's likely that at least one approach will succeed, but forecasts as to the timeline are anyone's guess. The chartering of 802.11bn tells us that the future of Wi-Fi is in higher frequencies than those used today.

The Application Context

Gigabit Ethernet has been available since 1999, following the ratification of IEEE 802.3ab;[65] gigabit Wi-Fi has been a reality since 11ax emerged twenty years later.[66] Where are the applications that depend on them?

4K video streaming, AR/VR, and high-resolution video conferencing are all great, but they work just as well at 100 Mbps as 1 Gbps. The demand for higher throughput only comes about in dense deployment

[64] Laurent Cariou, "IEEE P802.11 - Integrated Millimeter Wave Study Group," accessed May 12, 2024, https://www.ieee802.org/11/Reports/immw_update.htm.
[65] *802.3-2022*.
[66] Jim Salter, "Say Hello to 802.11ax: Wi-Fi 6 Device Certification Begins Today," Ars Technica, September 16, 2019, https://arstechnica.com/gadgets/2019/09/say-hello-to-802-11ax-wi-fi-6-device-certification-begins-today/.

scenarios such as enterprises, events, access to the cloud, and software development environments with NAS devices.

The value of ultra-high throughput is most evident when its efficiency aspect shines. When 100 people share a Wi-Fi network, every increase in throughput is a reduction in the time every individual task takes to complete. When I can download my file in half the time it used to take, more network capacity is available to the others who share a network with me. These effects are important in schools and offices with dozens or hundreds of users, but they have little significance for families.

At the moment, the appeal of gigabit networks is driven more by requirements to support hundreds of users than by individual applications. This can (and probably will) change at some point, but today's websites work perfectly well at humble access speeds of 25-50 Mbps.[67]

When the FCC released 6 GHz spectrum in 2020,[68] the Wi-Fi Alliance said it was going to be really, really big:

> *"This is the most monumental decision around Wi-Fi spectrum in its history, in the 20 years we've been around," Kevin Robinson, marketing leader for the Wi-Fi Alliance, an industry-backed group that oversees the implementation of Wi-Fi, said ahead of the vote. "We will not be in the same position we are today five years from now," Robinson said.*[69]

We certainly aren't in the same position. For the first time in my experience, Wi-Fi equipment vendors are saying *they're just not that into* the new batch of unlicensed spectrum. As noted, router companies are delegating the new channels to backhaul. In addition to the ones I've tested, Netgear sees Wi-Fi 7 as a backhaul technology:

> *"The performance boost using our Enhanced Dedicated Backhaul can immediately be observed even on WiFi 6 devices," said Sandeep Harpalani, VP Product Management for Netgear. "We see multi-gig speeds throughout the house. With our enhanced dedicated backhaul (using MLO to combine the dedicated 5 GHz backhaul radio and share 6 GHz for up to 10 Gbps), the backhaul throughput is 5x prior mesh systems."*[70]

Device manufacturers are waiting for demand to develop before upgrading. The iPad Pro upgrade announced in May 2024 is typical, sticking with the Wi-Fi 6E tech that shipped with the iPhone 15 Pro Max last year. Some vendors are currently shipping Wi-Fi 7-capable smartphones but not enabling it:

> *You may already have a Wi-Fi 7 smartphone if you own the Samsung Galaxy S23 Ultra. Qualcomm's FastConnect 7800 network adapter, which is now certified for the new Wi-Fi standard, is included with Samsung's 2023 flagship phone. The only trouble is, to date, Samsung hasn't enabled the feature. It would be a significant upgrade if it*

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67 Bennett, "You Get What You Measure."
68 "FCC Opens 6 GHz Band to Wi-Fi and Other Unlicensed Uses | Federal Communications Commission," news magazine, Lightwave, April 24, 2020, https://www.fcc.gov/document/fcc-opens-6-ghz-band-wi-fi-and-other-unlicensed-uses-0.
69 Jacob Kastrenakes, "Wi-Fi Is Getting Its Biggest Upgrade in 20 Years," The Verge, April 23, 2020, https://www.theverge.com/2020/4/23/21231623/6ghz-wifi-6e-explained-speed-availability-fcc-approval.
70 Hill, "Wi-Fi 7 Is Here for Early Adopters."

> *did, though, even if it only gets half of the 5.8Gbps throughput that Qualcomm claims on its site (given a Wi-Fi 7 router and a fast enough internet connection, that is).*[71]

They need signals that can propagate 15 – 35 feet without evaporating. They need standards that improve coordination, not just ones that generate more interference. While the FCC and the Wi-Fi Alliance were very excited about three 320 MHz channels four years ago, we're now seeing vendors disregarding them.

The normally boosterish tech blogs advise a wait-and-see approach. Verge's Wes Davis offers the summary: *If you're hoping for Wi-Fi 7 to fix your whole network, you should wait. With the spec incomplete and so few devices supporting it, you wouldn't see the benefit from it for months or even years.*[72]

The reality of 6 GHz signal degradation with distance, the complexity of Wi-Fi 7, the premium prices for multi-gigabit devices, and limited application appeal suggest that Wi-Fi 7's feature set may not be enough to enable better Wi-Fi networks in the near-term. At present, the greatest advantage of Wi-Fi 7 is MLO, a feature that increases performance without putting more spectrum in the unlicensed bank. In my testing, MLO increased near scenario throughput by 45% across the Wi-Fi 7 spectrum pool.

Conclusion

Wi-Fi advocates have succeeded in convincing regulators to allocate more and more spectrum to their use case largely on the basis of predictions about traffic growth and simulations predicting network performance improvements. Traffic growth is outside the scope of this study and inherently hard to characterize. By contrast, raw performance is relatively easy to measure. Measurement doesn't confirm the predictions.

Wi-Fi 4 brought about a major performance increase over previous standards. Wi-Fi 5 was similar, if less dramatic. Subsequent generations are much less impressive; in some scenarios Wi-Fi 6, 6E, and 7 are all pretty much the same as prior standards. In others, Wi-Fi 7 can perform quite well, especially at limited distances, depending on antenna characteristics. The approach of doubling channel width in every generation while dipping into the mid-band spectrum pool isn't working, especially at distances greater than 30 feet.

Wi-Fi should pursue a different approach, using higher millimeter wave frequencies and those above the RF range. It should also focus more on reliability than on raw performance. Fortunately, many in the IEEE 802 community seem to be realizing this imperative.

But politics plays a part in standards development, and some stakeholders are more concerned with taking spectrum off the table than simply making Wi-Fi work better. Wi-Fi simply doesn't show signs of being constrained by a dearth of mid-band spectrum today, or indeed for the foreseeable future. Wi-Fi has yet to capitalize on the 60 GHz spectrum already allocated to it or, for that matter, the 6 GHz band,

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[71] Wes Davis, "These Are the Certified Wi-Fi 7 Devices You Can Buy Now," The Verge, January 15, 2024, https://www.theverge.com/2024/1/14/24038284/wi-fi-certified-7-products-list-wi-fi-alliance.
[72] Wes Davis, "What Is Wi-Fi 7 — and Do You Even Need It?," The Verge, October 16, 2023, https://www.theverge.com/23902812/wi-fi-7-explained.

but the mmWave band is much more practical for limited-range networks than for those like cellular that need to operate outdoors at greater distances.

Advocates of unlicensed spectrum see it as free because they don't consider the high opportunity cost of assigning mid-band spectrum where it isn't needed rather than to applications and use cases that are able to fully exploit it for mobility, competitive residential broadband, secure networks, and the Internet of Things.

The immediate priorities for spectrum regulators may be stated simply: push indoor, limited-distance networks into the low propagation millimeter wave and optical bands, and assign more mid-band for licensed use by general-purpose networks.