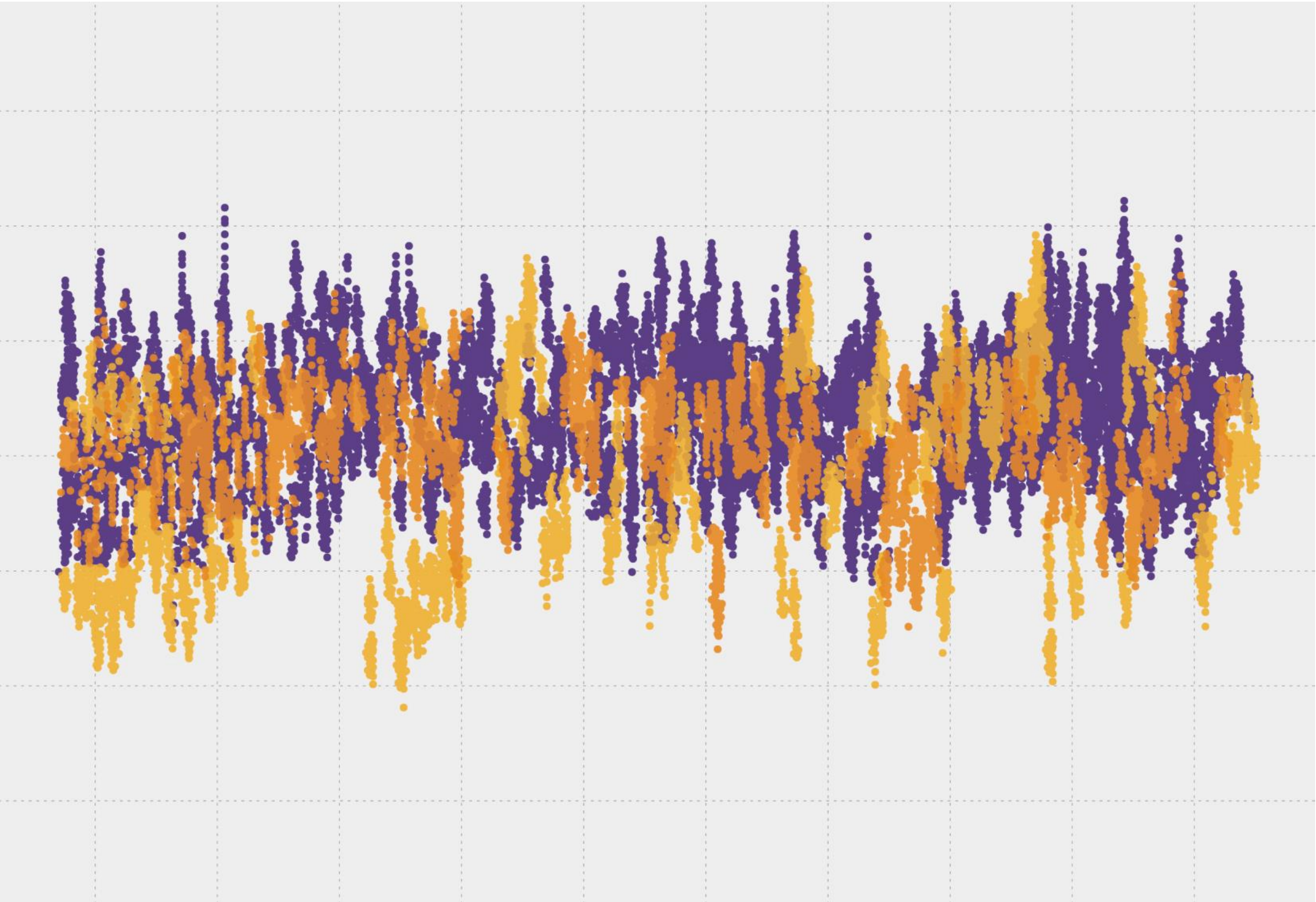
Wi-Fi® Spectrum Requirements

18 March 2024

Richard Rudd



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Plum offers strategy, policy, and regulatory advice on telecoms, spectrum, online, and audio-visual media issues. We draw on economics and engineering, our knowledge of the sector and our clients' understanding and perspective to shape and respond to convergence.

About this study

Policymakers in several countries are investing significant resources to upgrade connectivity infrastructure, targeting universal gigabit broadband within a decade. But with Wi-Fi® becoming the primary means by which people and devices connect to the Internet, the overall connectivity benefits depend on Wi-Fi performance. As with any wireless technology, inadequate spectrum capacity degrades Wi-Fi performance. This study for the Wi-Fi Alliance uses engineering models to analyse spectrum requirements for Wi-Fi technology to deliver gigabit connectivity to residential premises.

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Executive Summary

The EU's Gigabit Infrastructure Act and the Digital Decade Policy Programme 2030 aim to ensure that a fixed Gigabit network (i.e., one providing connectivity at a downlink speed of 1 Gbps) covers all EU households.[1] Wi-Fi plays a crucial role in the distribution of fixed broadband connectivity in homes, offices, and various other environments. The vast majority (up to 92%) of home internet traffic is connected to the end-user through Wi-Fi. In enterprise settings, Wi-Fi is essential for handling the large amounts of data and simultaneously connecting large number devices with improved reliability, higher data throughput and lower latencies. EU members are prioritizing deployment of very high-capacity fixed network infrastructure – but connectivity is only as good as the narrowest bottleneck. In short, Wi-Fi functionality is integral to the European modern connected lifestyle in homes, businesses, and public spaces.

As more people and more devices connect through Wi-Fi networks, the demand for spectrum bandwidth increases significantly. Proliferation of high-bandwidth applications, such as high-definition video streaming, automation, gaming, remote work and learning, augmented and virtual reality, and distributed computing are straining the available Wi-Fi spectrum capacity even further. The latest generations of Wi-Fi offer design features that significantly improve Wi-Fi spectral efficiency, particularly in environments with high user and device densities, but these technological improvements are not enough to overcome bandwidth constraints.[2] Adequate spectrum capacity (bandwidth) is imperative to Wi-Fi performance, ensuring that it does not become a bottleneck that constrains the end-to-end connectivity.

The focus of this study is to simulate and analyse the impact of spectrum availability on Wi-Fi ability to support gigabit connectivity in the European residential deployments. In most of Europe, only five 160 MHz channels (two[3] at 5 GHz, three at 6 GHz) are available for Wi-Fi access, whereas other countries have increase spectrum availability to up to ten 160 MHz channels (three at 5 GHz, seven at 6 GHz).[4] The simulation models high-density Wi-Fi deployment in a typical residential apartment building with gigabit fibre connectivity to every apartment. The model's is set to ensure that Wi-Fi spectrum congestion does not constrain (i.e., bottleneck) the gigabit connectivity. The model is based on the deployment pattern set out by the IEEE[5] for use in simulations.

The results of this study confirm that spectrum capacity available for Wi-Fi access in Europe is inadequate to support the EU's Gigabit policy objectives. Inadequate spectrum capacity degrades Wi-Fi performance and, ultimately, undermines the gigabit infrastructure investments and benefits. Europe's current five 160 MHz channels can only support gigabit coverage to approximately 50-60% of residential building area. To ensure whole-building coverage, a minimum of ten channels is necessary. Therefore, Wi-Fi access to the 6.425-7.125 GHz is imperative to support current and future generations of Wi-Fi in Europe.

Importantly, the ability of Wi-Fi to support gigabit connectivity is not limited to any specific region, including Europe. While factors such as regulatory environments, available spectrum, and usage patterns may vary from one region to another, the fundamental principles and technologies underlying Wi-Fi's ability to deliver gigabit speeds, and thereby results of this study, remain consistent globally.

[1] See Gigabit Infrastructure Act at https://digital-strategy.ec.europa.eu/en/policies/gigabit-infrastructure-act ; See Gigabit Infrastructure Act available at https://digital-strategy.ec.europa.eu/en/policies/gigabit-infrastructure-act ; Europe's Digital Decade Policy Programme available at https://digital-strategy.ec.europa.eu/en/policies/europes-digital-decade

[2] *Orthogonal Frequency Division Multiple Access* allows multiple devices to communicate simultaneously within a single Wi-Fi channel by dividing it into smaller sub-channels called resource units (RUs). *Basic Service Set Colouring* helps mitigate interference between neighbouring Wi-Fi networks operating on the same channel. *4096-QAM* increases the data transmission rate by encoding more bits per symbol compared to previous Wi-Fi standards. *Multi-Link Operation* enables the simultaneous use of multiple Wi-Fi channels for data transmission. *Target Wake Time* allows devices to schedule when they wake-up to communicate with the router, reducing unnecessary wait time and conserving power.

[3] In practical deployments, smaller channel widths will generally be selected at 5 GHz to give better re-use and accommodate legacy devices.

[4] Wi-Fi access to the 5 GHz channels is constrained by the Dynamic Frequency Selection (DFS) requirements. The DFS implementation complexities further reduce 5 GHz utilization, driving data traffic to other (unconstrained) channels.

[5] *IEEE P802.11 Wireless LANs - TGax Simulation Scenarios. IEEE 802.11-14/0980r16. IEEE, July 2015*

This study does not consider Wi-Fi performance in the enterprise settings. Today, enterprise Wi-Fi networks support a large variety of use cases and applications, in education, healthcare, logistics, manufacturing, hospitality, and large public venues. Importantly, enterprise Wi-Fi networks are precisely engineered for high-density deployments to maximize availability and reliability, to optimize performance parameters such as throughput and latency, and to reduce the impact of interference from external sources. It is expected that lack of spectrum capacity would have a significant and detrimental impact on the performance of enterprise Wi-Fi.

1 Introduction and background

Wireless has become the default way in which people and devices connect to the internet, and these connections are dominated by Wi-Fi. In Europe, 98% of home internet access is provided by fixed technologies (fibre and cable) and 92% of that traffic is then relayed by Wi-Fi to end users.[6] Not only is Wi-Fi used to connect devices to the internet, but it is also employed to connect devices, and the people that use them, to each other. The applications for these devices are expanding rapidly to smart cities and public venues such as educational institutions, stadiums, health care facilities (to connect critical care monitors and similar devices) as well as in the enterprise settings such as offices or manufacturing facilities (e.g., for industrial automation) and, of course, in homes to support a variety of high data throughput use cases.

Wi-Fi technology has evolved continually over more than two decades, using spectrum sensing and polite protocols to minimize interference to other services and leveraging techniques such as MIMO, larger channel bandwidths and frequency "colouring" to maximize spectrum efficiency. Over time, the spectrum available for Wi-Fi access expanded from the 80 megahertz (MHz) in the 2.4 gigahertz (GHz) spectrum, to the addition of 560 MHz in the 5 GHz range and then further to the new spectrum in 6 GHz. In several countries, Wi-Fi can access 1200 MHz of 6 GHz spectrum, but in Europe only 500 MHz in the lower 6 GHz band is available (a total of 1060 MHz).[7]

Despite this evolution, it is increasingly the case that Wi-Fi quality of service is being constrained by spectrum congestion. That congestion is being caused not only by the volume of Wi-Fi devices being used through the expanded use of Wi-Fi to connect people and things, but also the type of Wi-Fi applications. New uses such as augmented and virtual reality (AR/VR) devices require greater bandwidths and lower latency, which both require additional spectrum access.

In 2016 a study by Qualcomm [2] concluded that regulators should plan to ensure that approximately 1280 MHz of spectrum is available for Wi-Fi at "around 5 GHz." The study was updated in 2023, showing that the use cases modelled (Enterprise and Dense Residential) required a total of between 600 MHz and 2,400 MHz of spectrum.

A different technical modelling exercise (the "Wi-Fi Spectrum Needs Study") by Quotient Associates in 2017 [4] determined that a total of 1120 MHz (or 1920 MHz, taking a pessimistic "upper bound") would need to be available at 5/6 GHz by 2025, with the residential case being the most challenging. At the time, only 455 MHz of 5 GHz spectrum was available, giving a potential shortfall of 665 MHz (or 1465 MHz for the 'upper bound')[8].

Since the Quotient study, an additional 480 MHz in the lower 6 GHz band[9] has been made available for Wi-Fi use in Europe, but current regulations preclude Wi-Fi is access to the remaining portion of the 6 GHz band (6.425-7.125 GHz). Importantly, present and future generations of Wi-Fi are engineered for optimal performance in the 6 GHz band – there is no alternative spectrum.[10]

1.1 The latest Wi-Fi technologies improve spectrum efficiency

Since its first widespread adoption around the time of the Millenium, the "headline" bit rates available to Wi-Fi users have increased by three orders of magnitude. Over the same timescale, however, the data rates demanded by user applications have increased while the tolerance of latency has decreased for many applications. Furthermore, the sheer popularity of Wi-Fi has led to a much higher device density and a

[6] Digital Economy and Society Index (DESI) 2022 | Shaping Europe's digital future (europa.eu)
[7] *See* https://www.wi-fi.org/countries-enabling-wi-fi-6e
[8] These figures assume the use of spectrum constrained by the Dynamic Frequency Selection (DFS) requirement. The values are higher if this is not available.
[9] In two CEPT administrations, a further 125 MHz in the sub-band at 5725-5850 MHz has also been authorised for use.
[10] See Wi-Fi Certified 7™ available at https://www.wi-fi.org/news-events/newsroom/wi-fi-alliance-introduces-wi-fi-certified-7

consequent increase in mutual interference. According to a report[11] by IDC Research, there were 19.5 billion Wi-Fi devices in use in 2023.

Although the headline physical layer data rate in Wi-Fi 6 increases from 7 Gbit/s to 10 Gbit/s, such figures are increasing irrelevant in a spectrum contended environment. More significant in terms of practical user experience will be the adoption of OFDMA[12], which can greatly improve the throughput efficiency of real data over a given physical channel data rate.

Wi-Fi 6 also improves spectrum utilization though the use of BSS colouring[13], in which traffic within a particular network carries an identifying flag, or “colour.” This can be used to allow other networks to determine patterns of frequency, spatial, and temporal occupancy in their neighbourhood, and to optimize scheduling to minimize interference.

The new Wi-Fi 7 standard, with certification through Wi-Fi Alliance starting January 2024, doubles the maximum channel width from the 160 MHz of Wi-Fi 5 and Wi-Fi 6 to 320 MHz. In addition, the highest-order modulation increases from 1024-QAM to 4096-QAM (although there will be statistically few links with the signal-noise ratio required to exploit this). Multi-Link Operation (MLO) allows traffic to be aggregated across links established simultaneously on multiple bands. When applied to mesh networks, it can allow both backhaul and user traffic to be switched seamlessly between bands in response to interference or other link degradation.

Despite these substantial improvements in spectrum efficiency, the popularity and ubiquitous deployment of Wi-Fi networks means that in many cases, performance is limited by mutual interference, due to lack of spectrum resource.

A summary table of Wi-Fi technical characteristics across the generations is provided in Appendix B.

1.2 Current and prospective spectrum availability

1.2.1 History of Wi-Fi spectrum access

The history of spectrum availability is complicated and subject to considerable regional variations, which have created significant problems for manufacturers and users. The initial allocation in the Industrial, Scientific and Medical’ (ISM) spectrum at 2.4 GHz accommodates four non-overlapping 20 MHz channels.

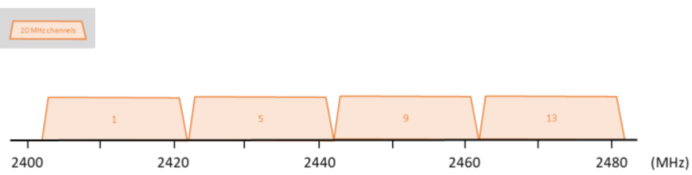


Figure 1.1: Spectrum at 2.4 GHz available for Wi-Fi access[14]

With the introduction of 802.11a in 1999, a further 200 MHz of spectrum became available at the lower end of the 5 GHz band (5150-5350 MHz) and this expanded over time to 5900 MHz. Use of the upper parts of the band are constrained by the need to protect radar and other systems, and there is a complicated pattern of regional

[11] IDC Worldwide Wi-Fi Technology Forecast, 2023-2027, March 2023
[12] Orthogonal Frequency-Division Multiple Access
[13] In Wi-Fi parlance, a ‘Basic Service Set’ defines a network of user devices connected to an Access Point.
[14] Other unlicensed technologies (e.g., Bluetooth) use portions of the 2.4 GHz band which further limits Wi-Fi spectrum access

power restrictions and mandatory requirements to implement Dynamic Frequency Selection (DFS) based on the detection of local radar emissions.

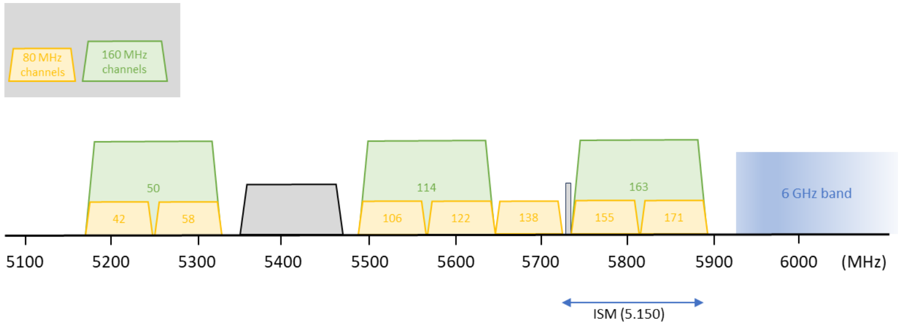


Figure 1.2: Spectrum at 5 GHz available for Wi-Fi (US)

The situation in Europe is even more constrained than in the US, with the spectrum at 5710-5875 MHz currently only available in most countries for 'Short-Range Devices' (SRD) operating indoors at low-power (<25mW) levels, inhibiting Wi-Fi connectivity. The limitation is due to concerns regarding coexistence with 'Intelligent Transport Systems' (ITS) such as road-tolling that operate in this spectrum[15]. This constraint is alleviated in some EU countries (e.g., Czech Republic) that approved use of this spectrum at 200mW equivalent isotropic radiated power (EIRP).

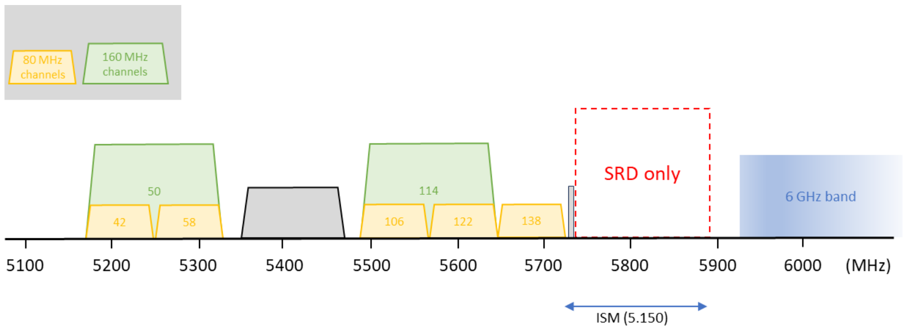


Figure 1.3: Spectrum at 5 GHz available for Wi-Fi (Europe)

With the release of 802.11ax (Wi-Fi 6), the ability to use spectrum at 6 GHz was added to the standard (for the subset of devices branded as Wi-Fi 6E[16]), enabling access to a further seven x 160 MHz channels. In the US, all channels are available for indoor use with EIRP up to 30dBm ("Low-power Indoor", or LPI) while four channels may also be used outdoors with up to 36dBm power.

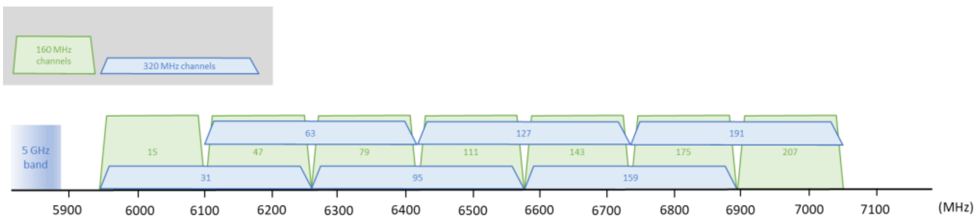


Figure 1.4a: Spectrum at 6 GHz available for Wi-Fi (US)

15 See: ECC Report 277 (cept.org)
16 'E' for 'Extended'

In Europe the situation is more constrained, with only the three lowest 160 MHz channels available.

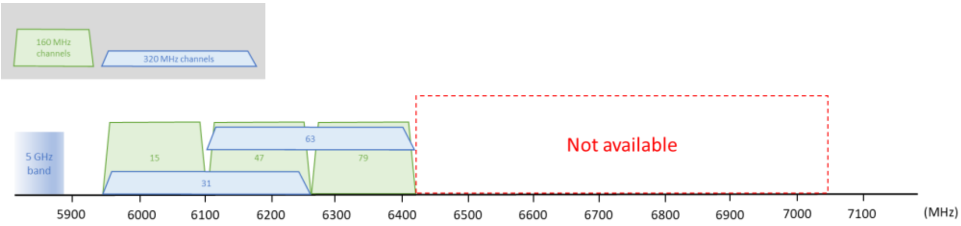


Figure 1.5b: Spectrum at 6 GHz available for Wi-Fi (Europe)

In the majority of Europe there are, therefore, only five 160 MHz channels currently available for use by Wi-Fi systems, compared with ten in the US.

1.2.2 Regulatory examination of possible spectrum scenarios

Since 2022, the European Conference of Postal and Telecommunications Administrations (CEPT) has been studying the coexistence of Wi-Fi with incumbent services in the upper 6 GHz band[17], and in 2023 it initiated an activity[18] to examine possible coexistence with IMT services in the same band. In the UK, Ofcom is studying[19] the options for "hybrid sharing" of this band between IMT, WLAN and incumbent services; their initial view is that IMT/WLAN coexistence is unlikely to be practical. Ofcom's work will continue in 2024 and may involve further consultation.

At WRC-23, the 6425-7125 MHz frequency band was identified for IMT in EMEA, but with a footnote emphasizing that "*The identification does not preclude any application of the services to which they are allocated and does not establish priority in the Radio Regulations. The frequency bands are also used for the implementation of wireless access systems (WAS), including radio local area networks (RLANs)*."

[17] See: ECC - Groups - ECC - WG SE - SE 45 - News (cept.org)
[18] ECC Work Item PT1_50: Feasibility and sharing studies on the potential shared use of the 6425-7125 MHz frequency band between MFCN and Wireless Access Systems including Radio Local Area Networks (WAS/RLAN)
[19] Consultation: Hybrid sharing: enabling both licensed mobile and Wi-Fi users to access the upper 6 GHz band - Ofcom

2 Modelling approach

The simulator is implemented in the C++ language as a Monte Carlo model.

The simulation is limited to the physical layer and focusses on establishing carrier to noise and interference ratios (C/(N+I)) values at each device at each timestep. These values then determine the instantaneous MCS[20] and hence traffic capacity for that link.

2.1 Model scenario

The model represents the high-density Wi-Fi use case of a domestic apartment building. It is assumed that gigabit fibre connectivity is provided to every apartment, and that there is a requirement to ensure that Wi-Fi spectrum congestion does not impose a bottleneck on the availability of this bandwidth. The model is based on the deployment pattern set out by the IEEE[21] for use in simulations.

The IEEE scenario assumes a building with a 100m x 20m footprint, with five floors. There are twenty 10x10m apartments on each floor. We have followed the Qualcomm modification, assuming a residential building of half the length (50m x 20m) with only three floors and ten apartments on each floor.

We assume that each apartment is served by a single AP with a gigabit fibre connection.

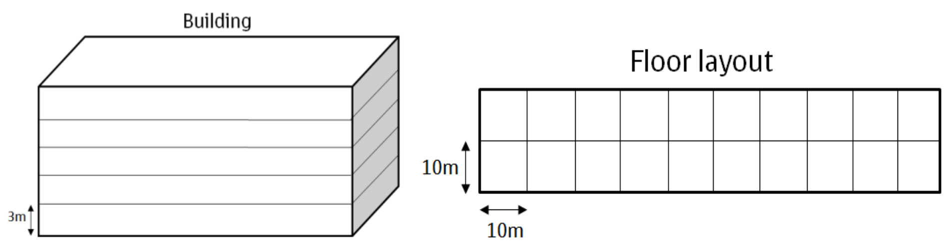


Figure 2.1: IEEE 'Dense Residential' scenario (modified in this study)

2.2 Model framework and methodology

The model consists of a semi-deterministic time-series simulator, in which access points can be deployed within a building and user terminals connect to them. The users move randomly within each room.

For each receiver, at each timestep, the received power at each user terminal is calculated from both the wanted AP and from all other AP transmitters in the simulation. This calculation accounts for propagation (the path between terminals is ray-traced, and intersections with walls, ceilings, etc. accounted for). A full-buffer traffic model is assumed.

In this simulation framework, the user terminals serve only as a tool for sampling the potential link quality as they move in the environment, gathering statistics as the simulation progresses. The actual deployment density of user terminals is irrelevant so long as the simulation run time allows the statistical output to converge.

[20] Modulation & Coding Scheme
[21] *IEEE P802.11 Wireless LANs - TGax Simulation Scenarios. IEEE 802.11-14/0980r16. IEEE, July 2015*

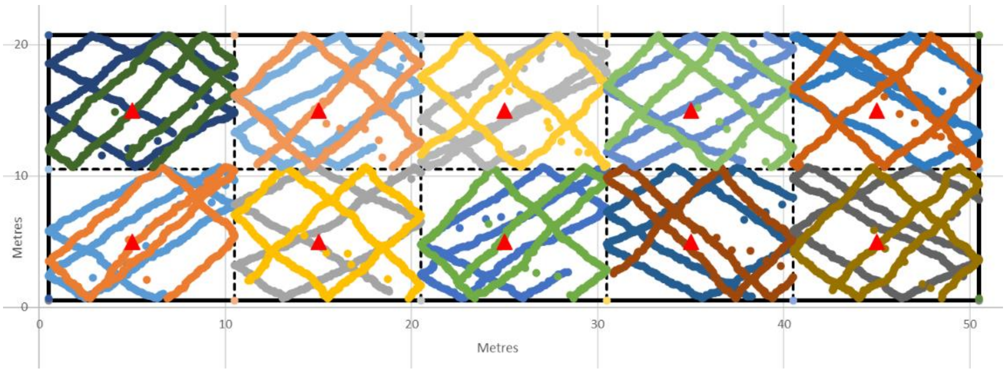


Figure 2.2: Simulation geometry: 'Dense Residential', showing single floor

At each timestep of the model, and for each AP-user link, the instantaneous C/(N+I) is then determined (Figure 2.3) and this is used to determine the highest MCS available for the link. The throughput for each link is then determined on this basis.

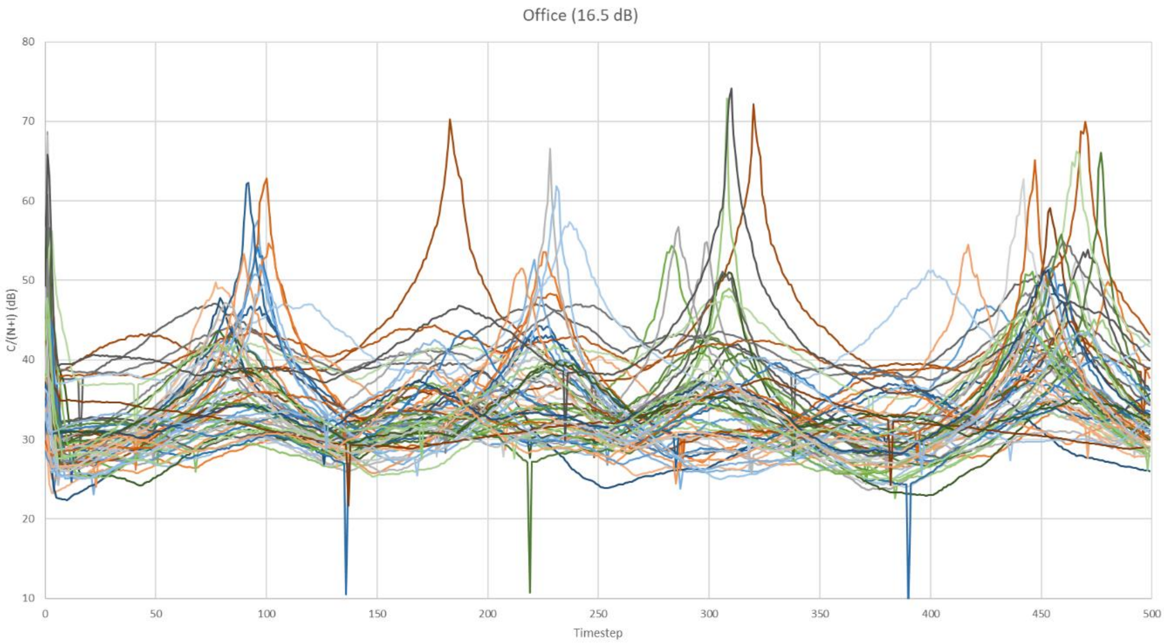


Figure 2.3: Evolution of C/(N+I) values for all terminals in a simulation

At the end of each simulation, a cumulative distribution of the downlink throughput for all links in the simulation is generated, allowing the location probability of any throughput value to be determined.

2.3 PHY parameters

The following parameters are assumed in the simulation.

Table 2.1: Simulation parameters

Parameter	Value
Antenna type (AP & user)	isotropic
Transmitter EIRP	23dBm
MIMO order	2
Receiver (user terminal) noise figure	10 dB
Sensitivity vs MCS	Table 27-58 of 802.11ax specification
C/(N+I) requirement per MCS	Derived from sensitivity and noise figure
Channel bandwidth	80 megahertz and 160 megahertz
Propagation model	P.1238 with variable wall/floor losses

Two MIMO spatial streams are assumed, as the majority of user devices only include two antennas.

2.4 Spectrum channel configurations studied

For the scenario under consideration, where domestic users require maximum throughput, the use of 160 megahertz or wider channels would be preferred to optimize network efficiencies.

In the modelling below, we explicitly examine the following cases for the availability of 160 MHz channels:

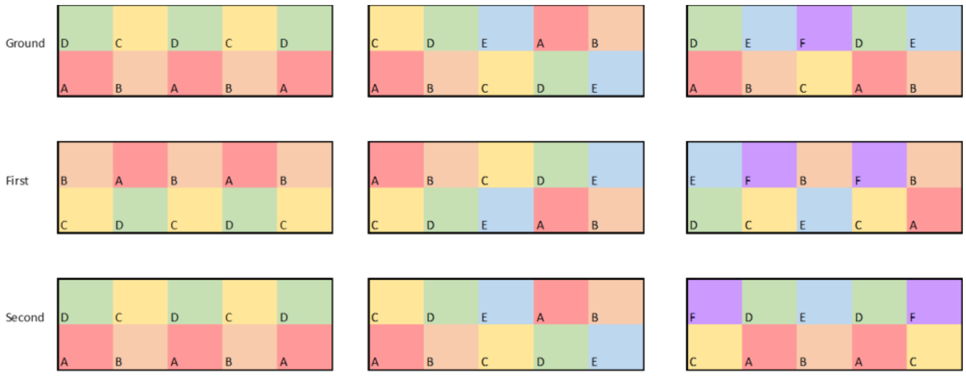
- 5 channels, two at 5 GHz, three at 6 GHz (Current case in most CEPT countries)
- 6 channels, three at 5 GHz, three at 6 GHz (Current UK and Czechia case)
- 9 Channels, two at 5 GHz, seven at 6 GHz (Future CEPT scenario)
- 10 Channels, three at 5 GHz, seven at 6 GHz (Future CEPT scenario)

Vendors have suggested to us, however, that it is unlikely that wider channels will be universally deployed in the 5 GHz band, due to the need to maximize frequency reuse options, and to accommodate legacy equipment. We have therefore additionally considered scenarios where 80 MHz channels are used. This finer granularity also allows the use of the spectrum at 5650-5730 MHz (ch.138). The 80 megahertz cases examined are:

- 11 channels, five at 5 GHz, six at 6 GHz (Current case in most CEPT countries)
- 13 channels, seven channels at 5 GHz, six at 6 GHz (Current UK and Czechia case)
- 19 channels, five at 5 GHz, fourteen at 6 GHz (Future CEPT scenario)
- 21 channels, seven at 5 GHz, fourteen at 6 GHz (Future CEPT scenario)

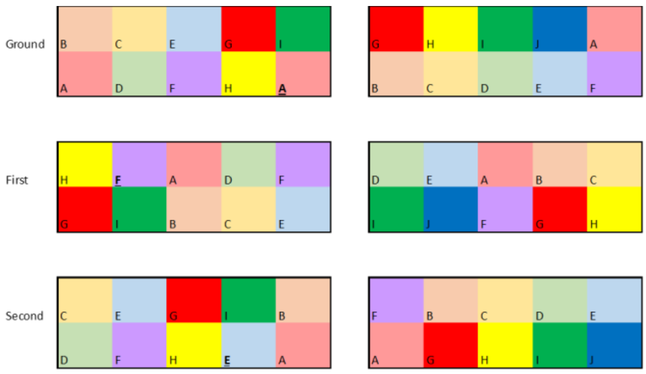
3 Results

The following frequency assignments are assumed in the modelling.



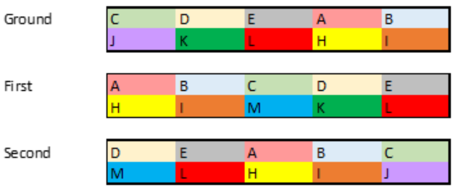
Ref	Ch. No.	MHz
A	50	5250
B	114	5570
C	163	5815
D	15	6025
E	47	6185
F	79	6345

Figure 3.1: 'Dense Residential' channel assignment (160 MHz, five and six channel cases)

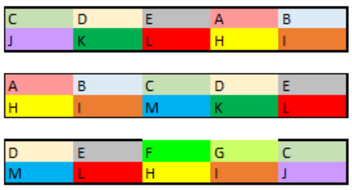


Ref	Ch. No.	MHz
A	50	5250
B	114	5570
C	163	5815
D	15	6025
E	47	6185
F	79	6345
G	111	6505
H	143	6665
I	175	6825
J	207	6985

Figure 3.2: 'Dense Residential' channel assignment (160 MHz, nine and ten channel cases)



Ref	Ch. No.	MHz
A	42	5210
B	58	5290
C	106	5530
D	122	5610
E	138	5690
H	7	5985
I	23	6065
J	39	6145
K	55	6225
L	71	6305
M	87	6385



Ref	Ch. No.	MHz
A	42	5210
B	58	5290
C	106	5530
D	122	5610
E	138	5690
F	155	5775
G	171	5855
H	7	5985
I	23	6065
J	39	6145
K	55	6225
L	71	6305
M	87	6385

Figure 3.3: 'Dense Residential' channel assignment (80 MHz, eleven and thirteen channel cases)

Floor					
Ground	A	B	C	I	J
	D	E	H	L	M
First	I	J	K	O	P
	L	M	N	R	S
Second	O	P	Q	A	B
	U	S	T	D	E

Ref	Ch. No.	MHz
A	42	5210
B	58	5290
C	106	5530
D	122	5610
E	138	5690
H	7	5985
I	23	6065
J	39	6145
K	55	6225
L	71	6305
M	87	6385
N	103	6465
O	119	6545
P	135	6625
Q	151	6705
R	167	6785
S	183	6865
T	199	6945
U	215	7025

Floor					
Ground	A	B	C	I	J
	D	E	H	L	M
First	I	J	K	F	P
	L	G	N	R	S
Second	O	P	Q	A	B
	U	S	T	D	E

Ref	Ch. No.	MHz
A	42	5210
B	58	5290
C	106	5530
D	122	5610
E	138	5690
F	155	5775
G	171	5855
H	7	5985
I	23	6065
J	39	6145
K	55	6225
L	71	6305
M	87	6385
N	103	6465
O	119	6545
P	135	6625
Q	151	6705
R	167	6785
S	183	6865
T	199	6945
U	215	7025

Figure 3.4: 'Dense Residential' channel assignment (80 MHz, nineteen and twenty-one channel cases)

The cumulative distribution functions (CDF) below shows the impact of the different frequency reuse options on the area of the building at which gigabit rates can be sustained, assuming a single fibre-connected AP in each apartment. The throughput values in the plot are those for individual links, with statistics aggregated across the whole scenario.

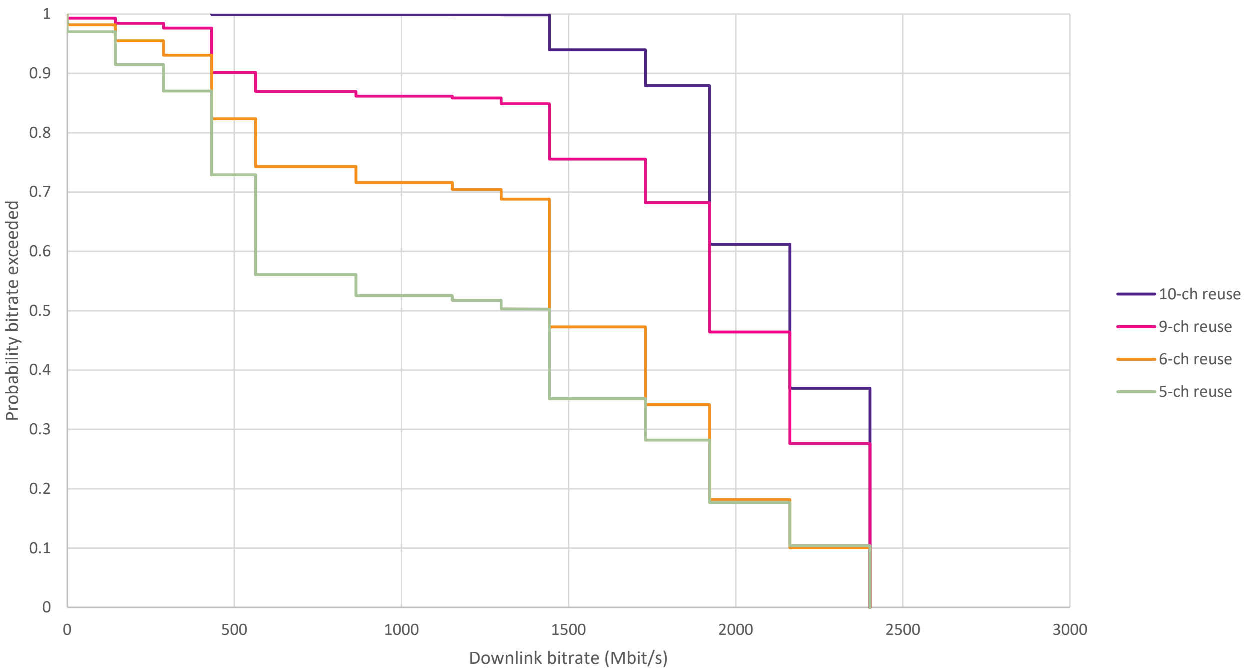


Figure 3.5: Throughput statistics for a 'Dense Residential' scenario with 160 MHz channels

Figure 3.5 shows that the gigabit target is reached for 52% of the building area with five x 160 MHz channels, 87% with nine x 160 MHz channels and 100% with ten channels. The corresponding statistics for the 80 MHz channel case are shown below.

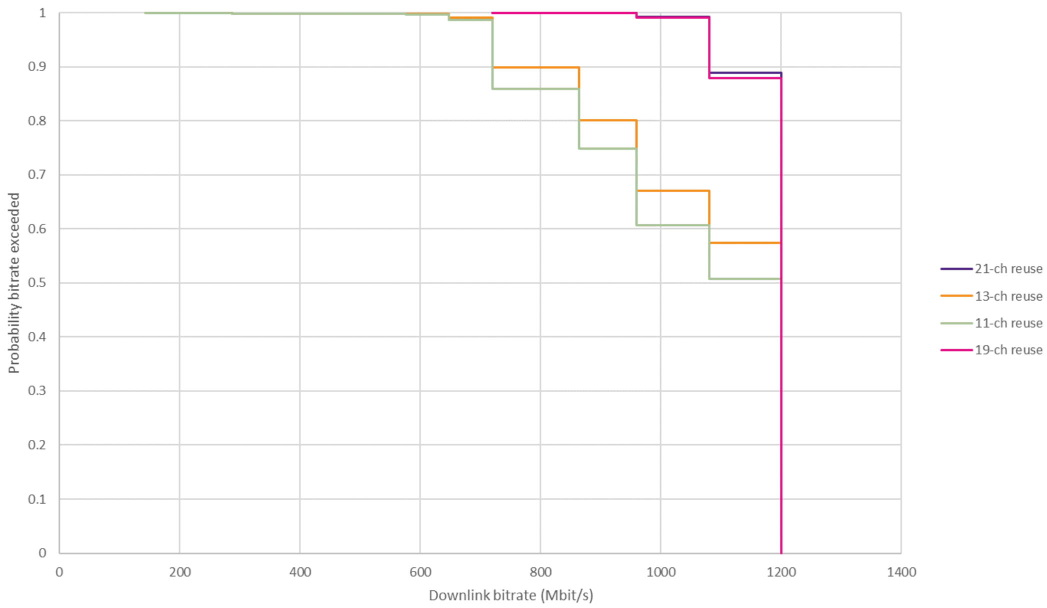


Figure 3.6: Throughput statistics for a 'Dense Residential' scenario with 80 MHz channels

The 11 channel cases allows 61% of the building area to achieve the gigabit target, while the use of 19 or 21 channels gives 99% coverage. In this case, it is not interference that is the issue, but that the carrier level is insufficient to close the link budget for the higher MCS required.

3.1 Summary and commentary

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).

If the upper 5 GHz channels are also available, 100% coverage can be achieved in the 160 MHz case, and just short of this in the 80 MHz case. With this amount of spectrum available, the constraint in the 80 MHz case is no longer that of interference, but simply that the link budget is too low in 1% of cases to allow the higher-order modulation that would be required to deliver a gigabit rate over the relatively narrow channel.

4 Conclusion

The simulations described above provide a quantitative illustration of the relationship between spectrum availability and Wi-Fi performance in residential deployments.

In most of Europe, only five 160 MHz channels (two at 5 GHz and three at 6 GHz) or eleven 80 MHz channels are available for Wi-Fi services. The results described above indicate that, for the dense use case examined, this is only sufficient bandwidth to support gigabit connectivity in around 50-60% of residential building area. To ensure whole-building coverage, a minimum of ten 160 MHz channels would be necessary, implying that both the 5710-5875 MHz sub-band and the upper 6 GHz band would need to be made available in Europe.

Although this study did not analyse Wi-Fi performance in enterprise settings, it is expected that the low number of non-overlapping channels greatly restricts the opportunities for high-density enterprise Wi-Fi in Europe.

Appendix A References

[1] Brian Williamson, Thomas Punton, Paul Hansell, "*Future proofing Wi-Fi – the case for more spectrum*", Plum Consulting report for Cisco, 2013.

[2] Rolf de Vegt, George Cherian, Gwen Barriac, Qingjiang Tian, "*A Quantification of 5 GHz Unlicensed Band Spectrum Needs*", Qualcomm Technologies, Inc., 2016. Revised in 2023.

[3] *IEEE P802.11 Wireless LANs - TGax Simulation Scenarios. IEEE 802.11-14/0980r16. IEEE, July 2015*

[4] Steve Methley, William Webb, "*Wi-Fi Spectrum Needs Study*", Quotient Associates for Wi-Fi Alliance, 2017

[5] Ing Peter Kroon, Ilsa Godlovitch, Dr Thomas Plückebaum, "Sustainability Benefits of 6 GHz Spectrum Policy", WIK consult for Wi-Fi Alliance, July 2023

[6] Akhmetov D., Arefi, R., Yaghoobi, H., Cordeiro, C. "White Paper on Next Generation Wi-Fi, Spectrum Needs of Wi-Fi 7", 2023. Intel Labs, 2023. (link)

Appendix B Wi-Fi standards

Table B.1: Outline of Wi-Fi technical characteristics

Date	Standard	Branding	Technology	Highest modulation order	MIMO		Maximum bandwidth	Spectrum (GHz band)			Max speed Raw PHY (typ user)
					Type[1]	Streams		2.4	5	6	
1997	802.11	-	FH	GFSK	-	-	1 MHz	✓			2 Mbit/s
1999	802.11b	(Wi-Fi 1)	DSSS	QPSK	-	-		✓			11 Mbit/s
1999	802.11a	(Wi-Fi 2)	OFDM	64QAM	-	-	20 MHz		✓		54 Mbit/s (~25 Mbit/s)
2003	802.11g	(Wi-Fi 3)	OFDM	64QAM	-	-	20 MHz	✓			54 Mbit/s
2008	802.11n	(Wi-Fi 4)	OFDM	64QAM	SU	4	40 MHz	✓	✓		600 Mbit/s
2014	802.11ac	(Wi-Fi 5)	OFDM	256QAM	MU(d)	8	160 MHz		✓		6.9 Gbit/s
2019	802.11ax	Wi-Fi 6/6E	OFDM OFDMA[22]	1024QAM	MU(du)	8	160 MHz	✓	✓	'6E'	9.6 Gbit/s (~1 Gbit/s)
2024	802.11be	Wi-Fi 7	OFDMA	4096QAM	MU(du)	8	320 MHz	✓	✓	✓	46 Gbit/s

Note 1: SU = Single-user MIMO, MU = multi-user MIMO, d = downlink only, du = bidirectional

In OFDMA, Resource Units (RU) may be of different sizes, from 26 subcarriers upwards (to 996). With a minimum subcarrier spacing of 78.125 kHz, this gives a minimum RU bandwidth of 2.031 MHz, of which 74 can be accommodated in a 160 MHz channel. This flexibility leads to significant improvements to data throughput in real-world mixed traffic environments.

BSS colouring: Prior to 802.11ax, Wi-Fi devices implemented a carrier-sense multiple access (CSMA) strategy. When a signal is detected, a device will wait for a random period before retrying, reducing throughput in a busy environment. With BSS colouring each AP (or network, or Basic Service Set, in Wi-Fi terminology) is assigned an identifier of 'colour'. These are used to determine whether it is acceptable for a device to transmit on an occupied channel or not (based on a negotiated understanding of relative signal strengths and overlapping coverage areas).

[22] With spatial re-use

Appendix C Previous studies

The extent to which Wi-Fi capacity is constrained by spectrum availability has been considered in a number of previous reports, briefly reviewed below.

C.1 "Future proofing Wi-Fi – the case for more spectrum", Plum for Cisco (2013)

The context for this 2013 report [1], produced for Cisco was the imminent release of the Wi-Fi 5 standard (802.11ac) and the need to accommodate 160 MHz channels.

At the time of the report, only 455 MHz of spectrum at 5 GHz was available to Wi-Fi and the report found that this was insufficient to support offered traffic in four scenarios in the near future. The Plum report assumes that an extra 320 MHz could be made available in Europe at 5350-5470 MHz and 5725-5925 MHz, and that this would allow Wi-Fi systems to accommodate the expected growth in offered data in a timeframe extending to 2024.

The most severe bottleneck was in the "transport hub" where demand would exceed existing Wi-Fi capacity in 2016. This point would be reached in 2021 for "office" and "apartment block" scenarios and in 2022 for "terraced housing."

The modelling took into account the increasing market penetration of devices that can exploit wider channels, the 5 GHz band and MIMO.

The simple modelling detailed in Annex C of the report uses figures for device density and the traffic per device to determine the overall traffic offered in a given environment. It takes into account approximations for Wi-Fi protocol efficiency (60%) and the network protocol overhead (65%). It also assumes that all devices are located at half the maximum range, imposing another throughput degradation (50%). Backhaul via both mesh networking and by Ethernet was considered.

For the case of the residential block, with 9 apartments each with a Wi-Fi network serving 1.5 people, demand exceeds capacity in 2021, when a total user data rate of 68 Mbit/s is offered to each network.

C.2 "A Quantification of 5 GHz Unlicensed Band Spectrum Needs", Qualcomm Technologies, Inc (2016, revised 2023)

This study [2] used detailed simulations to determine Wi-Fi spectrum requirements. It was assumed that 802.11ax (Wi-Fi 6) is used in "dense residential" and "dense enterprise" environments and is required to provide a universal service bitrate of 1 Gbit/s (also 0.1, 0.5, and 2.5 Gbit/s) over 99%[23] of the area simulated.

The simulation assumed a modified IEEE model for two cases:

Residential: An apartment block of 30 apartments of 4 rooms each, on three floors, with 10m x 10m apartment footprint. Each apartment is served either by a single AP, or by 4 APs fed by Ethernet or by 60 GHz or 5 GHz (in-band) backhaul.

[23] 95% in the 'residential' case

Enterprise: An office scenario with 8 rooms, each with four APs, and an overall area of 80 x 40m. Different assumptions were made regarding backhaul (WLAN or Ethernet) and MIMO order (2 - 8 antennas).

The modelling assumed 802.11ax features (numerology, use of colouring) and 20, 40, 80 and 160 MHz channel bandwidths, with transmit beamforming and MIMO. Optimal channel planning was assumed.

The modelling uses an iterative process, testing different frequency re-use factors and choosing the optimum. It is noted that "*using the best reuse factor and smart channel selection to compute the final bandwidth requirements leads to a conservative estimate of the necessary bandwidth*"

For the 1 Gbit/s benchmark, the lowest spectrum requirement (420 MHz) came from the use of Wi-Gig (60 GHz) for the user link, while the highest (1280 MHz) was for the residential case with 1 AP and 4-antenna user terminals. In most cases, 160 MHz bandwidth mode was found to be necessary (but only 80 MHz where Ethernet backhaul, 60 GHz user links, or 4x4 MIMO were assumed).

The conclusion (2017) is that regulators should plan for "*around 1280 MHz of unlicensed spectrum centred around the 5 GHz band*". This compares to the 1060 MHz currently available in Europe.

The study was updated in 2023, though not published except as a presentation to the UK Spectrum Forum. In this version, the simulated environments are the same. The new model assumed 6 GHz spectrum is available with LPI indoor power levels[24] and assumed Wi-Fi 7 (802.11be) technology. This allows both 5 and 6 GHz spectrum to be used, with channel bandwidths up to 320 MHz. Other modelling assumptions are the same.

The use scenarios are slightly different. There is no mention of 60 GHz. All APs are now 4-antenna, with all STAs being 2-antenna. The "residential 4AP, 2 Ant, Ethernet backhaul" scenario requires ~650 MHz (was ~480 MHz) while the Enterprise scenario needs 1250 MHz (was ~1250 MHz, for E1 with 2-antennas).

No 'conclusion' but final slide shows *need for total of between 600 MHz and 2400 MHz of spectrum*.

C.3 "Wi-Fi Spectrum Needs Study", Quotient Associates for Wi-Fi Alliance, 2017

Traffic offered

The starting point for this study [4] is an estimation (Section 1.1.2) of traffic expected to be offered in 2025. This is based on a survey of data from the UK, Germany, Korea and the USA. With the assumption that all traffic occurs in four "busy hours" each day and extrapolation to 2025, a figure of 4.5GB/person for the *average* traffic volume in a busy hour is derived. Office traffic is assessed (Section 1.3, Cisco VNI data) to be a quarter of the residential rate.

It is asserted that busy hour traffic is growing at a much faster rate than average traffic, as this period is dominated by video streaming (see Table 1-1). Busy hour rates are therefore set at 150% and 115% of average in 2020 and 2025 respectively. In addition, "upper bound" rates are also assumed based a 200% and 400% uplift from average respectively. With respect to the upper bound rate the report notes that "*it seems far from being out of the question that such volumes might occur. On the other hand it is significantly higher than any prediction we have seen reported elsewhere*"

Finally, the residential demand is set to twice the office demand, due to the use of self-backhaul. The final values (busy hour, 2025) are 5,063 MBytes/person (office) and 20,250 MBytes/person (residential).

[24] LPI or 'Low-power (indoor)' operation implies the use of a maximum 5dBm/MHz eirp, rather than the 36dBm (absolute) eirp permitted for 'Standard Power' operation. This gives 27 dBm for a 160 MHz channel, 30 dBm for 320 MHz (reaches absolute limit at 1260 MHz bandwidth).

Use cases, technologies and model inputs

A mix of devices (smartphones, laptops, tablets) is assumed, which is relevant for determining the population of different MIMO orders. Residential settings have a higher proportion of smartphone use (75% versus 50%). LTE use at 5 GHz is not modelled, but it is assumed that some 60 GHz Wi-Fi networks are available (10% of office networks, 20% residential).

The physical environments for office and residential scenarios are based on the IEEE assumptions [3]. A 30x300m shopping mall is also defined.

Model

Details of the model used are set out in the appendices.

Access point density is set as one per 100m^2 for the office and residential cases (corresponding to one AP per apartment in the residential case). There are 10 people per 100m^2 in the office and four in the residential case (i.e. four people per apartment). Each person has three "machines"; if these are active terminals this seems a surprisingly high figure.

A transmit power of 20dBm is assumed and an I/N criterion of 10dB applied at 5 GHz. The model runs as follows:

- Setup
  - Set physical environment and offered data
  - Place APs on rectangular grid
  - Assign channels (planned or random)
  - Place users
- Run
  - Find closest AP
  - Get all pathlosses, thus C/N+I
  - If an AP is > interference threshold, assume terminals will back off
  - Add non-Wi-Fi interference
  - Use look-up table to convert C/N+I to max data rate.
- Calculate transmit time per user
- Add total time per AP
- build congestion histogram

Evaluation

The evaluations have been based not on maximum speed (which is a matter of AP layout as much as spectrum) but on overall capacity. The key metrics chosen are:

- Percentage of offered traffic that is carried (target is 95%)
- AP utilization (that percentage of airtime that an AP observes as being utilised, both by itself and other neighbouring co-channel networks. Target is 70%).

The report notes the complexity of allowing for multiple bands, and therefore opts to deal with "generic" spectrum, nominally at 5 GHz, but the results could be generalized in the range 2-10 GHz.

Assumes *random channel assignment*, unlike the Qualcomm report which assumes optimization (this may only be for the residential case).

It is assumed that a minimum of four channels must be available to exceed excessive interference. The results for an 80 MHz bandwidth therefore begin at 320 MHz, those for 160 MHz bandwidth at 640 MHz.

Results

The results for the busy hour in 2025 are reproduced below.

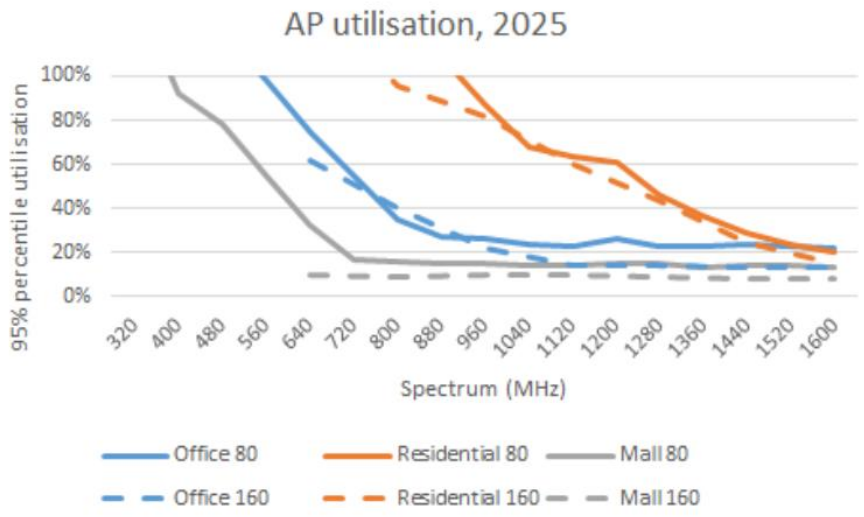


Figure 4.1: Busy Hour scenario, year 2025, using 80 and 160 MHz channels (Fig 5-3 in [4])

It is concluded that, based on busy hour results and the worst case residential scenario, there will be a need for 1120 MHz of available spectrum in 2025 (the equivalent upper-bound figure is 1920 MHz).

The final result (Report Figure 5-5) shows the impact of different power levels. Reducing the power by 10dB reduces spectrum requirement significantly, but this will be at the expense of overall throughput as the network becomes noise-limited.

C.4 2023: "Sustainability Benefits of 6 GHz Spectrum Policy", WIK consult for Wi-Fi Alliance

Authors: Ing Peter Kroon, Ilsa Godlovitch, Dr Thomas Plückebaum

This report [5] is a very different report that examines the link between spectrum availability for Wi-Fi and environmental impact.

It is suggested that insufficient spectrum availability for Wi-Fi would cause 15% of the data traffic to shift from Wi-Fi networks to 5G mobile networks. This would require 16% more energy, which translates to 3.2 megatons of additional CO_2 emissions in Europe per year.

The link between lack of spectrum and displaced data is taken from simulation work by Intel [6], which focusses on latency as the criterion of most relevance. The summary of the Intel work reports that "*it is demonstrated that in moderate to high traffic load environments, e.g., enterprises, industrial plants, homes, hotspots, the availability* *of a single 320 MHz channel is insufficient to meet the KPIs of these emerging applications. In particular, the latency performance goals cannot be met while maintaining the required reliability target. It is also shown that only when three non-overlapping 320 MHz channels are available can the latency performance and reliability be kept at acceptable levels, including for highly loaded scenarios".*

C.5 Summary of studies

Salient points of the earlier studies are summarised in the table below.

Table C.1: Summary of earlier studies

	Offered traffic	Environment	Model	Conclusion
Plum (2013)		Apartment block, Terraced House, Office block, Transport hub	High-level	Additional (e.g.320 MHz) spectrum required by 2016
Qualcomm (2016)	1 Gbit/s per user in 99% of area	Residential, Enterprise	Detailed simulation (PHY)	Total 1280 MHz spectrum required
Qualcomm (2023)	1 Gbit/s per user in 99% of area	Residential, Enterprise	Detailed simulation (PHY)	Total 1250 MHz spectrum required
Quotient (2017)		Office, Residential, shopping mall	Detailed simulation (PHY)	Total 1120 MHz 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 360 MHz channel assumed.	Detailed simulation (link-level)	960 MHz total required

It is interesting to note that in the Quotient study, the spectrum requirement is set by the residential case, while for the Qualcomm study it is the Enterprise scenario that determines the requirement.

It may be relevant that the Qualcomm study uses a modified version of the IEEE Dense Residential environment, with a footprint of half the area and only three, rather than five, floors.

The 2023 Qualcomm study is taken as a template for the scope of the present study.

Quotient: 1 x 20dBm AP per apartment

Qualcomm: 1 or 4 AP per apartment. 27dBm or 30 dBm (160/320 MHz) AP.

C.6 Path-loss models

C.6.1 IEEE

The IEEE document proposes the following models:

For the residential case:

$PL(d) = 40.05 + 20.\log10(f_c/2.4) + 20.\log_{10}(\min(d,5)) + (d>5) \times 35\log_{10}(d/5) + 18.3F^{(F+2)/(F+1)-0.46} + 5.W$

- d = max(3D distance [m], 1)
- f_c = frequency [GHz]
- F = number of floors traversed
- W = number of walls traversed

For the enterprise case:

$PL(d) = 40.05 + 20.\log_{10}(f_c/2.4) + 20.\log_{10}(\min(d,10)) + (d>10) \times 35.\log_{10}(d/10) + 7.W$

- d = max(3D-distance [m], 1)
- fc = frequency [GHz]
- W = number of office walls traversed

In both cases, lognormal shadowing is assumed, with a 5dB lognormal distribution.

C.6.2 Qualcomm

The Qualcomm model assumes a loss of 11 dB for walls and 18 dB for floors. Other details of the path loss model are not given. It is, perhaps, implied that the IEEE models are used.

C.6.3 Quotient

The reader is directed to Appendix B for the path loss coefficients, but none are given there.

C.6.4 ITU-R P.1238

The 'site specific' model has the following form:

$PL(d) = 20.\log_{10}(f)-28 + N.\log_{10}(d)+Lf(n)$

- N = distance power loss coefficient
- d = distance [m]
- f = frequency [MHz]
- Lf(n) floor penetration loss factor (dB) for n floor intersections

Although no values for N are given for frequencies below 28 GHz[25], values for Lf(n) <u>are</u> specified:

- House, Single floor, concrete, 5.2 GHz: 13 dB

[25] An older version of the Recommendation gives N=31 at 5.2 GHz

- Apartment, Single floor, wood & mortar, 5.2 GHz: 7 dB
- Office, Single floor: 16 dB
- Office, 5.8 GHz: 22 dB (1 floor), 28 dB (2 floors)