Wi-Fi indoor connectivity tests - Comtel
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1 EXECUTIVE SUMMARY

This document reports on the results of a test campaign aimed at assessing the real levels of performance that can be achieved with latest Wi-Fi technologies using the available spectrum resources in the 2.4 GHz, 5 GHz and Lower 6 GHz bands.

The key role played by indoor connectivity

Indoor digital connectivity, encompassing residential, public, and industrial scenarios, increasingly plays a pivotal role in our society. Statistics show mobile broadband continues to rise with over 70% of all mobile traffic originating from indoor users[1], and fixed broadband accounted for 83% of all traffic globally in 2022[2]. It is therefore essential to ensure that all connectivity options are seamless, high-capacity, reliable, and low-latency for both consumers and industrial users across all indoor environments. Notably, the European Union's Digital Decade Policy Programme 2030 has set goals with respect to the targeted gigabit connectivity for fixed locations, stating that: "By 2030, networks with gigabit speeds should become available to those who need or wish to have such capacity. All Union end-users should be able to use gigabit services provided by networks at a fixed location deployed up to the network termination point"[3].

Wi-Fi indoor connectivity tests

To assess the latest Wi-Fi technologies and spectrum bands against the EU's Digital Decade connectivity targets, tests were conducted across 42 rooms in a hotel in Lazise – Italy in February-March 2024, with the aim of replicating indoor Wi-Fi connectivity in two important scenarios: a) an apartment in a densely populated urban environment, and b) an isolated house/dwelling. The former also provides an indication of the type of performance that can be achieved by Wi-Fi in other settings such as schools.

With reference to Scenario (a), the main focus of our measurements was on the ability of Wi-Fi access points to maintain high throughput despite heavy interference between the access points, and their efficiency in handling data traffic under heavy network load both in uplink and downlink directions. Other performance parameters such as latency were also monitored since they are critical for time-sensitive applications requiring a stable and reliable connection, such as high-definition video streaming, gaming, as well as augmented and virtual reality communications.

Furthermore, specific test sessions assessed the extent of Wi-Fi signal propagation indoors within the three floors of the hotel.

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[1] Source: see for example Ericsson, "Planning indoor 5G coverage"; Cisco, "5G thriving indoors"; Huawei, "Better indoor coverage, better 5G networks".
[2] Source: ITU, "Measuring digital development – facts and figures 2023".
[3] DECISION (EU) 2022/2481 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 December 2022 establishing the Digital Decade Policy Programme 2030.

Generating sufficient traffic to utilize the full capacity of the Wi-Fi air interface

A key element of the tests involved generating enough traffic to fully utilize the capacity of each Wi-Fi access point while serving at least two Wi-Fi stations (each one connected to one laptop representing the end user). Specifically, this involved the use of 40 Gbit/s FTP and streaming servers installed on each of the three floors of the hotel, up to 44 Wi-Fi access points and 86 Wi-Fi stations across the three floors of the hotel. The Wi-Fi stations were in the form of Wi-Fi enabled laptops, while AR/VR Wi-Fi enabled glasses were also used in some tests. By pushing the access points to their operational limits, the tests could accurately measure their maximum throughput capabilities, as well as their resilience to high traffic loads.

Removing possible bottlenecks in the fixed network: a forward-looking setup

To ensure that the results correctly reflect the performance of the Wi-Fi air interface, any potential bottlenecks within the fixed network feeding the Wi-Fi access points were eliminated. This step was crucial to prevent external network limitations from influencing the test outcomes which focused exclusively on the Wi-Fi air interface. For the purposes of this test, the hotel was equipped with a 100 Gbit/s wired local area network (LAN), with 10 Gbit/s Ethernet connectivity to each Wi-Fi access point. All end user traffic remained within the hotel LAN during all test sessions. These future-looking arrangements of the fixed network deployed for the test campaign should be viewed in the relative context of the status of fixed broadband deployments in the European Union today: 55% of households in the European Union had a Fixed Broadband subscription with a nominal speed of at least 100 Mbit/s in 2023, and 14% of households had a Fixed Broadband subscription of at least 1 Gbit/s in the same year.[4]

Generating interference from a large number of Wi-Fi access points

To rigorously test the resilience and interference mitigation capabilities of the Wi-Fi equipment, interference was generated from a large number of access points in a relatively small area (40 access points installed in an area of ca. 900 m^2).

Noting that such a very high density of access points is not observed in residential scenarios today, and is also considered unlikely in the future, this “pessimistic” setup was intentionally designed to allow the tests to be performed in an extremely challenging environment, in terms of interference between access points and traffic transported across the air interface. This approach provides valuable insights into the robustness of Wi-Fi technology in adverse conditions and informs potential improvements in product design and network deployment strategies.

[4] Digital Economy and Society Index (DESI) 2023 indicators.

Indoor radio propagation

Our measurements of received Wi-Fi power throughout the hotel indicate that the 2.4 GHz band provides relatively good coverage from one access point to adjacent rooms. With the 5 GHz and Lower 6 GHz bands, propagation across walls becomes more problematic in adjacent rooms, leading to a more coverage-limited environment.

When all co-channel access points are switched on in different rooms, our measurements show substantial aggregate interference in the 2.4 GHz band. With the 5 GHz and Lower 6 GHz bands, the measured interference received from co-channel access points outside the target apartment reduces but is non-negligible.

Measurements of Wi-Fi throughput

With reference to the isolated house/dwelling scenario, our measurements of **one Wi-Fi access point** serving two user stations within a **single room** indicated a total throughput of around **1.5 Gbit/s**, summed over uplink and downlink and over both stations, using an 80 MHz channel at 5 GHz and a 160 MHz channel at Lower 6 GHz. Total throughput was observed to decrease to around **1.1 Gbit/s** with **one Wi-Fi access point** in the room serving a total of eight user stations in **four rooms** (two in the same room, and two in each of three adjacent rooms). This indicates the **coverage challenges** associated with Wi-Fi signal propagation between rooms: the stations that were located further away from the access point drained a disproportionate amount of radio resource from the access point (e.g. due to their need to adopt a lower-order modulation scheme) resulting in an overall reduction in throughput.

Further measurements involved **four Wi-Fi access points**, each deployed in one of **four rooms** in a so-called “target apartment”, and serving two stations in each room - with frequency reuse of 4 in the 5 GHz band (4 channels of 80 MHz) and frequency reuse 3 in the Lower 6 GHz band (3 channels of 160 MHz). In the absence of any interference from outside the four rooms, measurements indicated a total throughput of around **6.3 Gbit/s** in the target apartment. For similar scenarios as above but with only two and three access points in the target apartment, measurements indicated total throughputs of around **1.7 Gbit/s** and **4.1 Gbit/s**, respectively.

These can be considered to be typical of the data rates which can be delivered by Wi-Fi in **isolated houses/dwellings** and demonstrates the importance of Wi-Fi **access point densification** in enhancing capacity and coverage in such dwellings.

To address **densely populated urban apartment** environments, we also examined the same arrangement as above with **four Wi-Fi access points**, each deployed in one of **four rooms** in the “target apartment” and serving two stations in each room. But this time we also introduced **interference** from 40 Wi-Fi access points and 78 user stations deployed in 38 surrounding rooms across three floors of the hotel (again with frequency reuses of 4 at 5 GHz and of 3 at Lower 6 GHz). As expected, measurements indicated a **reduced throughput** due to the presence of interference from outside the target apartment, however the total throughput delivered to the apartment was observed to exceed **4.5 Gbit/s**, which is quite substantial given the challenging interference environment. Again, for similar scenarios as above but with only two and three access points in the target apartment, measurements indicated total throughputs of around **1.7 Gbit/s** and **2.4 Gbit/s**, respectively.

AR/VR smooth performance, even under heavy interference

We also undertook tests which demonstrated remarkably smooth operation of augmented reality (AR) and virtual reality (VR) sessions conducted within the target apartment. These sessions were specifically tested under conditions where all 44 access points in the hotel were fully loaded with traffic. This scenario was again designed to replicate a futuristic high-demand dense urban environment. The ability of the AR/VR applications to run smoothly under such conditions highlights the robustness and efficiency of the deployed Wi-Fi technology, particularly in handling heavy data loads and maintaining high-performance levels. This is especially relevant for AR/VR applications, which are highly sensitive to latency and jitter, as these factors can significantly impact the user experience and effectiveness of the technology.

Key takeaways

Using the available spectrum from 2.4, 5, and Lower 6 GHz bands, a throughput of at least 1 Gbit/s was recorded in the target apartment in all tested scenarios (uplink + downlink over all stations). This seems to be consistent with the European Union connectivity objectives for 2030 for all end users at a fixed location.

Going forward, the key constraint for Wi-Fi is coverage which can be effectivity addressed through densification of access points, i.e., increased number of access points deployed by the user. Once AP densification is applied, new RLAN technologies (e.g. Wi-Fi 8) will also have the opportunity to exploit the large bandwidth available at higher frequency bands, such as mmWaves, to deliver higher throughputs with lower latency, and in an interference-free manner (exploiting the higher wall penetration losses at high-bands).

2 TEST SETUP

In this section we describe the scope of the measurement campaign, present the architecture of the network deployed, and describe the characteristics of the Wi-Fi and fixed network equipment tested.

2.1 The scope of tests

The tests described in this report focus on the ability of Wi-Fi technology to meet the end users' connectivity needs. In particular, these tests aim at providing a factual contribution towards the understanding of the level of performance that can be achieved with the latest Wi-Fi technology using the available spectrum resources in the 2.4, 5 and Lower 6 GHz (L6 GHz) bands.

Tested Wi-Fi access points (APs) and client stations (STAs) were subjected to heavy traffic, both in uplink and downlink directions, in an environment with severe Wi-Fi interference. The main focus of our measurements was on the ability of Wi-Fi APs and STAs to maintain high throughput despite heavy inter-AP interference, and on their efficiency in handling data traffic under heavy network load. Other performance parameters such as latency and jitter were also monitored since they are critical for time-sensitive applications which require a stable and reliable connection, such as high-definition video streaming, gaming, augmented and virtual reality communications.

The tests aimed to challenge the Wi-Fi network's ability to manage co-channel and adjacent-channel Wi-Fi interference, a common issue in densely populated areas. The Wi-Fi performance was assessed with a gradually increasing number of interfering APs.

Specific test sessions assessed Wi-Fi signal propagation in the three bands: coverage maps are provided showing the wanted signal propagation, with other maps showing the inter-AP interference levels in the hotel rooms where the test campaign was undertaken.

2.2 Wi-Fi deployment setup

The test environment for assessing the performance of the latest Wi-Fi technology was carefully designed within an end-to-end controlled, standalone setting utilizing 42 hotel rooms located in three overlapping floors. This controlled yet complex setup provided a robust platform for rigorously evaluating the performance of cutting-edge Wi-Fi technology.

The overall test layout is illustrated in Figure 1. A video is also available[5] which shows the actual test site along with the set up. Information on the characteristics of the equipment used is provided in ANNEX 1.

[5] See video at www.comtelitalia.it/indoor_connectivity_test_en.

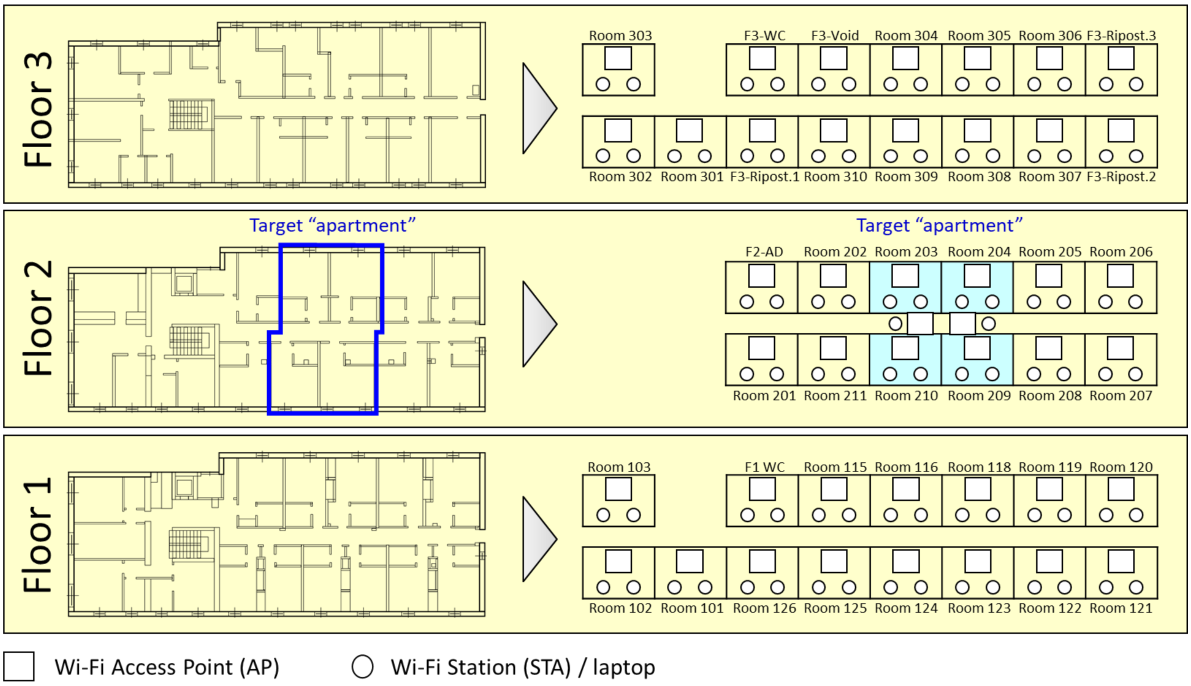

Figure 1: Test layout (15 + 12 +15 rooms across three floors), 44 APs, 86 STAs/laptops.

The test topology aimed at reproducing two main scenarios: a dense urban apartment, and an isolated house/dwelling, with the former providing an indication of the type of performance that can be achieved by Wi-Fi in other settings such as schools.

Each of the 42 rooms was equipped with one Wi-Fi AP and two STAs/laptops, leading to a total of 42 APs and 84 STAs/laptops. In addition, two extra APs were installed in the corridor in the middle of the second floor (see next).

The "target apartment"

Measurements were performed on Wi-Fi APs and STAs/laptops located in four rooms in the middle of the second (middle) floor: due to their central position, these rooms are subject to the highest levels of interference. These four rooms are referred to as the "target apartment" throughout this report.

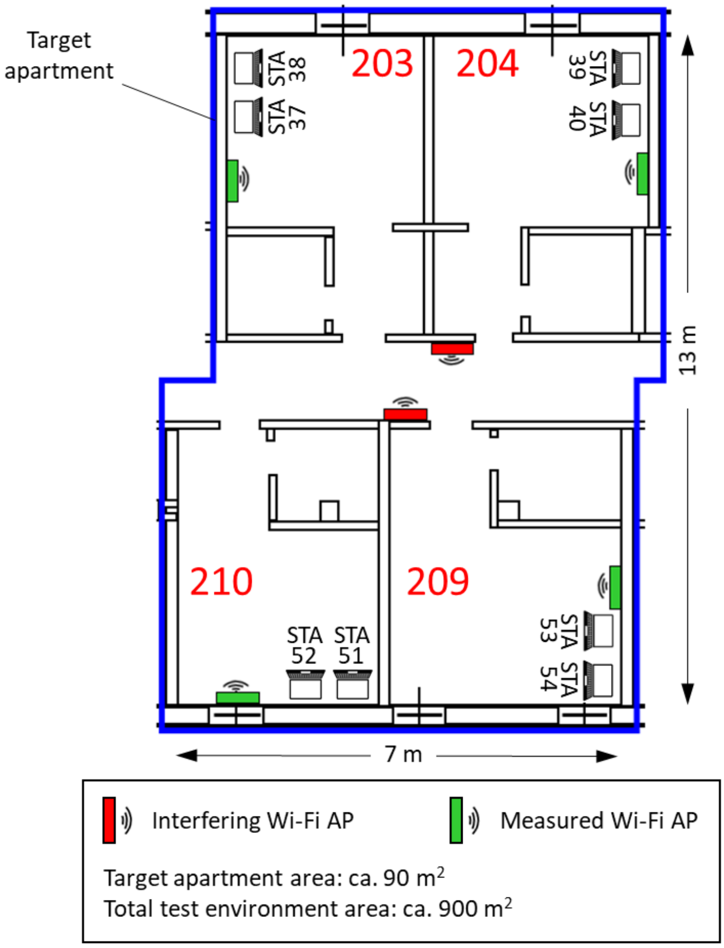

Figure 2: The target apartment.

As can be seen in Figure 1 and in Figure 2, the corridor which runs along the second floor divides the rooms in the central apartment into two pairs, and provides additional radio isolation between the two pairs of rooms (on account of the two walls of the corridor). In order to counter this additional isolation and the potential for reduced interference, two extra interfering APs were installed in the corridor. For logistic reasons and without any impact on the test results, these two APs were only connected to one STA/laptop each. Conservatively, the throughput associated with the two STAs in the corridor was not considered when computing the measured throughput within the target apartment.

Isolated house/dwelling

Where the four rooms in the target apartment are tested in isolation (i.e. are not subjected to the interference from APs in other rooms) the target apartment is a good representation of a one-story house dwelling, as illustrated in Figure 3 (a). This scenario was designed to assess the performance of Wi-Fi technology in an environment relatively free from external Wi-Fi interference. The objective was to determine the optimal performance characteristics of the Wi-Fi network in conditions that are ideal, where interfering Wi-Fi signals are minimal, such as that in an isolated house/dwelling. This setup helps us understand the best-case scenario for Wi-Fi technology in terms of signal strength, throughput, and reliability.

Dense urban apartment

In contrast, where the Wi-Fi APs in the rooms surrounding the target apartment are switched on, the target apartment provides a good representation of a typical apartment in a dense urban environment, as illustrated in Figure 3 (b).

This setup aimed at replicating a more challenging urban living environment where the presence of multiple overlapping Wi-Fi networks creates a high-interference backdrop. This scenario tests the Wi-Fi network's ability to maintain connectivity, speed, and data integrity in the face of significant external disturbances, mirroring the typical conditions many users experience in dense residential areas, as well as providing an indication of the type of performance that can be achieved by Wi-Fi in other settings such as schools.

Scenario (a)

Scenario (b)

Figure 3: (a) isolated house/dwelling, (b) dense urban apartment.

To rigorously test the resilience and interference mitigation capabilities of the Wi-Fi equipment, interference was generated from up to 40 APs in a relatively small area of ca. 900 m^2, (i.e. 1 AP / 22 m^2). Noting that such a very high density of access points is not observed in residential scenarios today, and is also considered unlikely in the future, this "pessimistic" setup was intentionally designed to allow the tests to be performed in an extremely challenging environment, in terms of interference between access points and traffic going across the air interface. This approach provides valuable insights into the robustness of Wi-Fi technology in adverse conditions and informs potential improvements in product design and network deployment strategies.

Various test sessions were carried out addressing different dense urban apartment topology scenarios with a growing number of interfering Wi-Fi APs outside the target apartment rooms progressively switched on (ranging from zero to a maximum of 40 interfering APs, distributed across the three overlapping hotel floors). Measurements were made for the different scenarios offering a reference for different dense urban residential environments.

The distribution of APs outside the target apartment was planned to maximize the level of interfering signals received by APs and STAs in the target apartment. In other words, these APs were not randomly placed, but were strategically located to maximize the overlap of Wi-Fi signals within the tested rooms. This is illustrated in Figure 4 for the second floor. The purpose behind this was not only to replicate an environment of dense urban apartment buildings where numerous Wi-Fi networks typically operate in close quarters, but also to push the limits of Wi-Fi technology by testing it against substantial levels of interference.

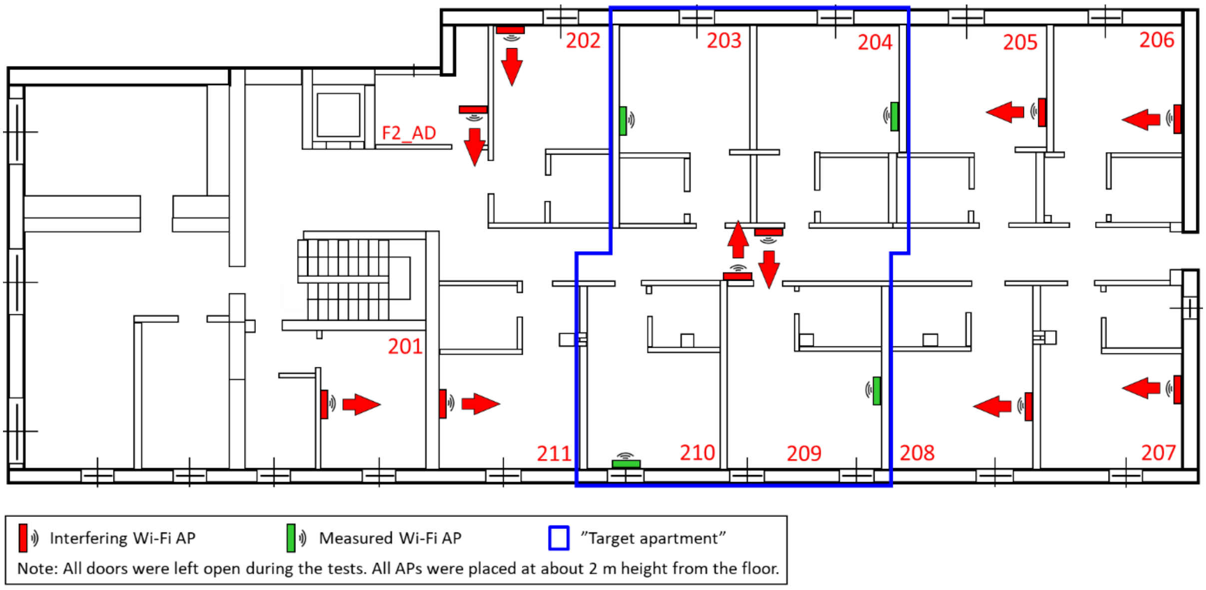

Figure 4: Interfering APs generating interference towards the target apartment (2nd floor).

2.3 Wi-Fi and network equipment

Figure 5 illustrates the network architecture used in the measurement campaign and which will be described further in the following sections. Further information on the equipment is available in ANNEX 1 and in the referenced on-line sources.

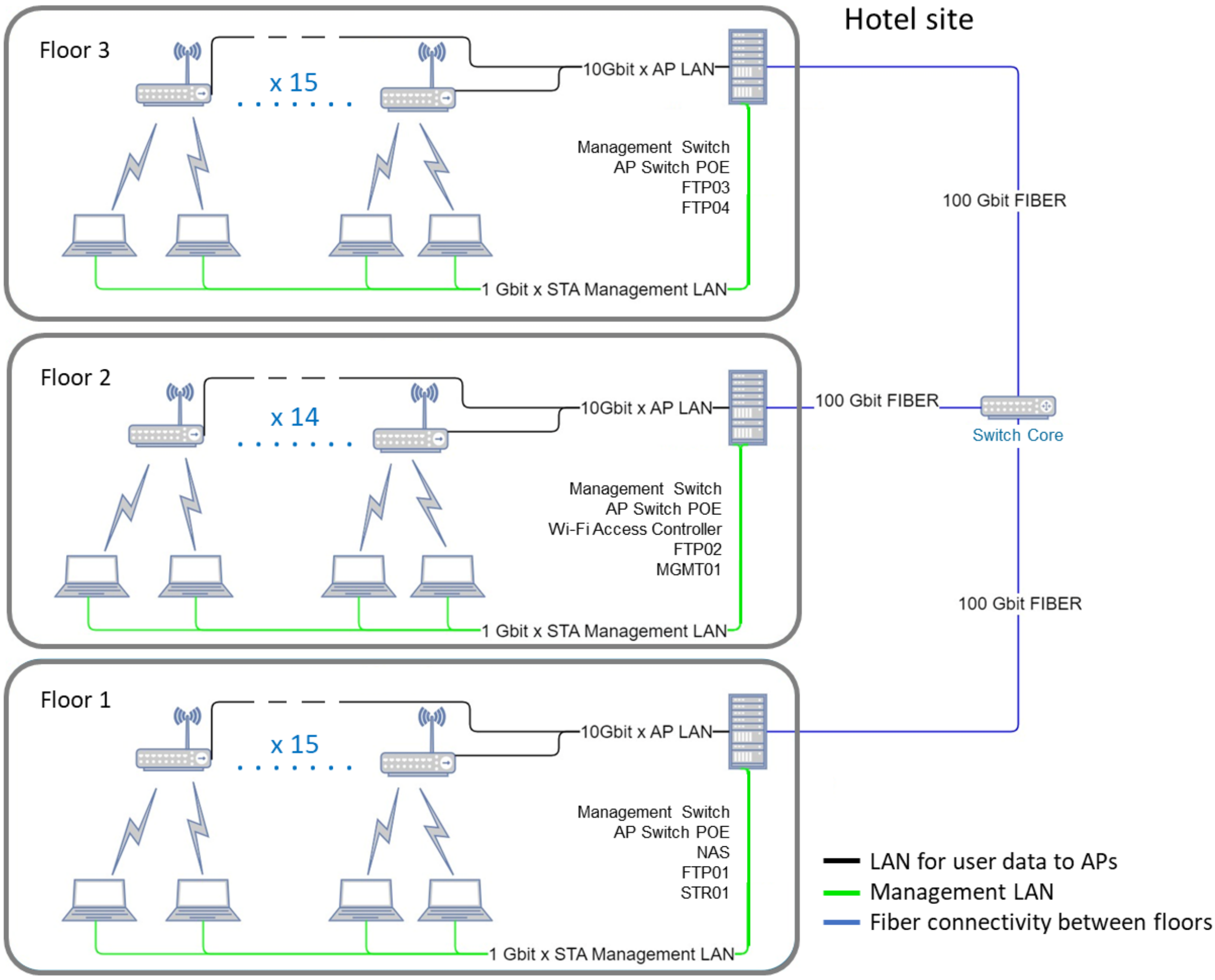

Figure 5: Network architecture.

Access points

A total of up to 44 Huawei AirEngine 8771-X1T Wi-Fi 7 APs were used, as shown in Figure 16 later. This specific model was selected for its advanced capabilities and enhanced connectivity options which are important to achieve optimal performance, and to push the boundaries of Wi-Fi performance. Product information is available at the supplier's website[6].

The tests were actually performed with 802.11ax (Wi-Fi 6E) due to the fact that the operating system (MS Windows 11) running on the laptops did not yet support Wi-Fi 7.

[6] https://e.huawei.com/en/products/wlan/indoor-access-points/airengine-8771-x1t.

Figure 6: Huawei AirEngine 8771-X1T access point.

The Wi-Fi APs were managed from the Huawei HW AC6508 AP controller which was merely used to facilitate configuring the APs to switch them on/off remotely: any advanced AP coordination features were disabled at the access controller side (e.g. the APs' output power management feature was disabled).

Each AP was positioned aiming at a layout that would be typical of room installations, while maximizing the interference towards the target apartment (for reasons explained earlier).

STAs/laptops/AR/VR devices

To ensure a comprehensive assessment, each AP was connected to two laptops equipped with Wi-Fi 6E technology. The test relied on Lenovo E15 G4 laptops equipped with the Intel Wi-Fi AX211 chip supporting 2x2 MIMO, OFDMA, and Target Wake Time (TWT).

AR/VR sessions were tested using the Meta Quest 3 mixed reality VR headset[7].

2.4 10/100 Gigabit LAN

Any potential bottlenecks within the fixed network behind the Wi-Fi APs were removed to ensure that the results would purely reflect the performance of the Wi-Fi air interface. All end user – related traffic remained within the hotel LAN during all test sessions. This step is crucial to prevent external network limitations from influencing the test outcomes which exclusively focused on the Wi-Fi air interface.

Hotel floors were interconnected with fiber cables through the 100 Gbit/s ports of the Huawei core switch HW S6730[8], ensuring high-speed data transmission capabilities and minimal latency.

Cat 6 certified cables capable of supporting 10 Gbit/s were used to reach all APs in the 42 rooms through the 10 Gbit/s power over ethernet (PoE) ports of the three Huawei HW S5735[9] floor switches.

[7] www.meta.com/gb/quest/.
[8] https://e.huawei.com/en/products/switches/campus-switches/s6730-h
[9] https://e.huawei.com/en/products/switches/campus-switches/s5735-s

The remote management of the laptops was ensured through the 1 Gbit/s ethernet connections from the three HW S5732[10] management switches.

2.5 Traffic servers

To replicate realistic and high-demand scenarios, 40 Gbit/s FTP and streaming servers were installed on each floor as illustrated in Figure 7. These servers were tasked with generating a significant amount of data, which was crucial for testing the Wi-Fi network's ability to manage high traffic loads and maintain high-speed data transfer rates across multiple Wi-Fi APs and client devices.

By ensuring that the underlying network infrastructure was capable of handling extremely high data throughputs, the test could accurately measure the performance of the Wi-Fi setup in a variety of demanding use cases, thereby providing valuable insights into its efficacy and reliability in real-world applications.

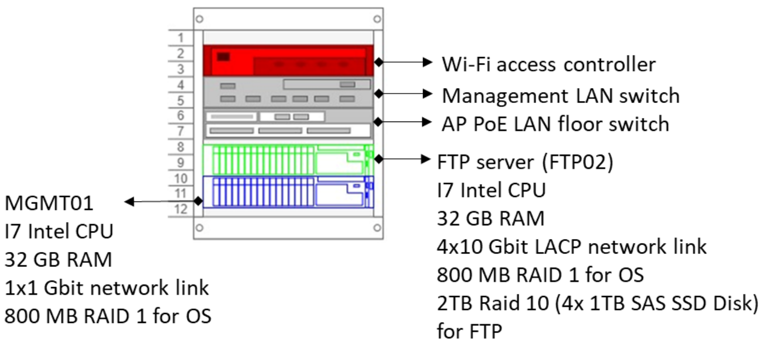

Figure 7: Networking equipment and servers in the second-floor rack.

Tests were performed for different traffic mixes towards/from the Wi-Fi STAs/laptops in the interfering rooms and in the target apartment:

a) Traffic towards/from each STA/laptop in the interfering rooms

- FTP DL (full buffer, 1 Gbit/s) and FTP UL (full buffer, 0.5 Gbit/s).

b) Alternative traffic models were used towards/from each STAs/laptops in the target apartment

- Traffic model type 1: 4K video streaming (ca. 10 Mbit/s),
- Traffic model type 2: FTP DL (full buffer, 1 Gbit/s), and FTP UL (full buffer, 0.5 Gbit/s),

[10] https://e.huawei.com/en/products/switches/campus-switches/s5732-h-multi-ge

- Traffic model type 3: FTP DL (full buffer, 1 Gbit/s), and FTP UL (full buffer, 0.5 Gbit/s), and 4K video streaming (ca. 10 Mbit/s).

FTP traffic load was selected in order to saturate the APs' available capacity even with the largest channel bandwidth (160 MHz in the L6 GHz band).

2.6 Frequency planning

Figure 8 shows the tested 20 MHz, 80 MHz and 160 MHz channels across the 2.4 GHz, 5 GHz and L6 GHz bands, respectively.

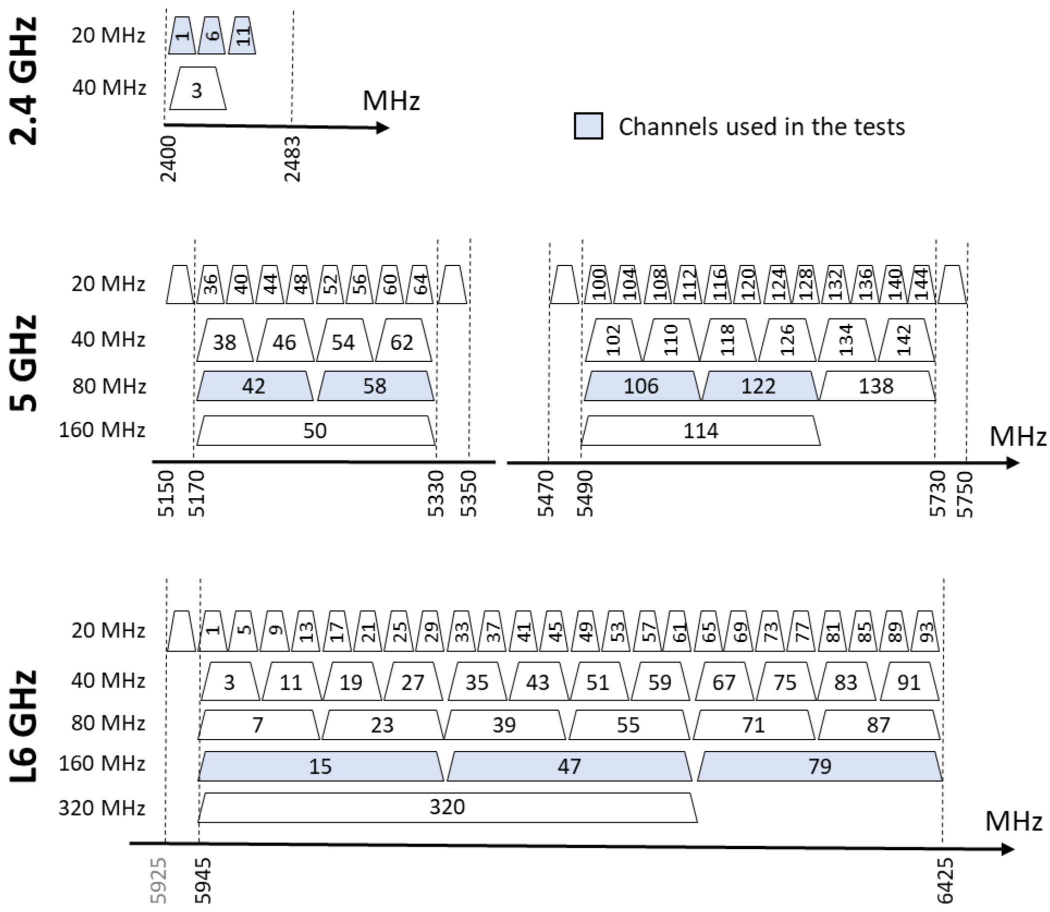

Figure 8: Channel arrangements for the three tested bands.

The frequency re-use patterns deployed in the tests are illustrated in Figure 9. Note that the channels were assigned manually to the Wi-Fi APs in each of the three bands. This manual process aimed at optimizing the frequency reuse by maximizing the physical distance between APs operating on the same channel. The channel assignment scheme employed in the tests was designed to mimic a typical

Wi-Fi deployment scenario where the APs autonomously select the best available channel. This selection is typically based on received signal strength indicator (RSSI) measurements of available channels within a specific band, which helps ensure optimal channel usage and minimal interference under normal operational conditions.

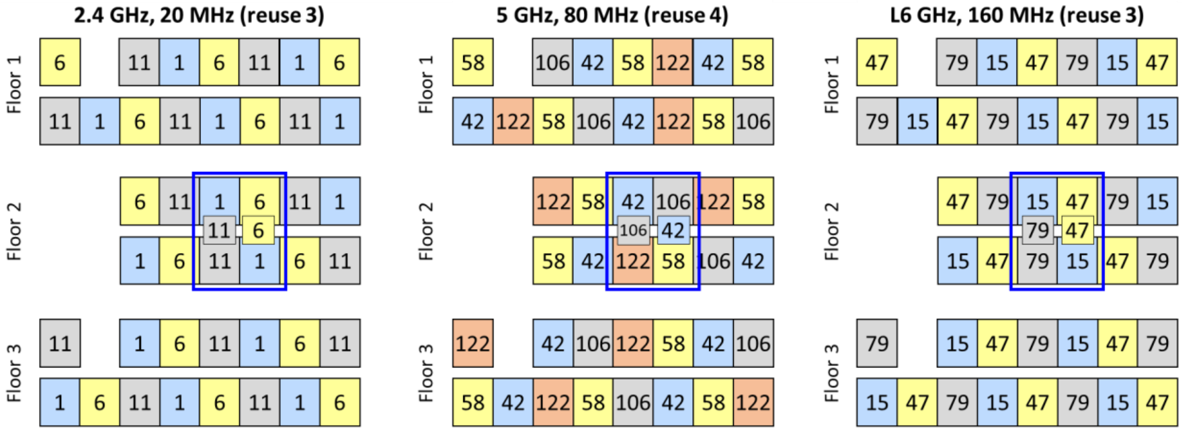

Figure 9: Frequency planning for the three bands.

The 5 GHz band performance was clearly affected by the smaller amount of the AP usable spectrum in this band (320 MHz) as well as by the channel bandwidth which is limited to 4 channels of 80 MHz each[11]. Channels with 160 MHz bandwidth could not be used in the 5 GHz band due to the current limitations in the equipment. We expect the 5 GHz Wi-Fi equipment to also support the 160 MHz channels in future product releases. Once the 160 MHz channel width will be supported in the 5 GHz band, the Wi-Fi 7 MLO feature will allow Wi-Fi APs to leverage the simultaneous availability of 5 channels of 160 MHz in most CEPT countries (two from the 5 GHz band and three from the L6 GHz band)[12].

2.7 Power management

Alongside frequency planning, controlling the maximum transmitted power for each band was another important element in the test setup. The APs' power levels were set to the maximum levels allowed by the EU regulations applicable to the three bands as summarized below in Figure 10.

The power levels used are conservative in the sense that multi-AP deployments within the same apartment / AP controller may implement techniques that manage the AP power levels (within the same apartment / AP controller domain) in a way that maximizes SINR, and therefore performance.

[11] Beyond the specific limitation to four 80 MHz channels at 5 GHz for the AP equipment used for this test, five 80 MHz channels at 5 GHz are actually currently available in most CEPT countries, while seven 80 MHz channels at 5 GHz are actually currently available in UK and Czech Republic.

[12] Six 160 MHz channels in UK and Czech Republic (three from the 5 GHz band and two from the L6 GHz band).

	2.4 GHz	5 GHz		L6 GHz
Applicable channels	1, 6, 11	36 - 64	100 - 144	1 - 93
Maximum transmit power (dBm)	20	23	30	23

Figure 10: APs' and STAs' power levels across the three bands.

For clarity and reference, a detailed list of all the equipment used in the testing, including model numbers, specifications, and configuration settings, is provided in ANNEX 1. This comprehensive detailing ensures transparency of the test setup and allows for accurate replication of the study in future tests. The equipment list helps in understanding the specific setup and configuration used during the testing, providing a complete overview of the technological framework within which the performance evaluations were conducted.

3 TEST METHODOLOGY

In this section we describe the methodologies and tools that were part of the test framework for assessing Wi-Fi performance in scenarios that aimed at replicating a high-density residential environment, enabling detailed insights into the capabilities and limitations of current Wi-Fi technology under various conditions.

3.1 Measurements of throughput

A suite of tools was employed, including:

WinSCP[13] – Utilized for FTP download and upload tests, WinSCP offers a robust platform for file transfer protocol operations, providing insights into the data transfer capabilities of the network.

Iperf3[14] – This tool was employed for conducting Iperf tests, which are crucial for measuring the maximum bandwidth achievable on IP networks. It helps in understanding the capabilities of the network infrastructure.

[13] https://winscp.net/eng/download.php
[14] https://iperf.fr/

VLC Media Player[15] – Used for streaming media files during the tests, VLC helps in assessing how well the network handles real-time video data streams.

Wireshark[16] – This network protocol analyzer was used for capturing and analyzing packets to calculate throughput and latency. It provides detailed insights into the volume, timing, and type of traffic flowing through the network.

Python Scripts – Custom Python scripts were developed to measure latency, jitter, and packet loss, giving a precise measurement of these critical parameters.

PowerShell Scripts – These scripts were used for controlling the test sequence, managing the STAs, and gathering logs, providing a streamlined and efficient testing process.

Filezilla FTP Server was also used, relying on the following features:

Simultaneous file transfers **–** Multiple simultaneous file transfer sessions are essential for testing the throughput and capacity of Wi-Fi networks under load. This feature was utilized to allow multiple users and devices to access the network simultaneously.

Transfer queue management **–** To manage queues of multiple files and directories to allow planning and execution of large-scale file transfers. This helped in maintaining a continuous flow of data, which is critical for accurate throughput measurement.

Transmission speed limits **–** Setting speed limits allowed testing different network conditions and to measure how the data rate variations affect performance metrics like latency and packet loss. Real-time status **–** Real-time status and logging gave immediate feedback on the success and speed of file transfers, offering insights into performance spikes, drops, and failures that were key for real-time analysis during the tests.

Throughput measurements were conducted using Wireshark network protocol analyzer software. Throughput was measured as the number of bits transmitted and successfully received per second over a roughly 90 second interval. This provides a robust assessment of network capacity accounting for overheads from various network layers. Figure 11 provides an illustrative example of how the throughput statistics were derived from the traffic traces collected for each Wi-Fi STA/laptop with the Wireshark software.

[15] https://www.videolan.org/vlc/
[16] https://www.wireshark.org/download.html

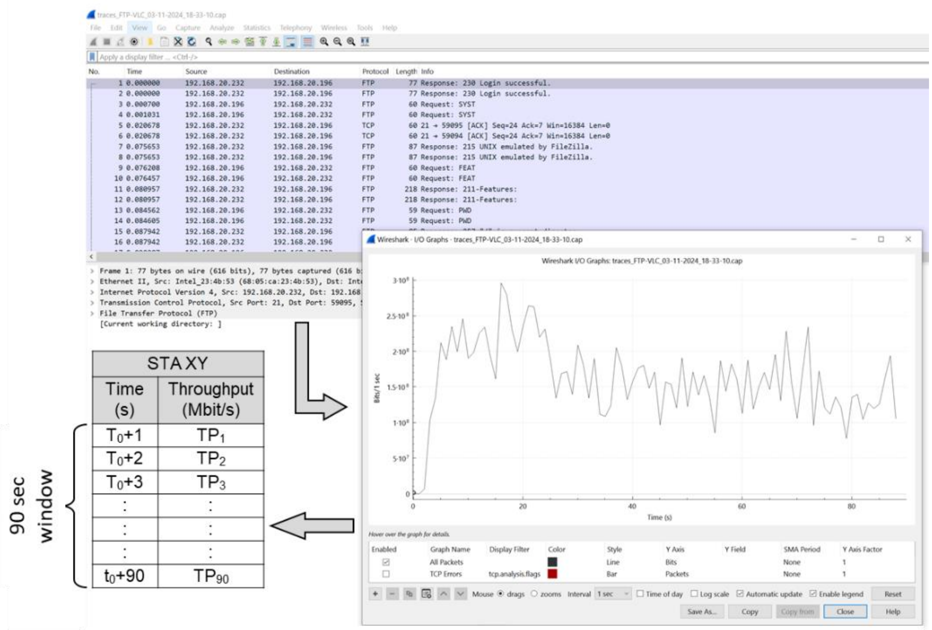

Figure 11: Derivation of throughput statistics from Wireshark software traces.

3.2 Measurement of indoor received powers

Two tools were used to perform indoor power measurements. They provide detailed insights into signal strength, coverage, and interference levels across different areas of the hotel. Measurements from the two tools were compared to verify consistency. The tools include:

Ekahau Sidekick 2[17] – Wi-Fi testing and measurement device for 2.4 GHz, 5 GHz, and 6 GHz bands,

Tamograph[18] – Wi-Fi planning, site survey and heatmap software.

Power measurements were performed across the three hotel floors, these measurements were aimed at quantifying the actual interference levels between APs, critical for optimizing AP placement and configuration.

Power measurements successfully verified the absence of any material signal levels in the 2.4 GHz, 5 GHz, and L6 GHz bands from possible sources other than the Wi-Fi equipment used in the tests.

3.3 Comtel test management software

More than 60 test sessions were undertaken, with measurements performed separately for the 2.4 GHz, 5 GHz, and L6 GHz bands. Test sessions were undertaken for different numbers of interfering

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[17] https://www.ekahau.com/
[18] https://www.tamos.com/products/wifi-site-survey

Wi-Fi APs (from zero APs up to 40 APs), for a growing number of APs in the target apartment (from 1 AP to 4 APs), and for different traffic models towards the STAs/laptops in the target apartment.

To manage the complexity and specific requirements of this test campaign, Comtel developed a dedicated centralized software interface (see Figure 12). This innovative platform was crucial for conveniently triggering traffic across all connected STAs/laptops through the Wi-Fi APs, and managing the different traffic models directed towards each STA/laptop. The software ensured accurate and reliable data collection and analysis.

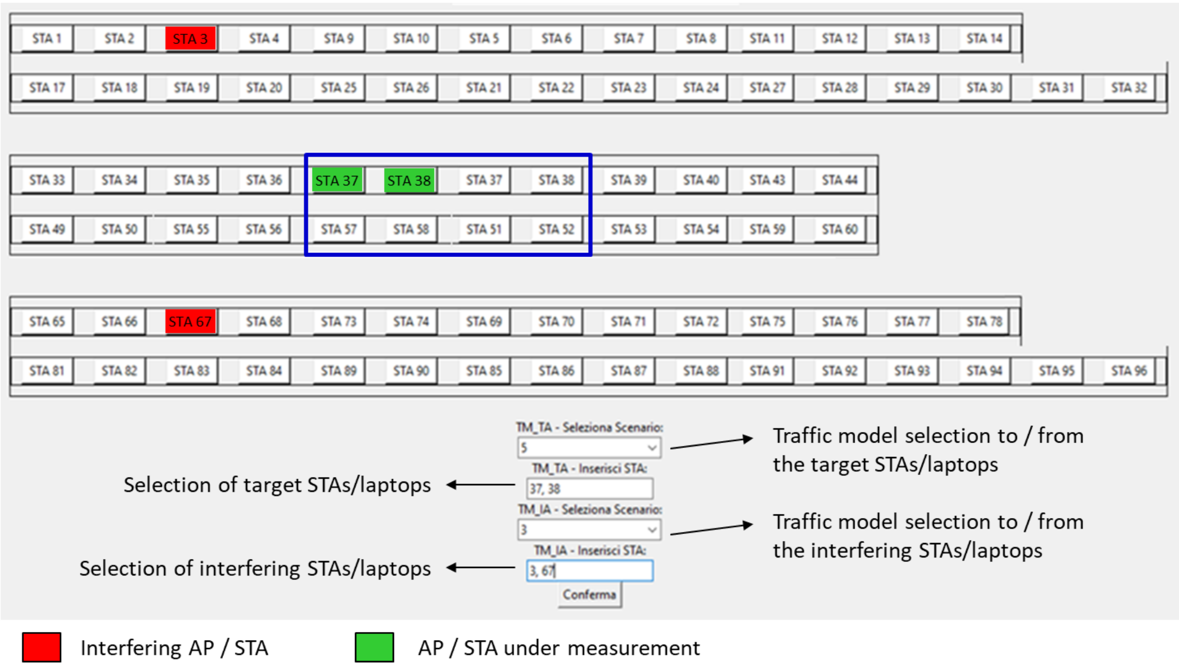

Figure 12: Test management software interface (Python and Power shell code from Comtel).

3.4 Topologies for generating increasing interference

Different "topology scenarios" were tested corresponding to varying patterns of interfering Wi-Fi APs. Test sessions started from measuring the performance of the APs in the target apartment in the absence of interference from APs in other rooms, while a number of sessions were dedicated to the cases where a growing number of interfering APs (up to 40 interfering APs) were switched on. Figure 13 provides an overview for the topology scenarios tested.

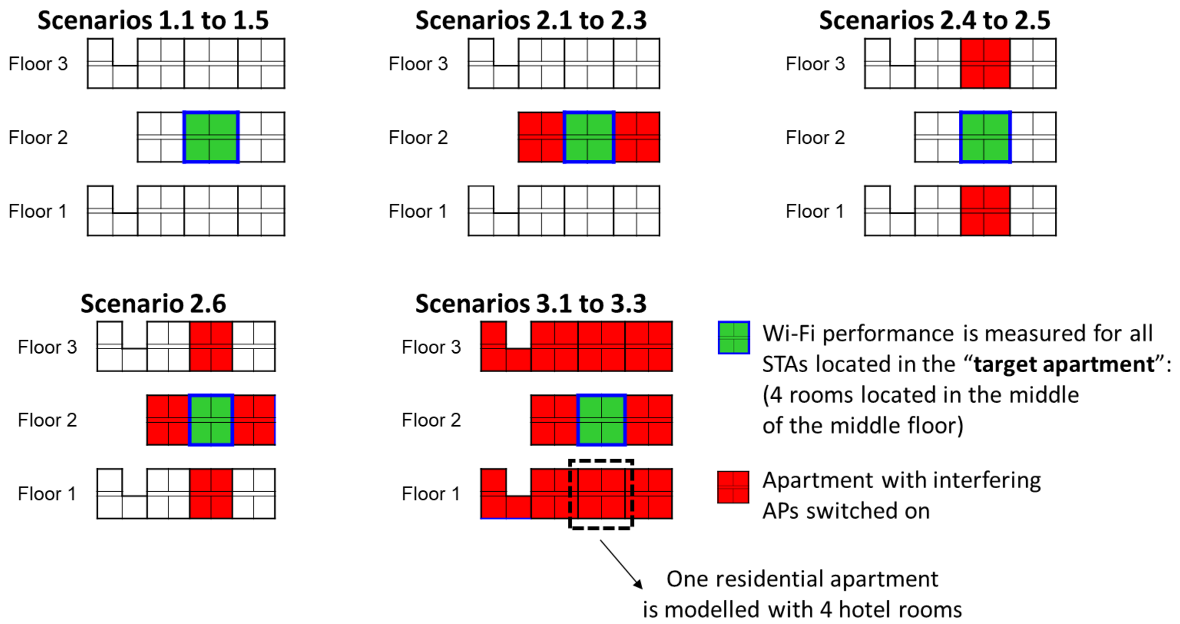

Figure 13: Topology scenarios tested.

More precisely, the above scenarios can be grouped into three main categories as follows:

<u>**Isolated house/dwelling (Scenarios 1.1 to 1.5)**</u>

These scenarios are shown in Figure 14 and aim at replicating an isolated house/dwelling with progressively increasing numbers of Wi-Fi APs and STAs/laptops within the target apartment to measure the network's internal handling capabilities without external interference:

Scenario 1.1 – Consisted of 1 AP with 2 STAs/laptops (within the same room) in the target apartment, establishing the baseline performance in a minimally connected environment.

Scenario 1.2 – Consisted of 1 AP with 8 STAs/laptops (across four rooms) in the target apartment to test the AP's ability to handle multiple devices in different rooms. This scenario has provided interesting data related to the coverage-limited performance of APs.

Scenarios 1.3 to 1.5 – Further expanded the setup by introducing additional APs within the target apartment (2, 3, and then 4 APs respectively, each scenario with 8 STAs/laptops). The corridor which runs along the second floor divides the rooms in the central apartment into two pairs, and provides additional radio isolation between the two pairs of rooms (on account of the two walls of the corridor). In order to counter this additional isolation and the potential for reduced interference, two extra interfering APs were installed in the corridor in each scenario. For logistic reasons and without any impact on the test results, these two APs were only connected to one STA/laptop each. Conservatively, the throughput associated with the two STAs in the corridor was not considered when computing the measured throughput within the target apartment.

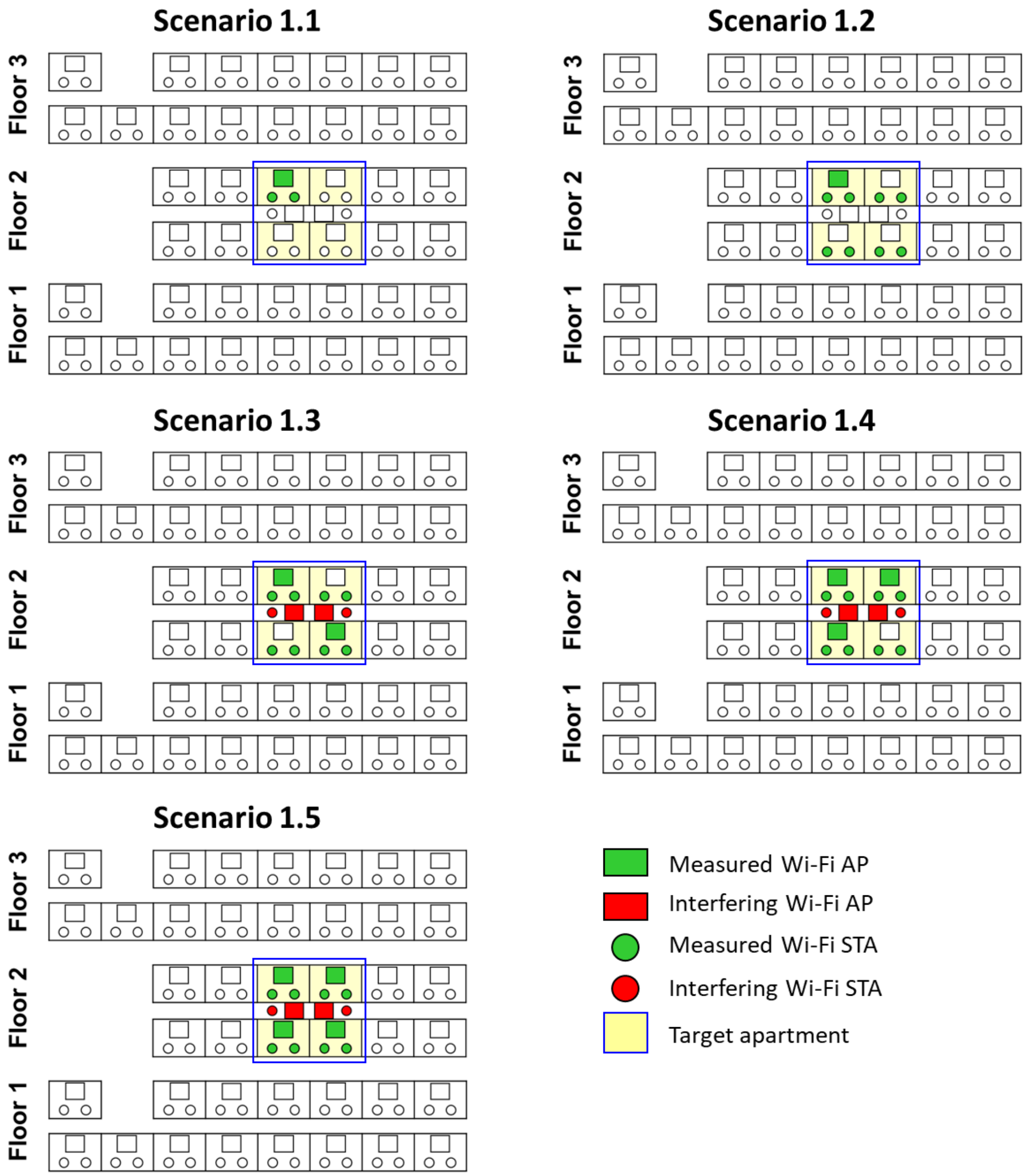

Figure 14: Topology scenarios 1.1 to 1.5 (isolated house/dwelling).

<u>Dense urban apartment: interference from immediately adjacent apartments (Scenarios 2.1 to 2.6)</u>

These scenarios are shown in Figure 15 and aim at replicating a dense urban apartment subject to interference from a growing number of other apartments within the same building block:

Scenarios 2.1 to 2.3 – Maintained 4 APs in the target apartment with 8 STAs (along with 2 APs in the corridor, each serving 1 STA) while increasing the number of interfering APs in neighboring apartments on the same floor (from 2 to 8 interfering APs, each serving 2 STAs).

Scenarios 2.4 and 2.5 – Examined the impact of interference from 1 AP serving 8 STAs or 4 APs serving 8 STAs located in apartments immediately above and below the target apartment (from 2 to 8 interfering APs, each serving 2 STAs).

Scenario 2.6 – Examined the impact of interference from 4 APs serving 8 STAs in each of the apartments immediately on either side (on the same floor) and above and below the target apartment (16 interfering APs, each serving 2 STAs).

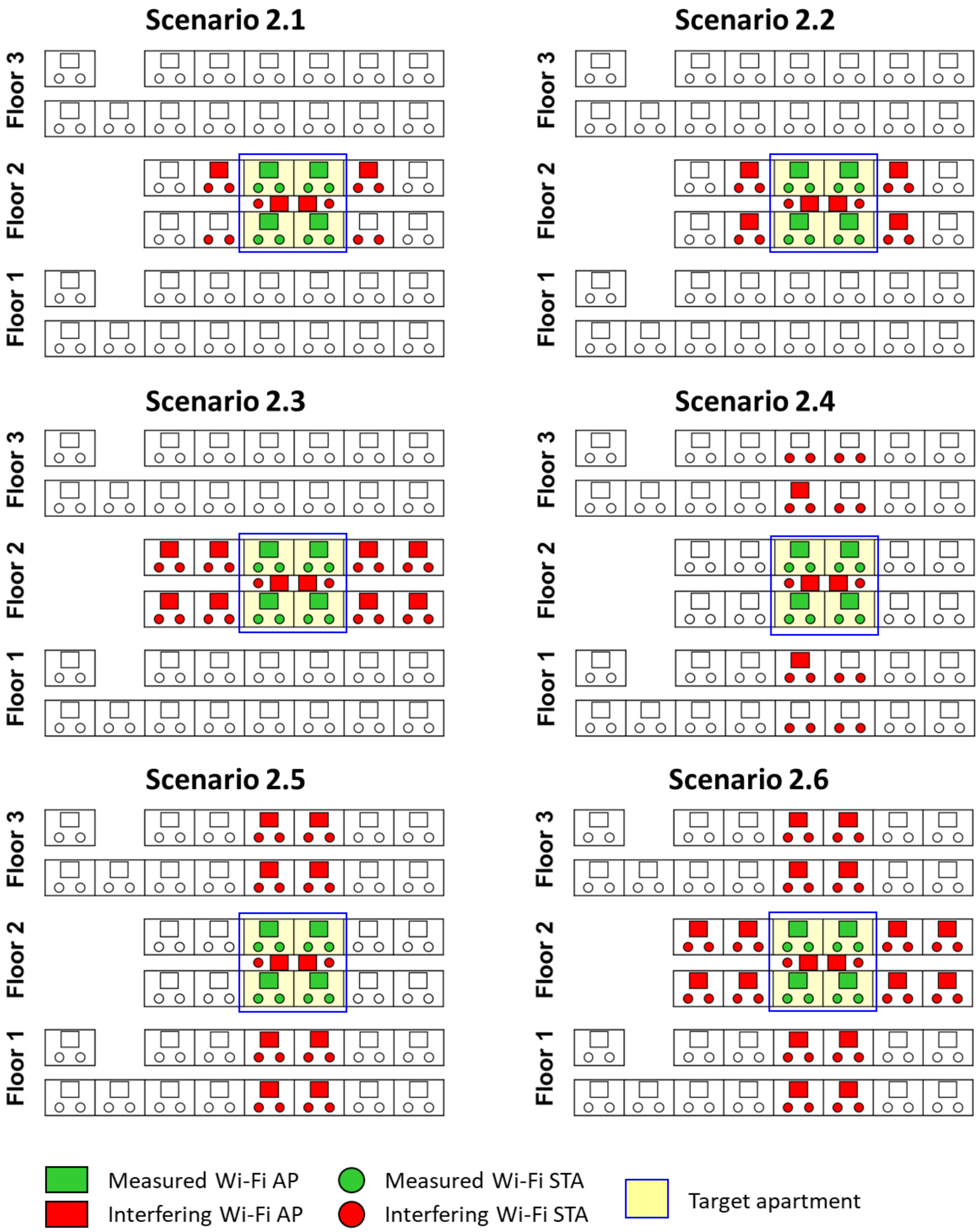

Figure 15: Topology scenarios 2.1 to 2.6.

Dense urban apartment: interference from all apartments
(Scenarios 3.1 to 3.3)

This group of scenarios are shown in Figure 16, and aim to explore the network's capacity to manage internal loads against a background of severe interference from 40 access points installed in an area of ca. 900 m^2, noting that such a very high density of access points is not observed in residential scenarios today, and is also considered unlikely in the future.

Scenarios 3.1 to 3.3 – Each scenario increased the number of APs within the target apartment (from 2 APs to 4 APs serving 8 STAs, and 2 interfering APs in the corridor each serving 1 STA), while the number of interfering APs from other apartments was fixed at 40 distributed across the upper, lower, and same floors.

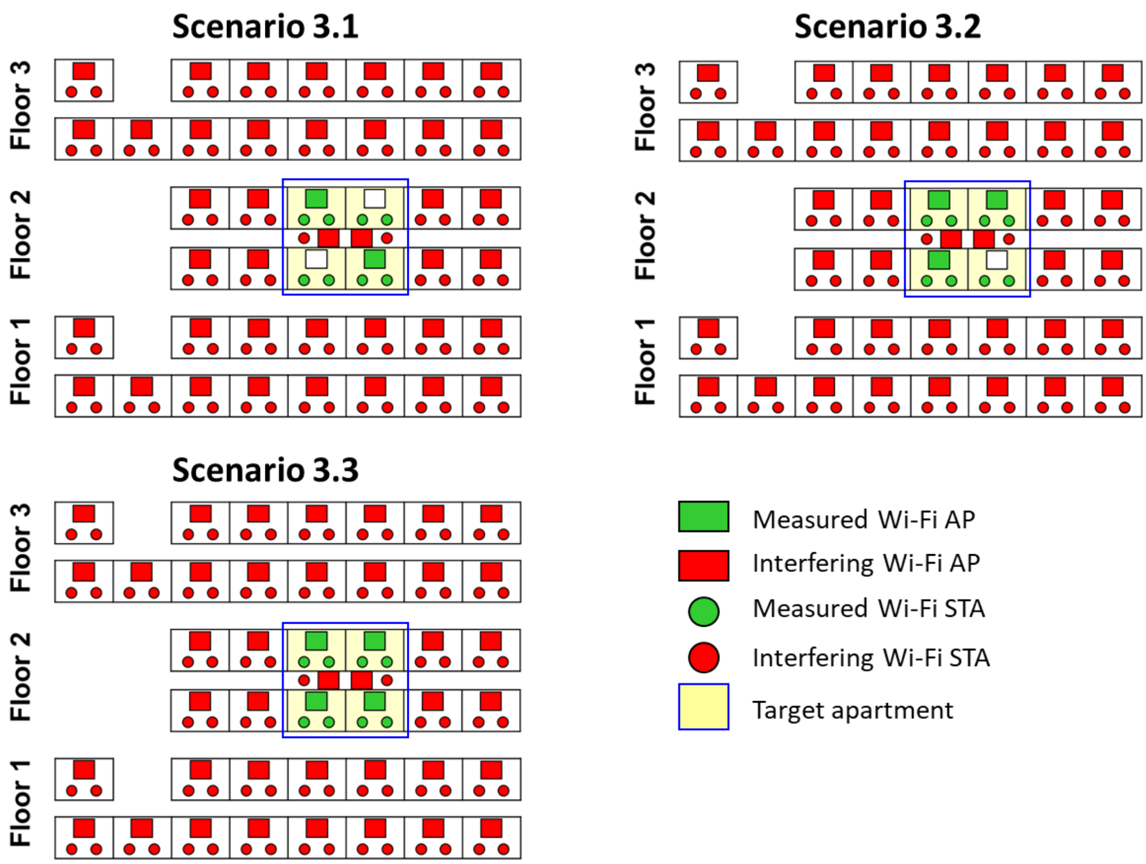

Figure 16: Topology scenarios 3.1 to 3.3.

Purely as a sensitivity exercise, we also examined a somewhat unrealistic scenario corresponding to only 1 AP in the entire target apartment serving 8 STAs (2 STA per room) while 40 APs and 78 STAs were active in all the remaining rooms/apartments in the hotel – i.e. no densification in the target apartment but full densification in the surrounding apartments.

These topology scenarios provided comprehensive insights into the Wi-Fi networks' performance under varied and escalating interference levels.

4 TEST RESULTS

In the following sections we detail the outcomes of our comprehensive tests, illustrating how each band handles different network loads and propagation challenges within the tested scenarios. This analysis aims at providing actionable insights into deploying efficient and effective Wi-Fi networks that are well-suited to the specific conditions of modern connectivity needs.

4.1 Theoretical performance of Wi-Fi networks at L6 GHz

Theoretical performance refers to the expected capabilities of Wi-Fi networks based on mathematical models and specifications without the practical limitations imposed by real-world factors such as physical obstructions, interference, and hardware limitations. By comparing the theoretical and actual performance, the testing aimed at identifying gaps that may exist due to practical challenges, such as building materials that block signals, the presence of many competing networks, or suboptimal Wi-Fi AP placements. Understanding these differences is crucial for network designers to realistically set expectations, plan network layouts, choose appropriate technologies, and for administrations to define the appropriate regulations.

The table in Figure 17 shows that Wi-Fi 6E can achieve a theoretical throughput of 2.4 Gbit/s when operating in a 160 MHz channel at the L6 GHz band, with 1024-QAM modulation (MCS 11) and a 2x2 MIMO configuration (i.e. two spatial streams). However, in our practical tests at the outset, we observed a peak link throughput that reached a maximum of only 1.5 Gbit/s at L6 GHz (in Scenario 1.1). This discrepancy between theoretical and practical performance highlights the real-world challenges that can affect Wi-Fi speeds, such as environmental interference, device capabilities, and network congestion. Despite not reaching the theoretical maximum, achieving a throughput of 1.5 Gbit/s is indicative of the substantial capacity and effectiveness of the L6 GHz band in supporting high-speed internet services.

Spatial streams	Modulation	Coding	GI: 0.8 µs				
			242-tone RU / 20 MHz	484-tone RU / 40 MHz	996-tone RU / 80 MHz	**2x996-tone RU / 160 MHz**	4x996-tone RU / 320 MHz
2	BPSQ	1/2	17	34	72	144	288
2	QPSK	1/2	34	69	144	288	577
2	QPSK	3/4	52	103	216	432	865
2	16-QAM	1/2	69	138	288	577	1153
2	16-QAM	3/4	103	207	432	865	1729
2	64-QAM	2/3	138	275	577	1153	2306
2	64-QAM	3/4	155	310	649	1297	2594
2	64-QAM	5/6	172	344	721	1441	2882
2	256-QAM	3/4	207	413	865	1729	3459
2	256-QAM	5/6	229	459	961	1922	3843
2	1024-QAM	3/4	258	516	1081	2162	4324
2	**1024-QAM**	**5/6**	287	574	1201	**2402**	4804
2	4096-QAM	3/4	310	619	1297	2594	5188
2	4096-QAM	5/6	344	688	1441	2882	5765
4	BPSQ	1/2	34	69	144	288	577
4	QPSK	1/2	69	138	288	577	1153
4	QPSK	3/4	103	207	432	865	1729
4	16-QAM	1/2	138	275	577	1153	2306
4	16-QAM	3/4	207	413	865	1729	3459
4	64-QAM	2/3	275	551	1153	2306	4612
4	64-QAM	3/4	310	619	1297	2594	5188
4	64-QAM	5/6	344	688	1441	2882	5765
4	256-QAM	3/4	413	826	1729	3459	6918
4	256-QAM	5/6	459	918	1922	3843	7686
4	1024-QAM	3/4	516	1032	2162	4324	8647
4	1024-QAM	5/6	574	1147	2402	4804	9608
4	4096-QAM	3/4	619	1239	2594	5188	10377
4	4096-QAM	5/6	688	1377	2882	5765	11529

GI: Guard Interval duration (0.8 µs was use in our test)
RU: Resource Unit
Source: SemFio Networks 2023 "Real World MCS Table"- https://mcsindex.net/

Figure 17: Wi-Fi 6E (802.11ax) MCS table - theoretical performance.

The following paragraphs provide a brief and non-exhaustive overview of the latest Wi-Fi enhancements and the expectations for the future.

As discussed above, recent products implementing the **802.11ax standard (Wi-Fi 6/6E)** deliver data rates that significantly exceed those of their predecessors: up to ca. 2.0 to 2.4 Gbit/s under optimal conditions, spread across two spatial streams for a 160 MHz channel (see Figure 17). This and other performance enhancements are due to the introduction of important enhancements such as: OFDMA[19], MU-MIMO[20], BSS coloring[21], improved power control to avoid interference, higher-order modulation (1024-QAM), wider channel bandwidths (160 MHz), reliability improvements such as lower power consumption via Target Wake Time[22], and security protocols like WPA3. Improvements to the Wi-Fi technology also aim at minimizing latency and jitter to levels suitable for real-time communications even under very high network load. There are also standards available which allow differentiated services by sorting and managing traffic according to the type of service (ToS)[23].

Similarly, the more recent **IEEE 802.11be standard (Wi-Fi 7)**[24] is expected to further increase these rates, supporting higher theoretical speeds leveraging advanced new features such as higher-order modulation schemes (4096-QAM), wider channel bandwidths (320 MHz), aggregation of multiple channels across different frequency bands or within the same band into a single connection (so-called Multi Link Operation, or MLO), support for MU-MIMO with 16 spatial streams, multi-AP operation, and deterministic low-latency among others.

IEEE 802.11bn (Wi-Fi 8), the next generation of Wi-Fi, will further improve performance with new features. It will likely offer even faster speeds, lower latency, and better performance than previous versions of Wi-Fi. Compared to the Extremely High Throughput MAC/PHY operation, 802.11bn enables at least one mode of operation capable of increasing throughput by 25%, reducing latency by 25% for

[19] OFDMA segregates the spectrum in time-frequency resource units (RUs). A central coordinating entity (the AP in 802.11ax) assigns RUs for reception or transmission to associated stations. Through the central scheduling of the RUs, contention overhead can be avoided, which increases efficiency in scenarios of dense deployments.
[20] With downlink MU-MIMO an AP may transmit concurrently to multiple stations and with uplink MU-MIMO an AP may simultaneously receive from multiple stations. Whereas OFDMA separates receivers to different RUs, with MU-MIMO the devices are separated to different spatial streams. In 802.11ax, MU-MIMO and OFDMA technologies can be used simultaneously. To enable uplink MU transmissions, the AP transmits a new control frame (Trigger) which contains scheduling information (RU allocations for stations, and the modulation and coding scheme (MCS) that shall be used for each station). Furthermore, Trigger also provides synchronization for an uplink transmission, since the transmission starts SIFS after the end of Trigger.
[21] Basic service set (BSS) coloring enables devices to differentiate transmissions in their own network from transmissions in neighboring networks. Adaptive power and sensitivity thresholds allow dynamic adjusting of transmit power and signal detection threshold to increase spatial reuse. Without spatial reuse capabilities devices refuse to transmit concurrently with transmissions ongoing in other neighboring networks. With BSS coloring, a wireless transmission is marked at its very beginning, helping surrounding devices to decide if a simultaneous use of the wireless medium is permissible. A station is allowed to consider the wireless medium as idle and start a new transmission even if the detected signal level from a neighboring network exceeds legacy signal detection threshold, provided that the transmit power for the new transmission is appropriately decreased.
[22] TWT reduces power consumption and medium access contention by allowing devices to wake up at other periods than the beacon transmission period. The AP may group devices to different TWT periods, thereby reducing the number of devices contending simultaneously for the wireless medium.
[23] CableLabs/Meta joint QoE assessment paper, “Impacts of WMM on Wi-Fi; Study of real-time communication quality and Wi-Fi multimedia”.
[24] https://spectrum.ieee.org/what-is-wifi-7

the 95th percentile of the latency distribution, reducing MAC Protocol Data Unit (MPDU) loss by 25%, and improving STA and AP power with backward compatibility. Wi-Fi 8 is expected to offer a range of powerful new features including multiple AP coordination and transmission, support for millimeter wave (mmWave) frequencies, and low-latency enhancements.

While there are no official details or specifications for Wi-Fi 8 at the moment, this new standard is expected to be finalized by 2028/2029.

4.2 Isolated house/dwelling (Scenarios 1.1 to 1.5)

The configuration of the four rooms within the target apartment, without interfering APs from outside the apartment, was designed to replicate an isolated house/dwelling, and to compare the test results for this setup against those for the dense urban apartment setup that is addressed in the following sections. This arrangement helps understanding how signal propagation and interference handling can vary within an isolated house/dwelling, offering insights that are applicable to real-world urban settings.

As illustrated in Figure 14 in Scenarios 1.3 to 1.5, two extra APs were located in the middle of the corridor in the target apartment, creating a controlled source of interference intended to compensate for the signal attenuation brought about by the two walls that separate the rooms sitting on the opposite sides of the hotel corridor. This replicates a highly challenging interference environment in the sense that while the two APs deliver performance-impacting interference to the four APs in the target apartment, the traffic delivered by these two additional interfering APs was not considered when calculating the total throughput in the target apartment.

4.2.1 Coverage limited scenario

Propagation decreases as frequencies increase: the 2.4 GHz band provides relatively good coverage across the target apartment (ca. 90 m^2).

With the 5 GHz, and L6 GHz bands, propagation across walls becomes more problematic in the target apartment areas that are further away from the AP, leading to a more coverage-limited environment.

Figure 18 shows that the throughput decreased when moving from Scenario 1.1 to Scenario 1.2, indicating the coverage challenges associated with Wi-Fi propagation between rooms: the STAs that were located further away from the AP drained a disproportionate amount of radio resource from the AP (e.g. due to their need to adopt a lower-order modulation scheme) leading to a 29% through reduction when moving from Scenario 1.1 to 1.2.

Topology Scenario 1.1			Throughput (Mbit/s)	
5 GHz (4 x 80 MHz)				
Room	203	STA 037	223	
		STA 038	229	
Target apartment (5 GHz)			**452**	→ $T_{5GHz\ Sc.\ 1.1}$
L6 GHz (3 x 160 MHz)				
Room	203	STA 037	708	
		STA 038	372	
Target apartment (L6 GHz)			**1,080**	→ $T_{L6GHz\ Sc.\ 1.1}$
Target apartment (5 + L6 GHz)			**1,532**	→ $T_{Sc.\ 1.1}$

Target apartment

Room 203 STA 37, STA 38	Room 204 STA 39, STA 40
Room 210 STA 51, STA 52	Room 209 STA 53, STA 54

Topology Scenario 1.2			Throughput (Mbit/s)	
5 GHz (4 x 80 MHz)				
Room	203	STA 037	58	49% of $T_{5GHz\ Sc.\ 1.2}$
		STA 038	64	
	204	STA 039	23	51% of $T_{5GHz\ Sc.\ 1.2}$
		STA 040	40	
	210	STA 051	15	
		STA 052	4	
	209	STA 053	18	
		STA 054	27	
Target apartment (5 GHz)			**250**	→ $T_{5GHz\ Sc.\ 1.2}$ (55% of $T_{5GHz\ Sc.\ 1.1}$)
L6 GHz (3 x 160 MHz)				
Room	203	STA 037	315	67% of $T_{L6GHz\ Sc.\ 1.2}$
		STA 038	247	
	204	STA 039	77	33% of $T_{L6GHz\ Sc.\ 1.2}$
		STA 040	43	
	210	STA 051	18	
		STA 052	18	
	209	STA 053	54	
		STA 054	65	
Target apartment (L6 GHz)			**838**	→ $T_{L6GHz\ Sc.\ 1.2}$ (78% of $T_{L6GHz\ Sc.\ 1.1}$)
Target apartment (5 + L6 GHz)			**1,087**	→ $T_{Sc.\ 1.2}$ (71% of $T_{Sc.\ 1.1}$)

Figure 18: Coverage-limited scenario.

4.2.2 Throughput performance results (Scenarios 1.1 to 1.5)

Our analysis focuses on evaluating how the increase in the numbers of APs and connected STAs, within the controlled environment of the target apartment, impacts key network performance indicators such as throughput.

below shows the variation of total throughout in the target apartment across the different scenarios (see Figure 14 for an illustration of the relevant scenarios).

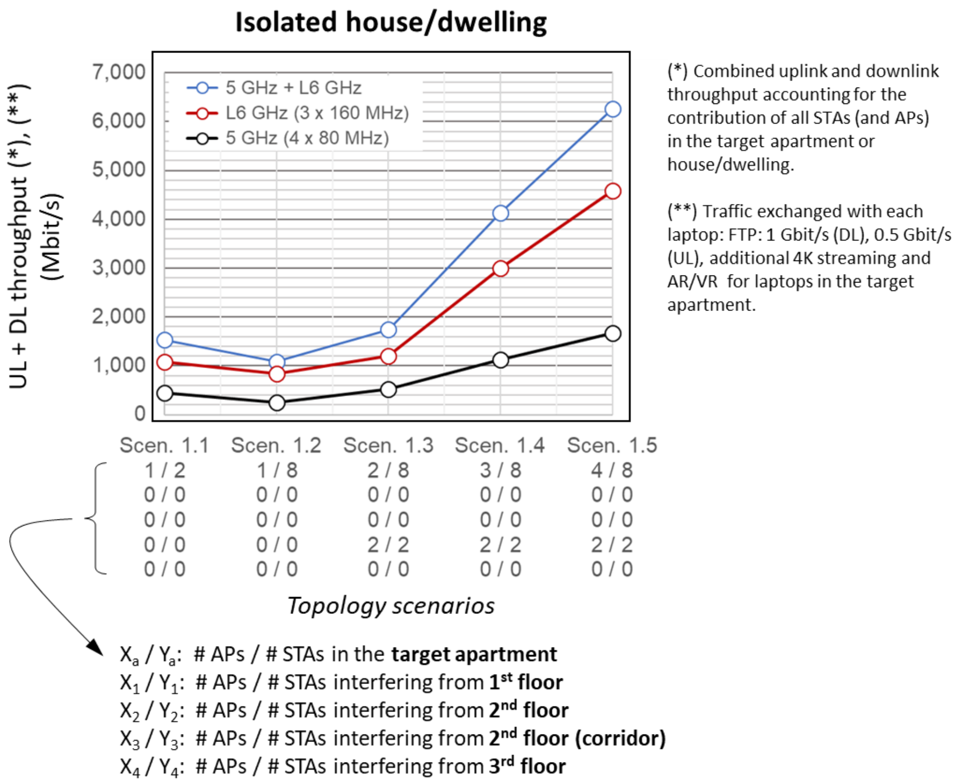

Figure 19: Measured total throughput in the target apartment across the 5 and L6 GHz bands – isolated house/dwelling (Scenarios 1.1 to 1.5).

Figure 19 shows that the total throughput delivered to the target apartment exceeded 1 Gbit/s for all scenarios.

With reference to Scenario 1.1, 1.5 Gbit/s was delivered with 1 AP connected to 2 STAs in the same room. In case of Scenario 1.5, 6.3 Gbit/s was reached with 4 APs deployed in the four rooms in the target apartment (each AP connected to two STAs within the same room).

As explained in Section 4.2.1, Figure 19 also shows that the throughput decreased when moving from Scenario 1.1 to Scenario 1.2, indicating the coverage challenges associated with Wi-Fi propagation between rooms.

With the fixed number of 8 STAs served in the test Scenarios 1.2 to 1.5, we distinctly observe enhancements in the target apartment's total throughput as APs are added within the target apartment. Specifically, as Figure 20 shows, the deployment of a second AP (Scenario 1.3) resulted in a considerable increase in throughput, demonstrating improved data transmission rates and network efficiency.

		Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5
# APs / # STAs	In the **target apartment**	1 / 2	1 / 8	2 / 8	3 / 8	4 / 8
	Interfering from **1st floor**	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
	Interfering from **2nd floor**	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
	Interfering from **2nd floor (corridor)**	0 / 0	0 / 0	2 / 2	2 / 2	2 / 2
	Interfering from **3rd floor**	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
		Throughput (Mbit/s)				
5 GHz (4 x 80 MHz)		452	250	529	1,133	1,677
L6 GHz (3 x 160 MHz)		1080	838	1,210	3,005	4,582
Total		1,532	1,087	1,739	4,138	6,259

+60% +137% +51%

Figure 20: Increase in measured total throughput in the target apartment as a result of AP densification across the 5 and L6 GHz bands – isolated house/dwelling (Scenarios 1.1 to 1.5).

The results clearly demonstrate a consistent increase in throughput as the number of APs within the apartment rose from one to four, and how the network's ability to handle simultaneous data transmissions improved significantly. With one AP per room in the final scenario, the network achieved optimal distribution of traffic load, minimizing bottlenecks and maximizing data flow efficiency.

Spectral efficiency assessment

Figure 21 shows how the spectral efficiency for the target apartment can be derived for all scenarios based on the total throughput delivered to the STAs in the target apartment and accounting for the frequency channels' bandwidth used by the APs in the apartment.

$$S = \frac{T}{BW} = \frac{T}{N \times B} = \frac{T}{\times B}$$

S	Spectral efficiency in target apartment (bit/s/Hz)
T	Throughput in target apartment (bit/s)
BW	Total bandwidth used in target apartment (Hz)
N	Number of channels used in target apartment
B	Channel bandwidth (Hz)
N_{AP}	Number of APs in target apartment
F	Frequency reuse

Figure 21: Derivation of the spectral efficiency for the target apartment for all scenarios.

The target apartment spectral efficiency values shown in Figure 22 for Scenarios 1.1 to 1.2 account for the decrease in efficiency due to the coverage challenges when only one AP is deployed in the target apartment. Values for Scenarios 1.2 to 1.5 show the spectral efficiency increase when coverage limitations are mitigated by the progressive addition of APs in the rooms within the target apartment.

	Scenario 1.1		Scenario 1.2		Scenario 1.3		Scenario 1.4		Scenario 1.5	
Frequency band (GHz)	5	L6	5	L6	5	L6	5	L6	5	L6
Throughput in target apartment (Mbit/s)	452	1,080	250	838	529	1,210	1,133	3,005	1,677	4,582
Number of APs in target apartment	1	1	1	1	2	2	3	3	4	4
Channel BW in the band (MHz)	80	160	80	160	80	160	80	160	80	160
Frequency reuse in band	4	3	4	3	4	3	4	3	4	3
Number of channels in target apartment	1	1	1	1	2	2	3	3	4	3
BW used in target apartment (MHz)	80	160	80	160	160	320	240	480	320	480
Spectral efficiency in target apartment (bit/s/Hz)	**5.7**	**6.8**	**3.1**	**5.2**	**3.3**	**3.8**	**4.7**	**6.3**	**5.2**	**9.5**

Figure 22: Measured spectral efficiency for the target apartment in Scenarios 1.1 to 1.5.

These results highlight the benefits of strategic AP placement and density optimization and can guide effective network planning and management in these contexts.

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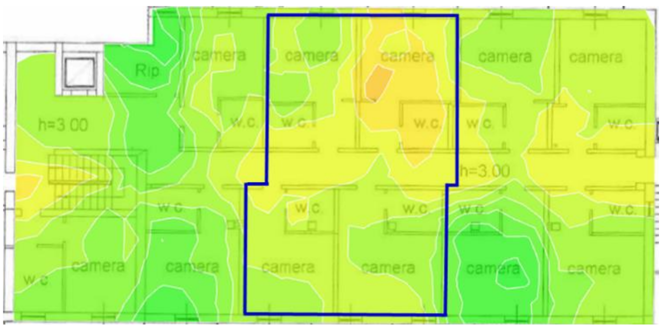
4.3 Dense urban apartment (Scenarios 2.1 to 2.6 and 3.1 to 3.3)

4.3.1 Indoor coverage maps (Scenario 3.3)

Given one specific frequency channel in each of the three bands, the maps[25] displayed in Figure 23, Figure 24, and Figure 25 show the aggregate interference footprint visible on the 2nd floor originating from the APs transmitting on those same channels from the 1st floor, from the 2nd floor itself (excluding the APs in the target apartment) and from the 3rd floor.

The maps refer to Scenario 3.3 (see Figure 16 for an illustration of this scenario) where FTP traffic was transmitted between the interfering APs and their respective served STAs/laptops, while FTP and 4K video streaming were simultaneously transmitted between the APs in the target apartment and their associated STAs/laptops (see Section 2.5 for information on traffic models).



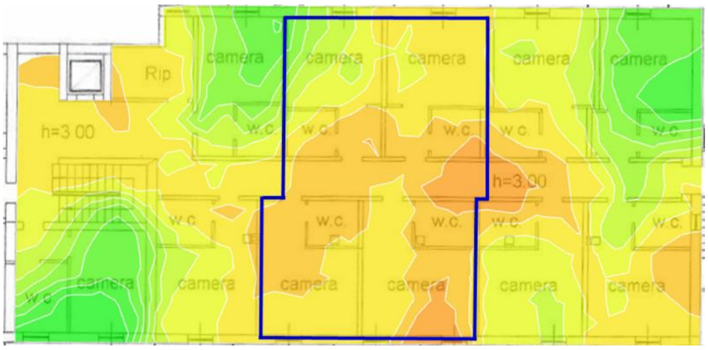
Interference from all 14 APs which use channel 6 in the 2.4 GHz band:

- From rooms in floor 1: 103, 116, 120, 123, 126
- From rooms in floor 2: 208, 211, F2_ad
- From rooms in floor 3: 301, 306, 309, F3_void, F3_rip_2

-80 dBm / (20 MHz)　　-55 dBm / (20 MHz)　　-30 dBm / (20 MHz)

Figure 23: Interference footprint for topology Scenario 3.3, measured on the 2nd floor and originating from all the APs which use channel 6 in the 2.4 GHz band (see Figure 9) in floor 1, floor 2 (excluding room 204 from the target apartment), and floor 3.

[25] Maps were produced with Ekahau Sidekick 2 Wi-Fi testing and measurement device.

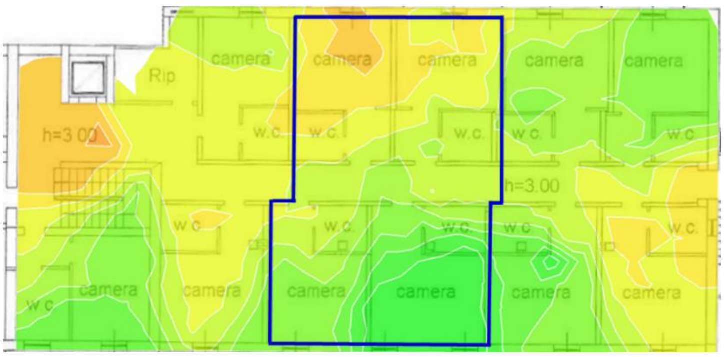


Interference originating from all 12 APs which use channel 58 in the 5 GHz band:

- From rooms in floor 1: 103, 116, 120. 122, 126
- From rooms in floor 2: 201, 202, 206
- From rooms in floor 3: 302, 305, 307, 310

-80 dBm / (80 MHz) -55 dBm / (80 MHz) -30 dBm / (80 MHz)

Figure 24: Interference footprint for topology Scenario 3.3, measured on the 2nd floor and originating from all the APs which use channel 58 in the 5 GHz band (see Figure 9) in floor 1, floor 2 (excluding room 209 from the target apartment), and floor 3.



Interference originating from all 13 APs which use channel 15 in the U6 GHz band:

- From rooms in floor 1: 101, 115, 119, 121, 124
- From rooms in floor 2: 201, 206, 209 (room 209 belongs to the target apartment)
  From rooms in floor 3: F3_wc, 302, 305, 307, 310

-80 dBm / (160 MHz) -55 dBm / (160 MHz) -30 dBm / (160 MHz)

Figure 25: Interference footprint for topology Scenario 3.3, measured on the 2nd floor and originating from all the APs which use channel 15 in the L6 GHz band (see Figure 9) in floor 1, floor 2 (excluding rooms 203 from the target apartment), and floor 3.

With reference to the 2.4 and 5 GHz bands, the measured interference footprints show significant aggregate interference received at the target apartment from the interfering APs located in the rooms outside[26] the target apartment.

As expected, the measured interference footprint associated with the L6 GHz band is significantly smaller than the interference footprint in the target apartment for the 2.4 GHz band due to the better propagation at lower frequencies.

The measured interference footprint for the L6 GHz band is greater than for the 5 GHz band due to the fewer channels available at L6 GHz compared with 5 GHz (3 vs. 4), which means that the measured channel is reused by a greater number of APs in close proximity to and even inside the target apartment[27]. However, reuse of 3 allowed the use of larger 160 MHz channels which led to significant throughput and spectral efficiency in the L6 GHz band (see Figure 30).

As shown in Figure 18, propagation of the wanted signal at the 5 GHz and L6 GHz bands becomes more problematic in the apartment areas that are further away from the AP, leading to a coverage-limited environment.

At the same time, Figure 24 shows that the 5 GHz and L6 GHz bands still allow non-negligible propagation across rooms for the interfering signals.

4.3.2 Throughput performance results (Scenarios 2.1 to 2.6)

Here, we explore the network performance measurement results obtained from the dense urban apartment scenarios with progressively increasing levels of interference. Our analysis concentrates on assessing how escalating interference levels, while maintaining a constant number of APs and connected STAs in the target apartment, affect throughput and packet loss. This evaluation provides insights into how Wi-Fi networks perform under progressively challenging conditions of external interference in environments where device density in the target apartment remains constant.

Figure 26 shows the variation of throughput in the target apartment across the different scenarios. See Figure 15 for an illustration of the relevant scenarios.

[26] For the case of the L6 GHz band where there are two APs in the target apartment using channel 15, the measured interference footprints include the emissions from one of those two APs in room 209.
[27] The AP in room 209, inside the target apartment, also uses channel 15.

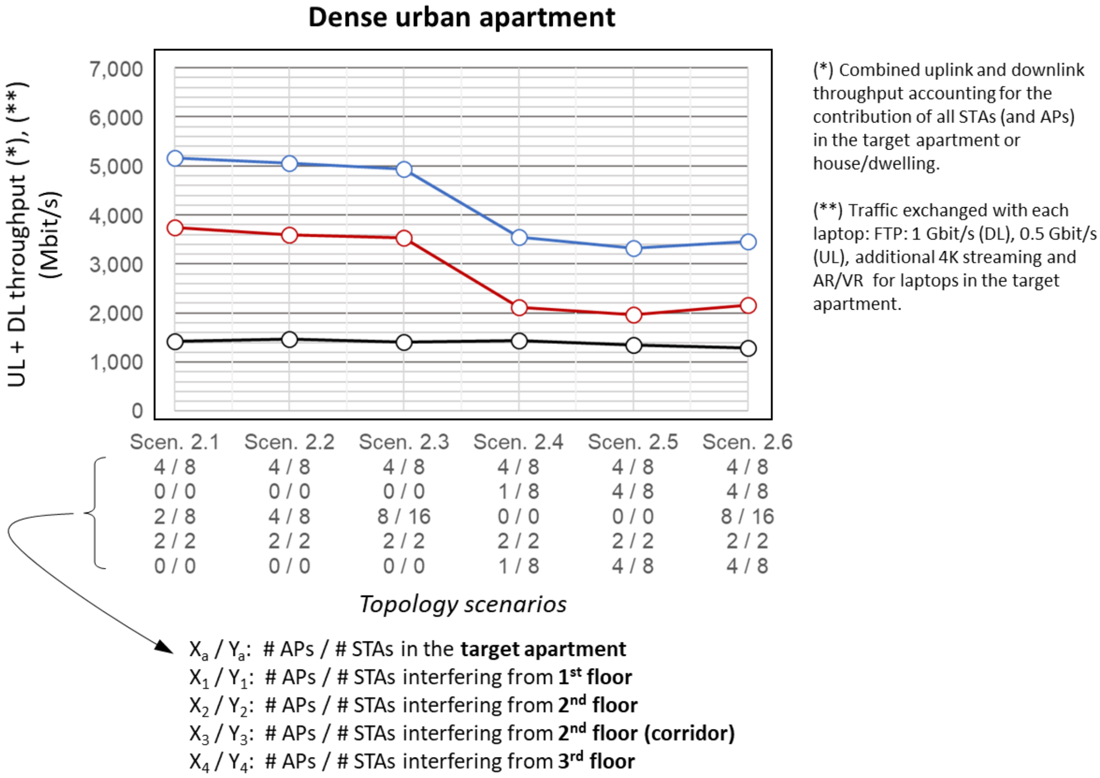


Figure 26: Measured total throughput in the target apartment across the 5 and L6 GHz bands – dense urban apartment Scenarios 2.1 to 2.6.

Figure 26 shows that the total throughput delivered to the target apartment readily exceeded 1 Gbit/s for all scenarios.

With a constant number of APs and connected STAs within the target apartment, we clearly observed a gradual decline in throughput for the APs in the target apartment as interference from APs in adjacent apartments increases.

Notably, there is a significant drop in throughput in Scenario 2.4, with the introduction of interference from APs located on the floors above and below the target apartment, particularly evident in the L6 GHz band.

Another noteworthy observation is in Scenario 2.6, where there is a slight improvement in throughput performance despite the introduction of a considerable number of interfering APs. This seemingly paradoxical improvement indicates that as the number of interfering APs increases, their access to the shared channel is also limited due to the interference, thereby impacting their own performance and therefore reducing their ability to interfere with the APs in the target apartment.

Spectral efficiency assessment

The values of spectral efficiency in the target apartment as shown in Figure 27 for Scenarios 2.1 to 2.6 account for the decrease in efficiency due to the increasing interference from the APs outside the rooms in the target apartment. Values are derived as described in Figure 27.

	Scenario 2.1		Scenario 2.2		Scenario 2.3		Scenario 2.4		Scenario 2.5		Scenario 2.6	
Frequency band (GHz)	5	L6	5	L6	5	L6	5	L6	5	L6	5	L6
Throughput in target apartment (Mbit/s)	1,424	3,740	1,467	3,596	1,402	3,532	1,437	2,112	1,347	1,973	1,291	2,169
Number of APs in target apartment	4	4	4	4	4	4	4	4	4	4	4	4
Channel BW in the band (MHz)	80	160	80	160	80	160	80	160	80	160	80	160
Frequency reuse in band	4	3	4	3	4	3	4	3	4	3	4	3
Number of channels in target apartment	4	3	4	3	4	3	4	3	4	3	4	3
BW used in target apartment (MHz)	320	480	320	480	320	480	320	480	320	480	320	480
Spectral efficiency in target apartment (bit/s/Hz)	**4.5**	**7.8**	**4.6**	**7.5**	**4.4**	**7.4**	**4.5**	**4.4**	**4.2**	**4.1**	**4.0**	**4.5**

Figure 27: Measured spectral efficiency for the target apartment for Scenarios 2.1 to 2.6.

4.3.3 Throughput measurements results (Scenarios 3.1 to 3.3)

Here, we investigate the impact of increasing the number of APs within the target apartment, set against a backdrop of fixed and maximum external interference from outside the rooms in the target apartment. This analysis forms part of our broader evaluation of Wi-Fi performance in multi-apartment scenarios, specifically designed to assess network resilience and capacity under challenging conditions.

Figure 28 below shows the variation of throughout in the target apartment across the different scenarios. See Figure 16 for an illustration of the relevant scenarios.

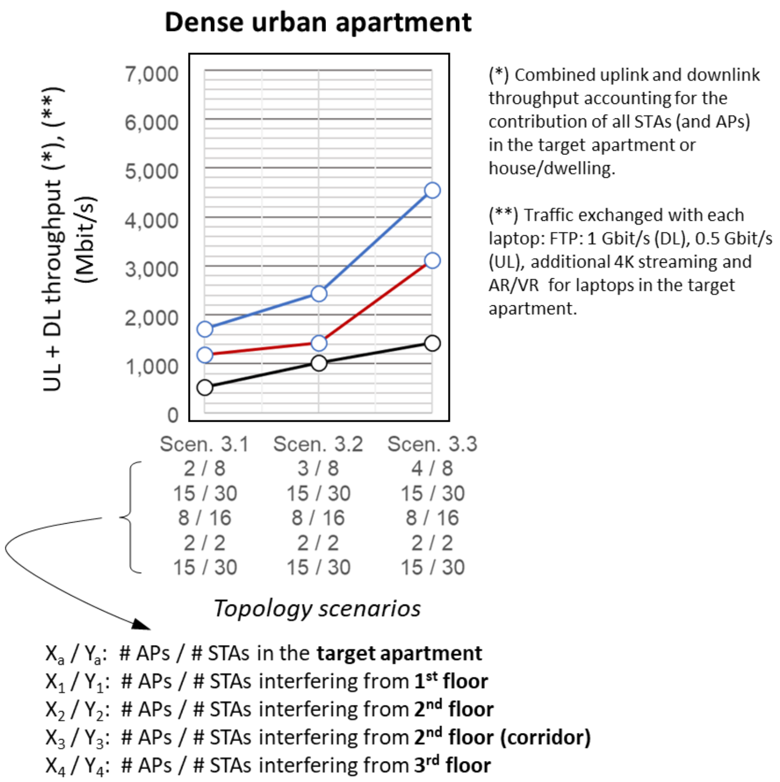


Figure 28: Measured total throughput in the target apartment across the 5 and L6 GHz bands – dense urban apartment Scenarios 3.1 to 3.3.

Figure 28 shows that the total throughput delivered to the target apartment well exceeded 1 Gbit/s for all scenarios with 40 interfering APs and 78 interfering STAs outside the rooms in the target apartment generating interference.

We observe a significant increase in the apartment throughput as the number of APs in the target apartment increases from 2 APs to 4 APs.

Another noteworthy observation is in Scenario 3.3, where despite the presence of a considerable number of interfering APs, a robust throughput performance was recorded. This is because with a large number of interfering APs, their access to the shared channel is also limited due to interference, which somewhat mitigates their impact on the network's performance in the target apartment.

The results from the dense urban scenarios also serve as meaningful references for other use cases such as schools.

With the fixed number of 8 STAs served in the test Scenarios 3.1 to 3.3, we distinctly observe an increase in the target apartment throughput as APs are added in the target apartment rooms. Specifically, as Figure 29 shows, the deployment of a third AP (Scenario 3.2) resulted in a considerable increase in throughput, demonstrating improved data transmission rates and network efficiency.

		Scenario 3.1	Scenario 3.2	Scenario 3.3
# APs / # STAs	In the **target apartment**	2 / 8	3 / 8	4 / 8
# APs / # STAs	Interfering from **1st floor**	15 / 30	15 / 30	15 / 30
# APs / # STAs	Interfering from **2nd floor**	8 / 16	8 / 16	8 / 16
# APs / # STAs	Interfering from **2nd floor (corridor)**	2 / 2	2 / 2	2 / 2
# APs / # STAs	Interfering from **3rd floor**	15 / 30	15 / 30	15 / 30
5 GHz (4 x 80 MHz)		529	1,021	1,429
		Throughput (Mbit/s)		
L6 GHz (3 x 160 MHz)		1,191	1,423	3,116
Total		1,720	2,445	4,544
			+42%	+86%

Figure 29: Increase in measured total throughput in the target apartment as a result of AP densification across the 5 and L6 GHz bands – dense urban apartment (Scenarios 3.1 to 3.3).

Purely as a sensitivity exercise, we also examined a somewhat unrealistic scenario corresponding to only 1 AP in the entire target apartment serving 8 STAs (2 STA per room) while 40 APs and 78 STAs were active in all the remaining rooms/apartments in the hotel – i.e. no densification in the target apartment but full densification in the surrounding apartments. The measurements indicated a throughput of around 700 Mbit/s, due to the exceptional levels of interference and the absence of AP densification in the target apartment which would result in poor coverage.

<u>Spectral efficiency assessment</u>

The target apartment spectral efficiency values shown in Figure 30 for Scenarios 3.1 to 3.3 account for the decrease in efficiency due to the increasing interference from the APs outside the rooms in the target apartment. Values are derived as described in Figure 21.

	Scenario 3.1		Scenario 3.2		Scenario 3.3	
Frequency band (GHz)	5	L6	5	L6	5	L6
Throughput in target apartment (Mbit/s)	529	1,191	1,021	1,423	1,429	3,116
Number of APs in target apartment	2	2	3	3	4	4
Channel BW in the band (MHz)	80	160	80	160	80	160
Frequency reuse in band	4	3	4	3	4	3
Number of channels in target apartment	2	2	3	3	4	3
BW used in target apartment (MHz)	160	320	240	480	320	480
Spectral efficiency in target apartment (bit/s/Hz)	**3.3**	**3.7**	**4.3**	**3.0**	**4.5**	**6.5**

Figure 30: Measured spectral efficiency for the target apartment for Scenarios 3.1 to 3.3.

On the relationship between spectral efficiency and channel bandwidths

In general, there are two factors that play a role in opposite directions in relation with spectral efficiency. A larger channel bandwidth leads to higher throughput. However, given a certain amount of spectrum available in a certain frequency band, a larger channel bandwidth also leads to a small number of channels which leads to a smaller frequency reuse and therefore a larger number of co-channel interfering APs around the target apartment. As can be seen from Figure 30, these two factors balance each other in different ways depending on the topology, the environment and actual propagation (see section 4.3.1)

On the relationship between spectral efficiency and the number of APs in the target apartment

In general, here there are (at least) two factors that play roles in opposite directions when considering the impact of the number of APs deployed in the target apartment and the associated spectral efficiency. Adding APs allows the use of more spectrum within the apartment, and allows better connections to STAs (i.e. STAs will use higher-order modulation schemes leading to higher spectral efficiency). On the other hand, adding APs also increases co-channel interference for each AP. As shown in Figure 30, these two factors balance each other in different ways depending on the topology, the environment, and actual propagation.

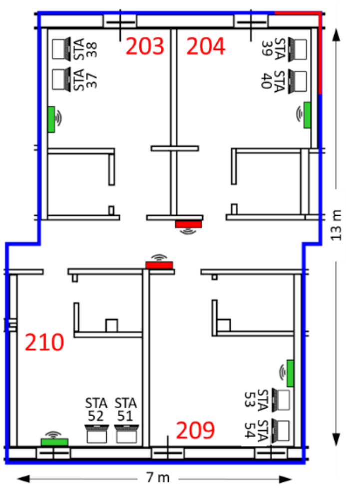
4.3.4 Sensitivity to STA/laptops physical locations

Specific sessions aimed at identifying the impact of the physical location of the 8 STA/laptops within the rooms in the target apartment.

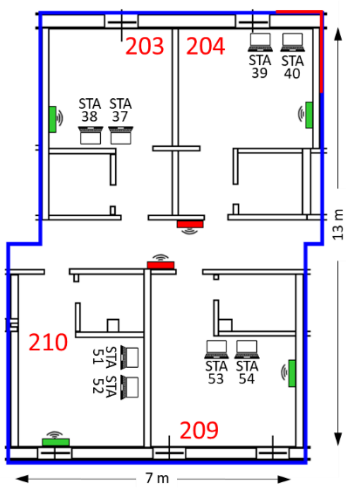
Sessions were carried out for Scenario 3.3 where the 4 APs in the target apartment were subject to the maximum level of interference from outside the target apartment. The locations of the STA/laptops tested are shown in Figure 31.

The insights gained from this sensitivity testing guide strategic decisions on network setup, including the best placement for APs to ensure comprehensive coverage and optimal performance across all room configurations.

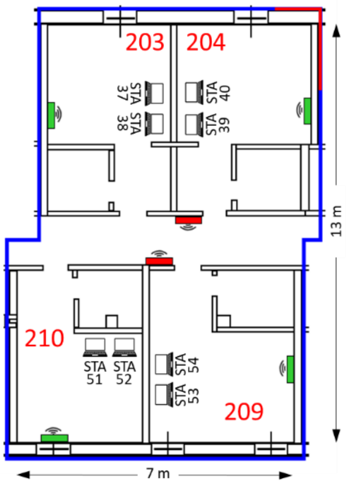
This sensitivity test not only tests the limits of the network's performance under extreme interference but also checks the efficacy of the network's spatial distribution of service. Such rigorous testing ensures that our Wi-Fi setup recommendations are robust, reliable, and applicable in diverse real-world conditions, significantly enhancing user satisfaction and network usability.



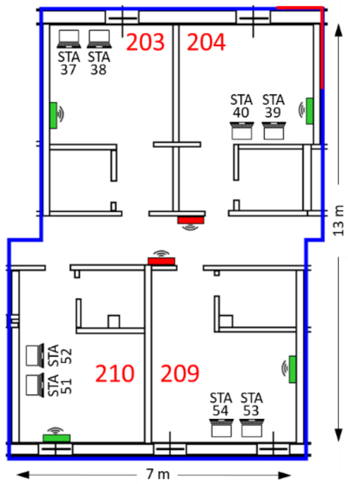
Physical locations set #1 (default)



Physical locations set #2



Physical locations set #3



Physical locations set #4

Figure 31: Four sets of physical locations for the 8 STAs/laptops in the target apartment.

Figure 32 shows a slight/moderate increase in the target apartment throughput as the STAs/laptops where moved to different sets of physical locations compared to the default locations. These measurements therefore indicate reasonably consistent coverage (i.e. consistent SINR) within the target apartment.

		Topology scenario 3.3 Throughput (Mbit/s)			
		4 sets of STA/laptop physical locations			
		Set #1 (default)	Set #2	Set #3	Set #4
		L6 GHz (3 x 160 MHz)			
Room 203	STA 037	277	389	428	37
	STA 038	442	487	464	573
Room 204	STA 039	446	437	363	467
	STA 040	424	426	462	318
Room 210	STA 051	435	414	511	495
	STA 052	457	448	302	450
Room 209	STA 053	257	488	617	681
	STA 054	378	304	333	370
Total		3,116	3,394	3,480	3,391

Figure 32: Measured throughput in the target apartment for the different sets of physical locations for the 8 STAs/laptops (Scenario 3.3).

4.3.5 Sensitivity to the interference from the 2 APs in the target apartment corridor

As described in Section 2.2, the corridor which runs along the second floor divides the rooms in the central apartment into two pairs, and provides additional radio isolation between the two pairs of rooms (on account of the two walls of the corridor). In order to counter this additional isolation and the potential for reduced interference, two extra interfering APs were installed in the corridor. For logistic reasons and without any impact on the test results, these two APs were only connected to one STA/laptop each. Conservatively, the throughput associated with the two STAs in the corridor was not considered when computing the measured throughput within the target apartment.

Specific sessions were then performed to assess the impact of the 2 corridor APs on the target apartment throughput. Sessions were carried out for Scenario 3.3 where the 4 APs in the target apartment were subject to the maximum level of interference from the rooms outside the apartment.

		Topology scenario 3.3 Throughput (Mbit/s)	
		Floor 2 corridor APs switched ON (default)	Floor 2 corridor APs switched OFF
		L6 GHz (3 x 160 MHz)	
Room 203	STA 037	277	473
	STA 038	442	498
Room 204	STA 039	446	454
	STA 040	424	488
Room 210	STA 051	435	356
	STA 052	457	358
Room 209	STA 053	257	501
	STA 054	378	443
Total		3,116	3,572

Figure 33: Measured throughput in the target apartment depending on the presence of the 2 interfering APs in the corridor within the target apartment (Scenario 3.3).

Figure 33 shows a notable decrease in the throughput in the target apartment when the 2 corridor APs are switch on. This indicates that – as intended – the inclusion of the two corridor APs as sources of interference in the measurements helps to counter the isolation between the Wi-Fi equipment across the corridor.

4.4 Discussion of key features of the field tests

Conservative features

The following are some of the test features which might be considered conservative in assessing the quality of performance which might be typically delivered by Wi-Fi:

- Interference was generated from a large number of APs in a relatively small area (44 APs installed in an area of ca. 900 m^2 across the 3 hotel floors), noting that such a high density of access points is not observed in residential scenarios today, and is also considered unlikely in the future. All APs operated at maximum power – no power coordination between APs was implemented.

- Measurements were performed in the rooms of the target apartment (middle rooms in the middle floor) and were subjected to highest interference.
- APs' emissions were directed towards the target apartment.
- All doors were left open in all rooms thereby enhancing the propagation of interference among different rooms.
- Two extra APs were added in the corridor of the target apartment generating extra interference (conservatively, their traffic was not considered within the measurements of the throughput in the target apartment, even though the APs were positioned inside the target apartment).
- 1 Gbit/s (500 Mbit/s) FTP traffic in DL (UL) was exchanged between all 44 APs and the served 86 STAs in the hotel which is actually not expected to happen in real-world apartments in the foreseeable future, but helped to stress test the capability of the Wi-Fi air-interface. In addition, the 8 STAs in the target apartment were also served with 4K video streaming traffic (40 Gbit/s FTP and streaming servers installed on each of the three floors of the hotel): such high traffic density is higher than what would be expected in residential scenarios in the short-to medium-term future.
- To ensure that the results correctly reflect the performance of the Wi-Fi air interface, any potential bottlenecks within the fixed network feeding the Wi-Fi APs were eliminated. This step was crucial to prevent external network limitations from influencing the test outcomes which focused exclusively on the Wi-Fi air interface. For the purposes of this test, the hotel was equipped with a 100 Gbit/s wired local area network (LAN), with 10 Gbit/s Ethernet connectivity to each AP. This forward-looking arrangement should be viewed in the context of the status of fixed broadband deployments in the European Union today and in the future: 55% of households in the European Union had a fixed broadband subscription with a nominal speed of at least 100 Mbit/s in 2023, and 14% of households had a fixed broadband subscription of at least 1 Gbit/s in the same year.[28]
- Only 4×80 = 320 MHz of bandwidth was used at 5 GHz[29], 160 MHz channels could not be used in this band due to equipment limitations.

[28] Digital Economy and Society Index (DESI) 2023 indicators.

[29] Beyond the specific limitation to four 80 MHz channels at 5 GHz for the AP equipment used for this test, five 80 MHz channels at 5 GHz are actually currently available in most CEPT countries, while seven 80 MHz channels at 5 GHz are actually currently available in UK and Czech Republic.

- Due to limitations in the laptops' operating system, Wi-Fi 6E (802.11ax) was used in the measurements, and the higher modulation and the multilink operation (MLO) features of Wi-Fi 7 could not be utilised.
- Throughput measurements for the target apartment do not include the contribution from the 2.4 GHz band.

"Optimistic" features

The high-end Huawei AirEngine 8771-X1T APs were used for the tests.

Note: The frequency planning was performed manually with the purpose of maximizing the physical distance between co-channel APs. Normally, the APs would automatically select the least-interfered channel which should lead to a similar frequency planning as implemented in the tests.

5 CONCLUSIONS

This document reports on the results of measurements of the performance of Wi-Fi undertaken in a test campaign across 42 rooms in a hotel in Lazise – Italy in February-March 2024.

The importance of the Lower 6 GHz band

The test results serve to demonstrate the important contribution of the Lower 6 GHz band (5945-6425 MHz) to the performance delivered by Wi-Fi under scenarios of extreme network traffic and interference. This is due to the 480 MHz available in this band which allows for 3 channels of 160 MHz which enable efficient data handling

In comparison, the performance of Wi-Fi in the 2.4 GHz band (2400-2483.5 MHz) is impacted by the significantly smaller available spectrum in this band (80 MHz in total) as well as the channel bandwidth (4 channels of 20 MHz each). The better radio propagation in this band was also observed to facilitate the propagation of interference among different Wi-Fi networks.

Compared with the Lower 6 GHz band, the performance of Wi-Fi in the 5 GHz band was seen to be affected by the smaller amount of usable spectrum in this band (320 MHz in total) and the channel bandwidth which was limited to 80 MHz (4 channels of 80 MHz) in the tests. Compared with the 2.4 GHz band, the 5 GHz band was observed to be less impacted by interference from other rooms and supported higher data rates. Compared with the Lower 6 GHz band, the 5 GHz band showed reduced performance under heavy traffic load and co-channel interference from APs in the other rooms. This was evident through the occasional decrease in data rates, highlighting the limits of the 5 GHz band when dealing with a large number of concurrent connections and exceptional interference. Channels with 160 MHz bandwidth could not be used in the 5 GHz band due to the current limitations in the equipment. We expect Wi-Fi equipment to also support 160 MHz channels in the 5 GHz band in future product releases, at which point the Wi-Fi 7 multi-link operation (MLO) feature will allow Wi-Fi APs to leverage the simultaneous availability of 5 channels of 160 MHz (2 from the 5 GHz band and 3 from the Lower 6 GHz band).

These findings suggest that while the 2.4 GHz and 5 GHz bands are still viable for general usage, their performance under heavy network congestion can be suboptimal, making them less suitable for environments with high device density or heavy data traffic. In contrast, the Lower 6 GHz band, with its enhanced capacity and advanced technological capabilities, stands out as a robust solution for maintaining high performance in congested network environments.

Indoor radio propagation

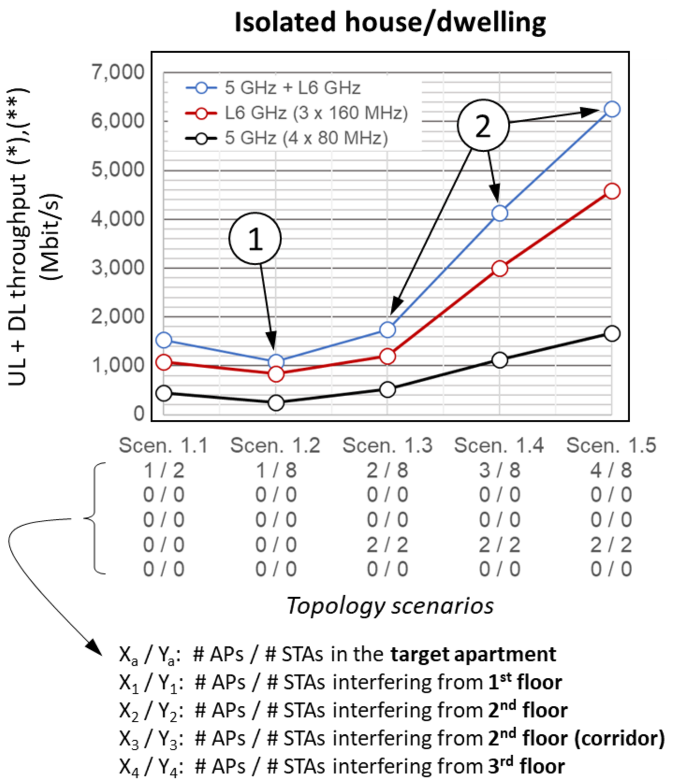
Measurements of received Wi-Fi power throughout the hotel with only one AP switched on in the target apartment, clearly show how propagation decreases as frequencies increase: the 2.4 GHz band provides relatively good coverage across the target apartment (ca. 90 m^2). With the 5 GHz and Lower 6 GHz bands, propagation across walls becomes more problematic in the target apartment areas that are further away from the AP, leading to a more coverage-limited environment.

With reference to the dense urban apartment scenarios and all co-channel APs switched on in different rooms, the measurements show substantial aggregate interference received at the target apartment in the 2.4 GHz band from the interfering APs located in the rooms outside the target apartment. With the 5 GHz and Lower 6 GHz bands, the measured interference received from co-channel APs outside the target apartment reduces but is non-negligible.

Measurements of Wi-Fi throughput

As shown in Figure 34, for an Isolated house/dwelling setting (Scenarios 1.1 to 1.5), the total measured throughput (summed uplink and downlink over all stations) delivered to the target apartment **exceeded 1 Gbit/s for all scenarios**.

Specifically, a total throughput of **1.5 Gbit/s** was measured when 1 AP was connected to 2 STAs in the same room (Scenario 1.1) with no sources of interference. The total throughput was seen to decrease to around **1.1 Gbit/s** when the number of served STAs was increased to 8 (2 per room within the target apartment), indicating the **coverage challenges** associated with Wi-Fi propagation between rooms: the STAs that were located further away from the AP drained a disproportionate amount of radio resource from the AP (e.g. due to their need to adopt a lower-order modulation scheme) leading to an overall reduction in throughput. However, the total throughput was measured to increase to **6.3 Gbit/s** when 4 APs were deployed, one in each of the four rooms in the target apartment, and with each AP serving two STAs within the same room (Scenario 1.5). For similar arrangements as above but with only 2 and 3 APs in the target apartment (Scenarios 1.3 and 1.4), measurements indicated total throughputs of around **1.7 Gbit/s** and **4.1 Gbit/s**, respectively.

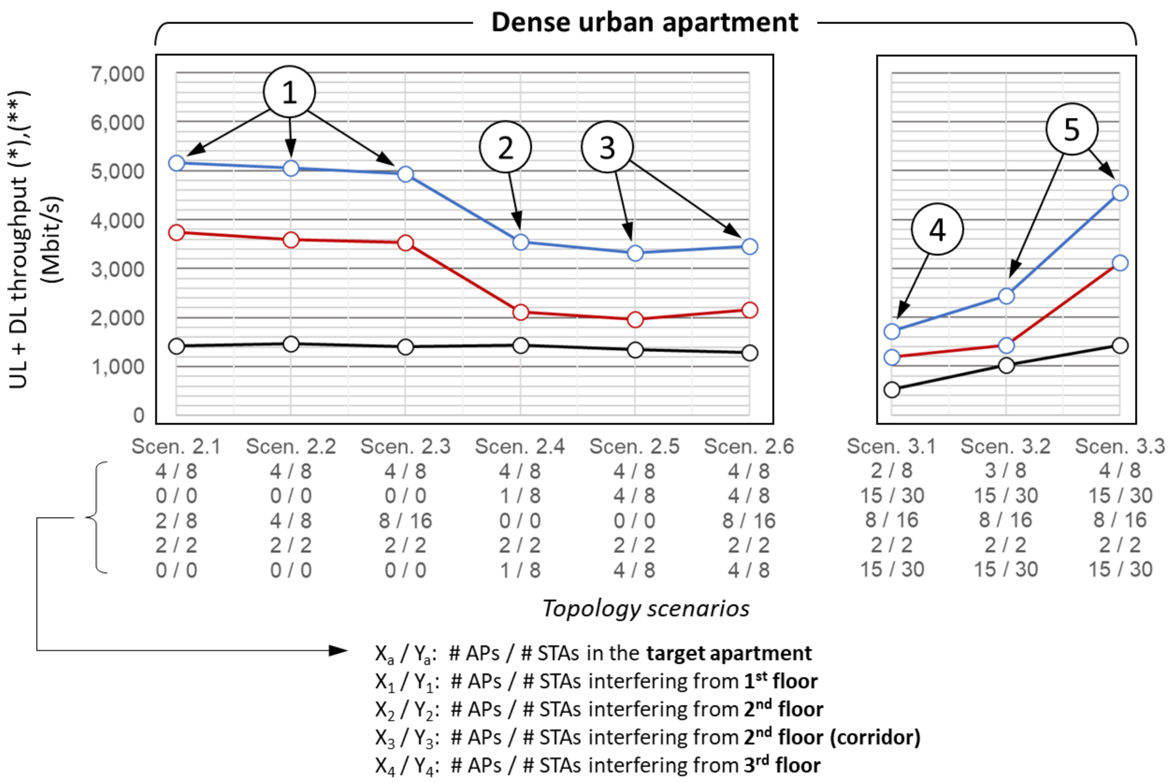


(1) Coverage-driven: The STAs/laptops that are further away from the AP drain capacity from the AP (e.g. lower modulation).
(2) The number of target APs grows from 1 to 4.

(*) Combined uplink and downlink throughput accounting for the contribution of all STAs (and APs) in the target apartment or house/dwelling.
(**) Traffic exchanged with each laptop: FTP: 1 Gbit/s (DL), 0.5 Gbit/s (UL), additional 4K streaming and AR/VR for laptops in the target apartment.

Figure 34: Target apartment throughput across the 5 and Lower 6 GHz bands – house/dwelling – all scenarios.

Also as shown in Figure 35, for dense urban apartment settings (Scenarios 2.1 to 2.6), and again with 4 APs deployed, one in each of the four rooms in the target apartment, and with each AP serving two STAs within the same room, we clearly observed a gradual decline in total throughput delivered to the target apartment as the interference from APs in adjacent apartments increases. Nevertheless, the total throughput delivered to the target apartment **always remained above 3 Gbit/s**.



(1) The number of interfering APs grows from 4 to 10.
(2) From closest interfering APs in the same floor to closest interfering APs from other floors.
(3) As the number of interfering APs grows, the interference also limits the interfering APs' access to the shared channel.
(4) The number of interfering APs grows from 18 to 40. The number of target APs drops from 4 to 2.
(5) The number of target APs grows from 2 to 4.

(*) Combined uplink and downlink throughput accounting for the contribution of all STAs (and APs) in the target apartment or house/dwelling.
(**) Traffic exchanged with each laptop: FTP: 1 Gbit/s (DL), 0.5 Gbit/s (UL), additional 4K streaming and AR/VR for laptops in the target apartment.

Figure 35: Target apartment throughput across the 5 and Lower 6 GHz bands – dense urban apartment – all scenarios.

Finally, Figure 35 shows the results of measurements for dense urban apartment settings (Scenarios 3.1 to 3.3) in the presence of interference generated by 40 APs and 78 STAs outside the target apartment rooms. Here, we observed a significant increase in the total throughput delivered to the target apartment as the number of APs in the target apartment increased from 2 to 4 (each serving two STAs in their respective rooms). With 4 APs (Scenario 3.3), we measured a total throughput of around **4.6 Gbit/s**. Again, for similar arrangements as above but with only 2 and 3 APs in the target apartment (Scenarios 3.1 and 3.2), measurements indicated total throughputs of around **1.7 Gbit/s** and **2.4 Gbit/s**, respectively.

Notably, the above throughput for Scenario 3.3 is greater than the throughput for Scenarios 2.1 to 2.6 where there are fewer interferers. This is because with a large number of interfering APs, their access to the shared channel also becomes limited due to interference, which somewhat mitigates their impact on the network's performance in the target apartment.

The above results indicate that the key constraint for Wi-Fi is coverage which can be effectivity addressed through densification of access points, i.e., increased number of APs within a dwelling.

Purely as a sensitivity exercise, we also examined a somewhat unrealistic scenario corresponding to only 1 AP in the entire target apartment serving 8 STAs (2 STA per room) while 40 APs and 78 STAs were active in all the remaining rooms/apartments in the hotel – i.e. no densification in the target apartment but full densification in the surrounding apartments. The measurements indicated a throughput of around 700 Mbit/s, due to the exceptional levels of interference and the absence of AP densification in the target apartment which would result in poor coverage.

AR/VR smooth performance, even under heavy interference

Test sessions have also shown remarkably smooth operation of augmented reality (AR) and virtual reality (VR) sessions conducted within the target apartment. These sessions were specifically tested under conditions where all 44 APs distributed across the testing site were fully loaded with traffic. This scenario was again designed to replicate a futuristic high-demand dense urban environment. The ability of the AR/VR applications to run smoothly under such conditions highlights the robustness and efficiency of the deployed Wi-Fi technology, particularly in handling heavy data loads and maintaining high-performance levels. This is especially relevant for AR/VR applications, which are highly sensitive to latency and jitter, as these factors can significantly impact the user experience and effectiveness of the technology.

Key takeaways

Using the available spectrum from the 2.4, 5, and Lower 6 GHz bands, a throughput of at least 1 Gbit/s was recorded in the target apartment in all tested scenarios (uplink + downlink over all stations). This seems to be consistent with the European Union Digital Decade connectivity objectives for 2030 specified in relation to all end users at a fixed location.

Going forward, the key constraint for Wi-Fi is coverage which can be effectivity addressed through densification of access points, i.e., increased number of APs deployed by the user. Once access point densification is applied, new Wi-Fi technologies (e.g. Wi-Fi 8) will also have the opportunity to exploit the large bandwidths available at higher frequency bands, such as mmWaves, to deliver higher throughputs with lower latency, and in an interference-free manner (exploiting the higher wall penetration losses at high bands).

ANNEX 1: EQUIPMENT LIST

	Quantity	Brand	Model	Remarks
AP	44	Huawei	AirEngine 8771 – X1T	Wi-Fi standard: Wi-Fi 7 supported (Wi-Fi-6E used) No QoS configuration is applied Antenna configuration: 4x4 3 SSID for each AP (2.4, 5 and 6 GHz) with room number in the SSID
Laptop	96	Lenovo	E15 gen 4	Antenna configuration: 2x2
STA: laptop card	96	Intel	AX211	Antenna configuration: 2x2 Wi-Fi standard: Wi-Fi 6E
STA: USB adapter	1	Netgear	AXE3000	Triband Wi-Fi 6E Not used for test session due to worse performance
Management switch	3	Huawei	S5735-L48T4XE	
Core Switch between the floors	1	Huawei	S6730-H28X6CZ	
Floor switch	3	Huawei	S5732-H24UM4Y2CZ	PoE towards APs
Wi-Fi controller	1	Huawei	AC6508	For AP remote configuration
FTP server for DL	4	Dell	R740	Filezilla FTP server on Windows 2022 server Capped at 1 Gbit/s towards STA for each session
FTP server for UL	4	Dell	R740	Filezilla FTP server on Windows 2022 server Capped at 0.5 Gbit/s towards STA from each session
Streaming server	1	Dell	R740	VLC server on Windows 2022 server
NAS	1	QNAP	TS211	DNLA, SMB and UPNP enabled
Optical transceiver	6	Huawei	QSFP28-100GSR4	100GBase optical transceiver
Optical Transceiver	8	Huawei	OMXD30000	Optical transceiver SFP+
Rack	3			Rack 23U
Network cables	144 m	Huawei	AC6508	Cat.6 certified
AR/VR visors	4	Meta	Quest 3	Wi-Fi 6E support

Figure 36: Equipment list.

ANNEX 2: LIST OF FIGURES

ANNEX 3: ACRONYMS

AP - Access Point

AR - Augmented Reality

BSS - Basic Service Set

DL – Download

EU - European Union

FTP - File Transfer Protocol

GHz - Gigahertz

L6 GHz - Lower 6 Gigahertz

LAN - Local Area Network

MCS - Modulation and Coding Scheme

MIMO - Multiple Input, Multiple Output

MLO - Multi Link Operation

OFDMA - Orthogonal Frequency-Division Multiple Access

QAM - Quadrature Amplitude Modulation

QoS - Quality of Service

RSSI - Received Signal Strength Indicator

SINR - Signal-to-Interference-plus-Noise Ratio

STA - Station Devices

ToS - Type of Service

TWT - Target Wake Time

UL - Upload

VR - Virtual Reality

Wi-Fi 6E - Sixth Generation Wi-Fi, Extended

Wi-Fi 7 - Seventh Generation Wi-Fi

Wi-Fi 8 - Eighth Generation Wi-Fi

WPA3 - Wi-Fi Protected Access 3