Wi-Fi indoor connectivity tests

March 2024

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EU Digital Decade Policy Programme connectivity objectives for 2030

In Europe, administrations need to support the widespread deployment and take-up of very high-capacity networks to meet the ambitious connectivity objectives for the Union.

Article 4 – Digital Targets

"2) secure, resilient, performant and sustainable digital infrastructures, where:

(a) all end users at a fixed location are covered by a gigabit network up to the network termination point, and all populated areas are covered by next-generation wireless high-speed networks with performance at least equivalent to that of 5G, in accordance with the principle of technological neutrality;

Source: DECISION (EU) 2022/2481 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 December 2022 establishing the Digital Decade Policy Programme 2030

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Comtel Wi-Fi indoor connectivity tests

See report for full details of measurements

The key question:

- Is the **currently available Wi-Fi spectrum** an obstacle in meeting the following EU Digital Decade connectivity objective for 2030:

"… all end users at a fixed location are covered by a gigabit network up to the network termination point…"?

Approach:

- Assess the performance of latest Wi-Fi products' air interface @ **2.4**, **5**, **Lower 6 GHz** bands
- Replicate as much as possible the **dense urban apartment** and the **isolated house** scenarios
- Remove any possible **bottlenecks** for the **fixed broadband** network behind the Wi-Fi APs
- Generate sufficient traffic to and from each Wi-Fi STA/laptop using all available capacity of the APs
- Generate interference from a high density of Wi-Fi APs: beyond any realistic worst-case scenario

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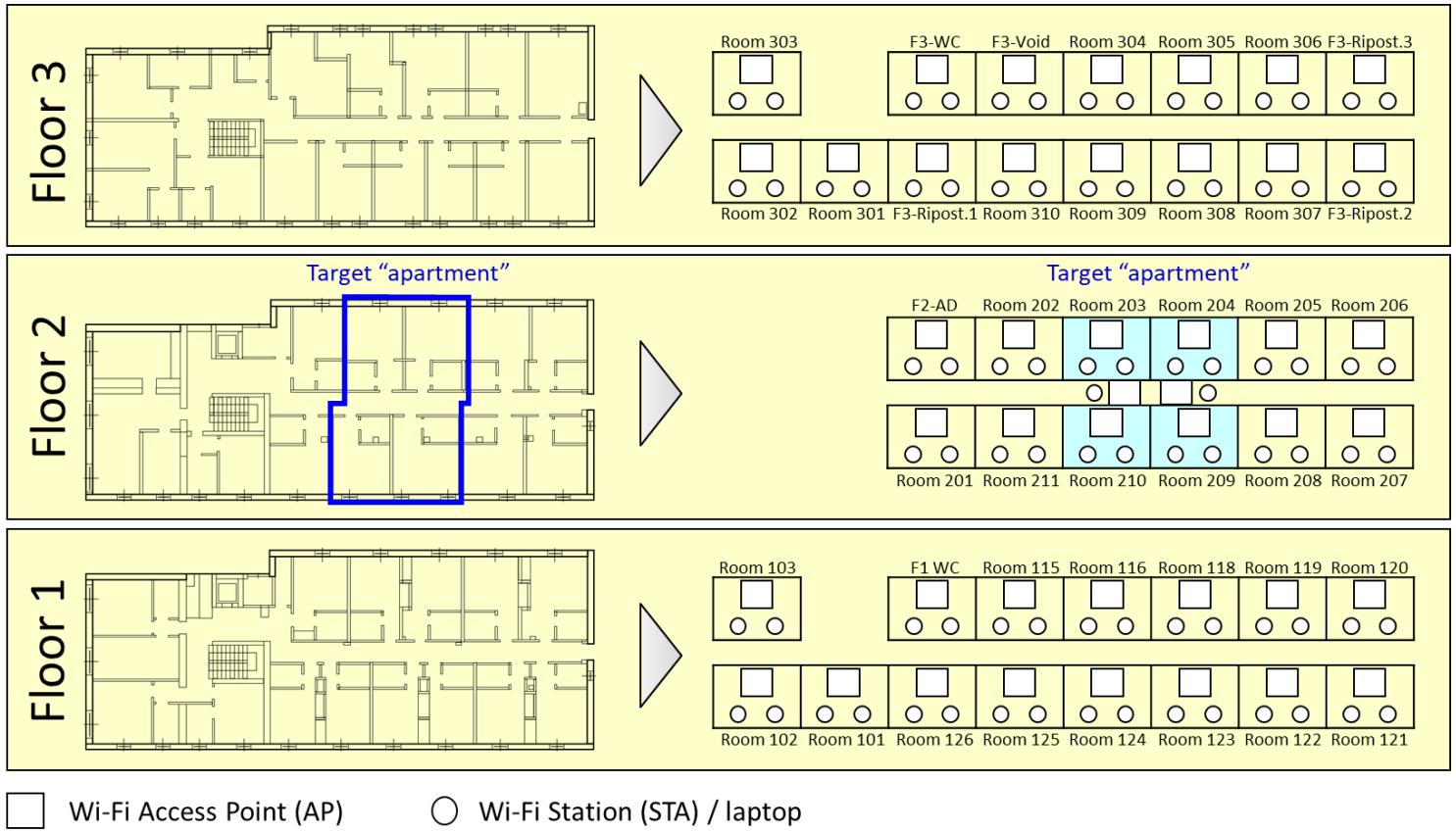
Comtel Wi-Fi indoor connectivity test setup

Wi-Fi deployment in 42 hotel rooms in 3 overlapping floors.



- **44 APs:**
  - Up to 4 APs in 4 adjacent rooms in the middle of the middle (second) floor; the "Target apartment".
  - Up to 40 APs generating interference.
- **86 laptops.**
- **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.
  - 40 Gbit/s FTP and streaming servers installed on each floor.
- **10 / 100 Gbit/s LAN**
  - 100 Gbit/s core switch.
  - Floor switches with 10 Gbit/s to APs.

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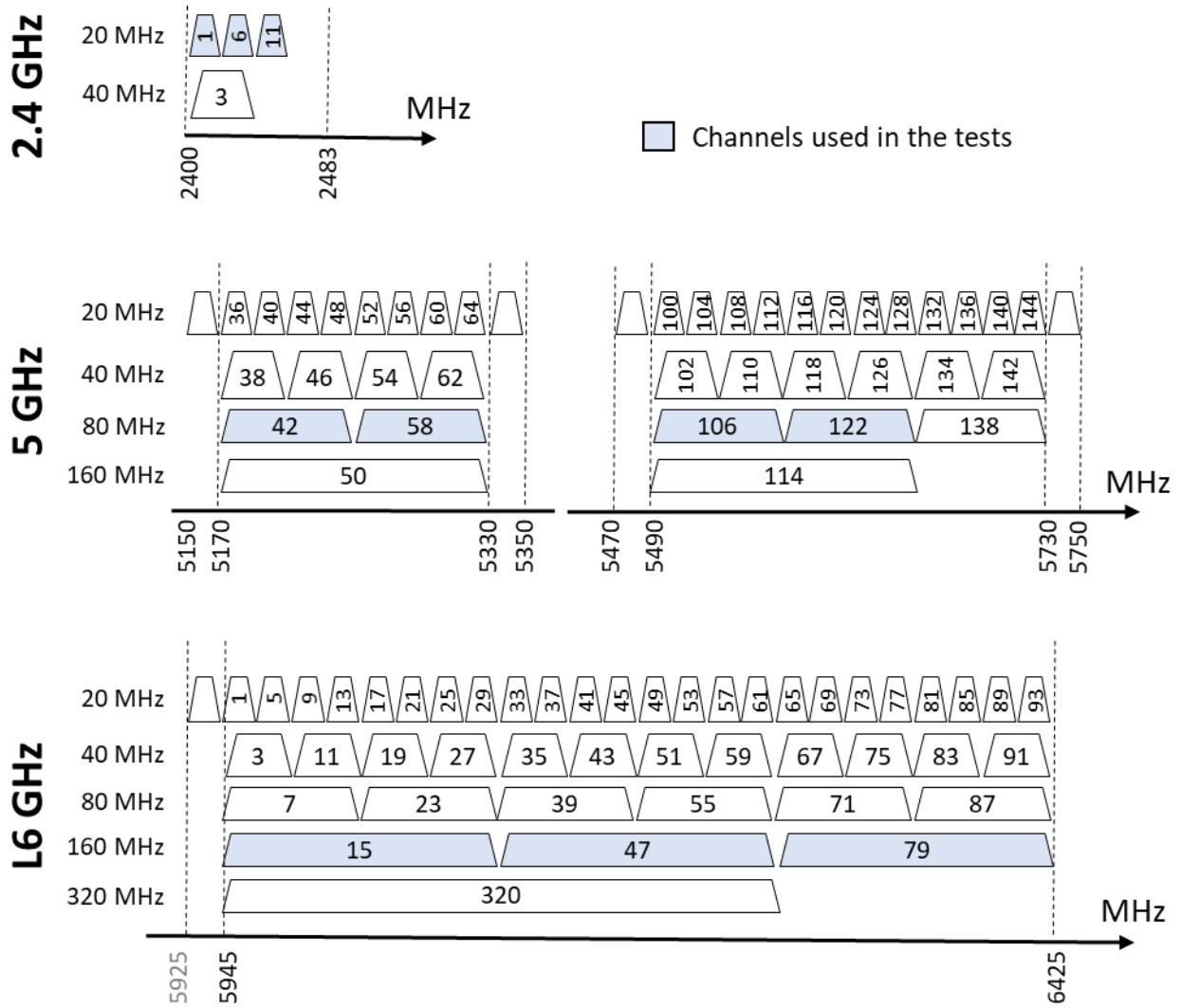
Available channels across the 2.4, 5, L6 GHz bands



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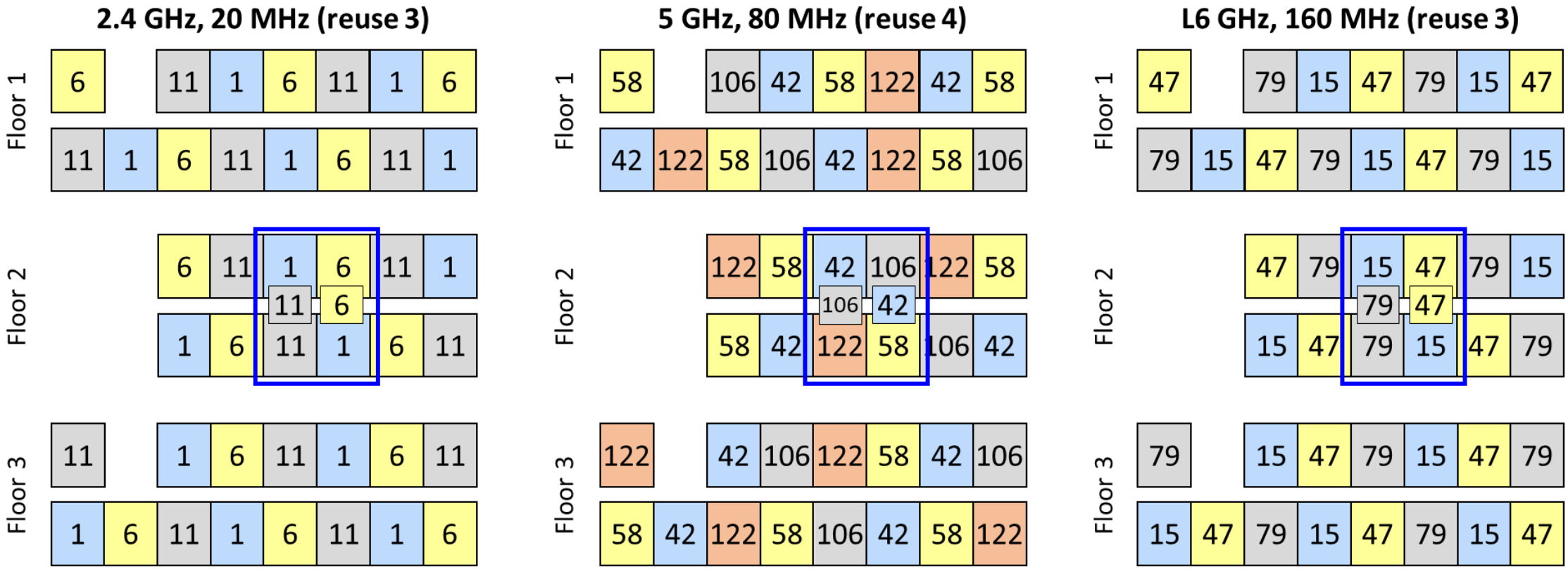
Wi-Fi channels used in the various rooms



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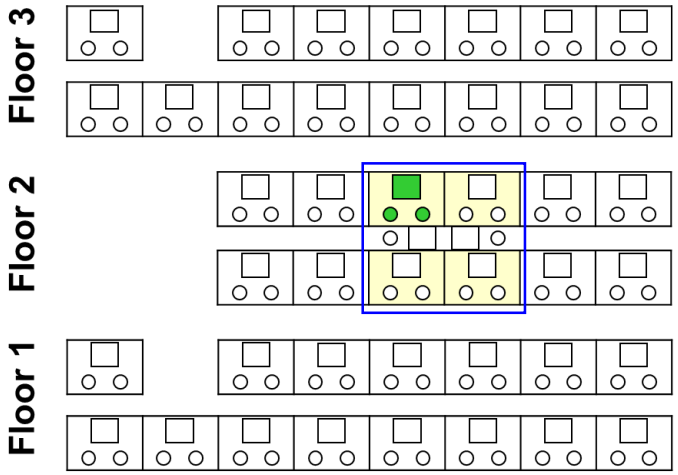
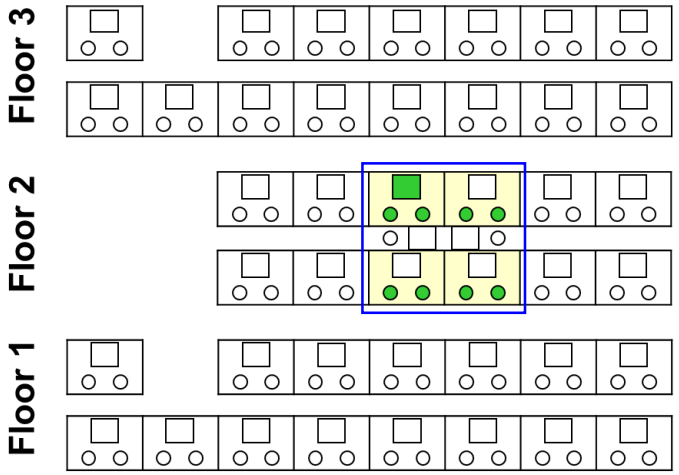
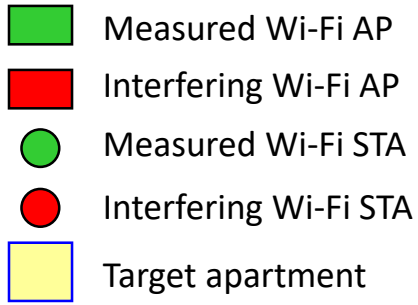
Scenarios 1.1 – 1.5: isolated house/dwelling

Scenario 1.1

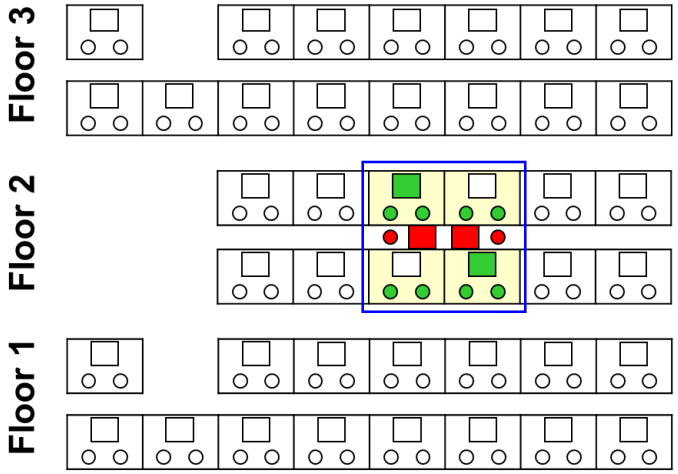


Scenario 1.2

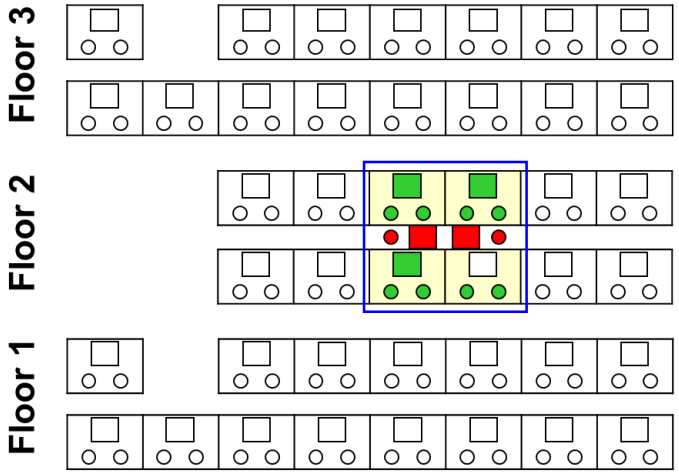




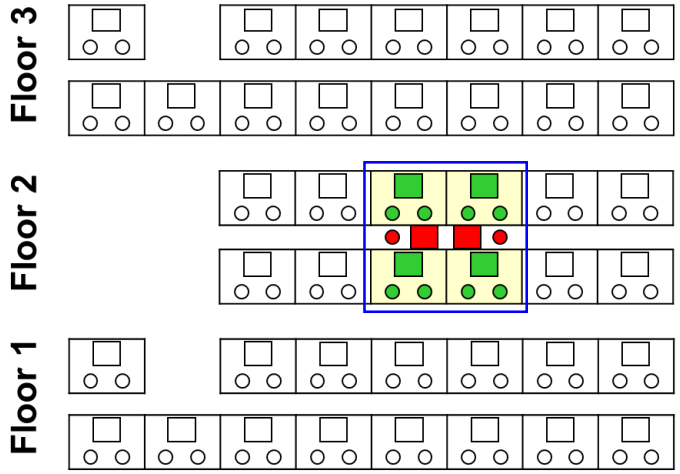
Scenario 1.3



Scenario 1.4



Scenario 1.5



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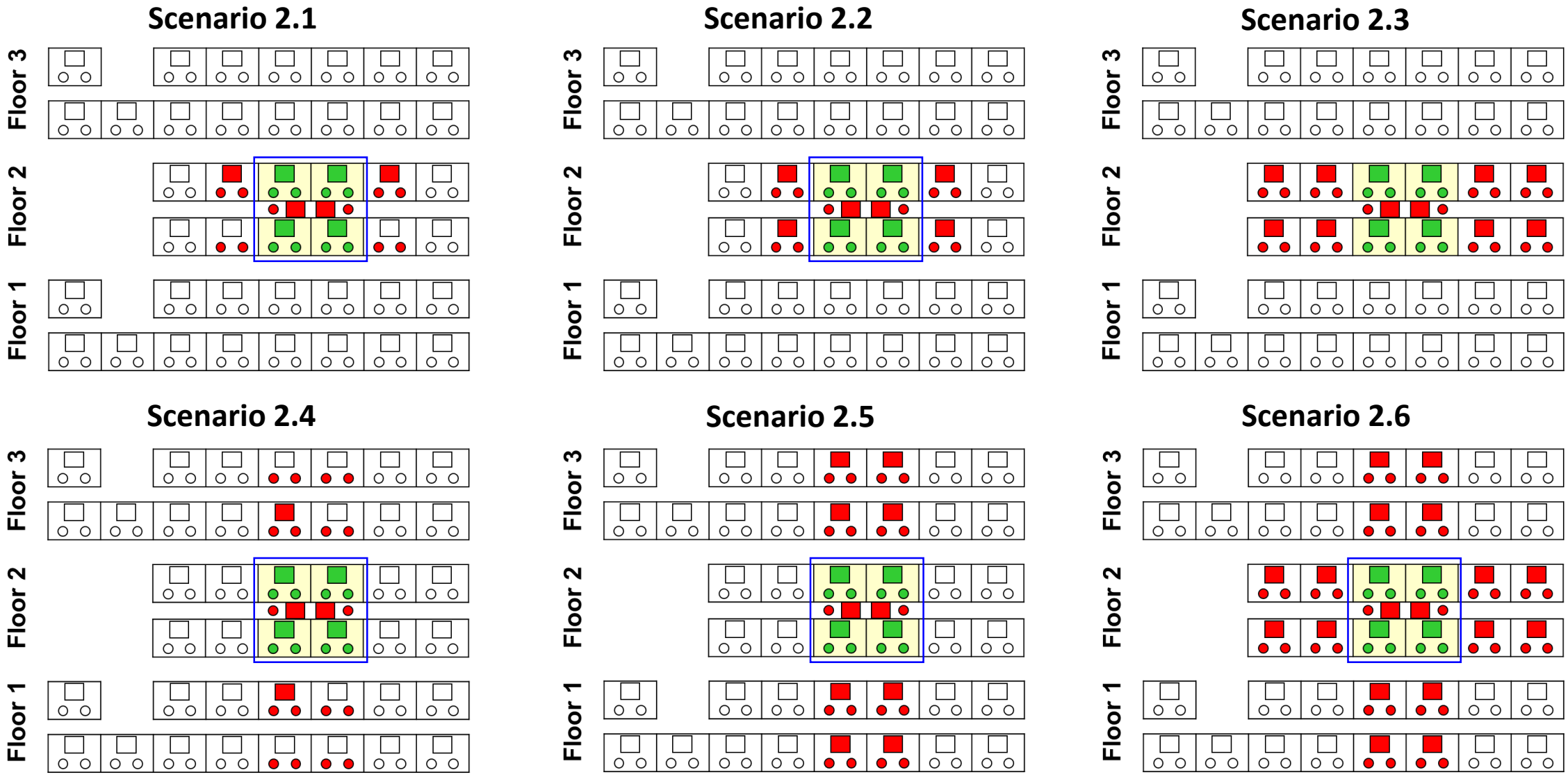
Scenarios 2.1 – 2.6: dense urban deployment



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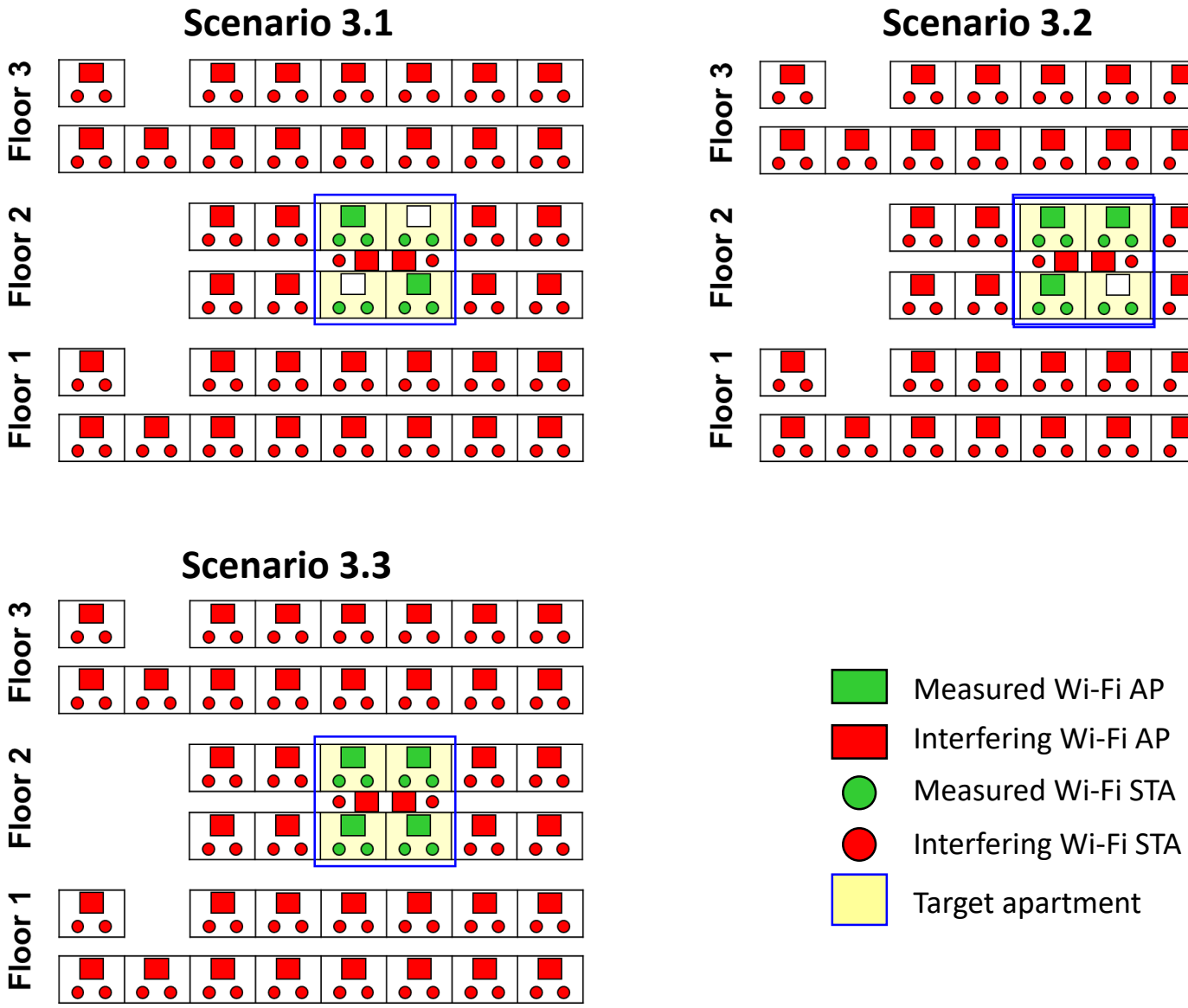
Scenarios 3.1 – 3.3: dense urban deployment



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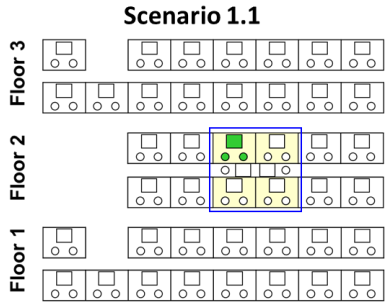
Coverage-limited scenario (1/2)

Single AP serving one room



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

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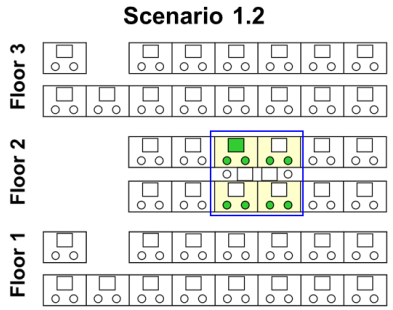
Coverage-limited scenario (2/2)

Single AP serving four rooms



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 $T_{Sc.\ 1.1}$)

- **Coverage-limited scenario:**

  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.

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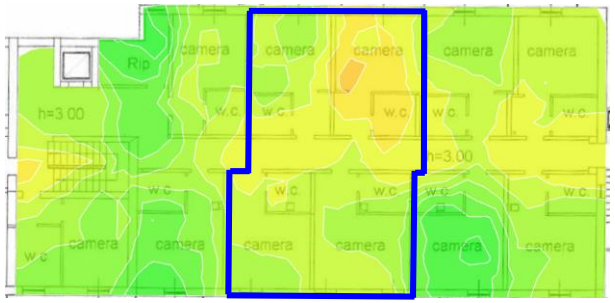
Interference footprint in the target apartment – Scenario 3.3

Dense urban apartment environment

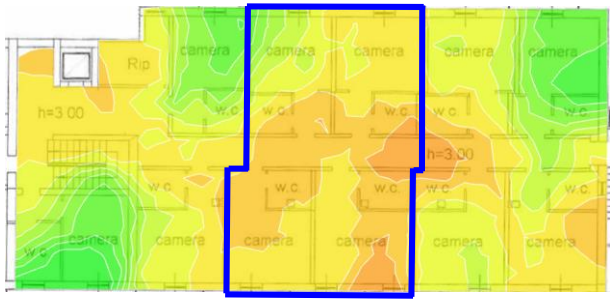
2.4 GHz band:
ch. 6 interference
from floors 1, 2, 3
(AP in room 204 switched off)
to floor 2



14 visible co-channel APs from rooms:

- 103, 116, 120, 123, 126
- 208, 211, F2_ad. F2_sud
- 301, 306, 309, F3_void, F3_rip_2

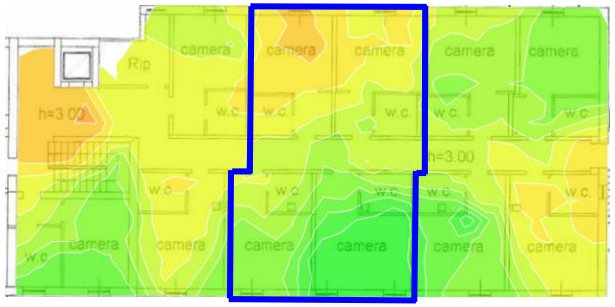
5 GHz band:
ch. 58 interference
from floors 1, 2, 3
(AP in room 209 switched off)
to floor 2



12 visible co-channel APs from rooms:

- 103, 116, 120. 122, 126
- 201, 202, 206
- 302, 305, 307, 310

L6 GHz band:
ch. 15 interference
from floors 1, 2, 3
(AP in room 203 switched off)
to floor 2



13 visible co-channel APs from rooms:

- 101, 115, 119, 121, 124
- 201, 206, 209 (*)
- F3_wc, 302, 305, 307, 310

(*) Room 209 belongs to the target apartment

- The measured **L6 GHz interference footprint** associated is significantly **smaller than** the **2.4 GHz interference footprint** due to the better propagation at lower frequencies.
- The measured **L6 GHz interference footprint** 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
- 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

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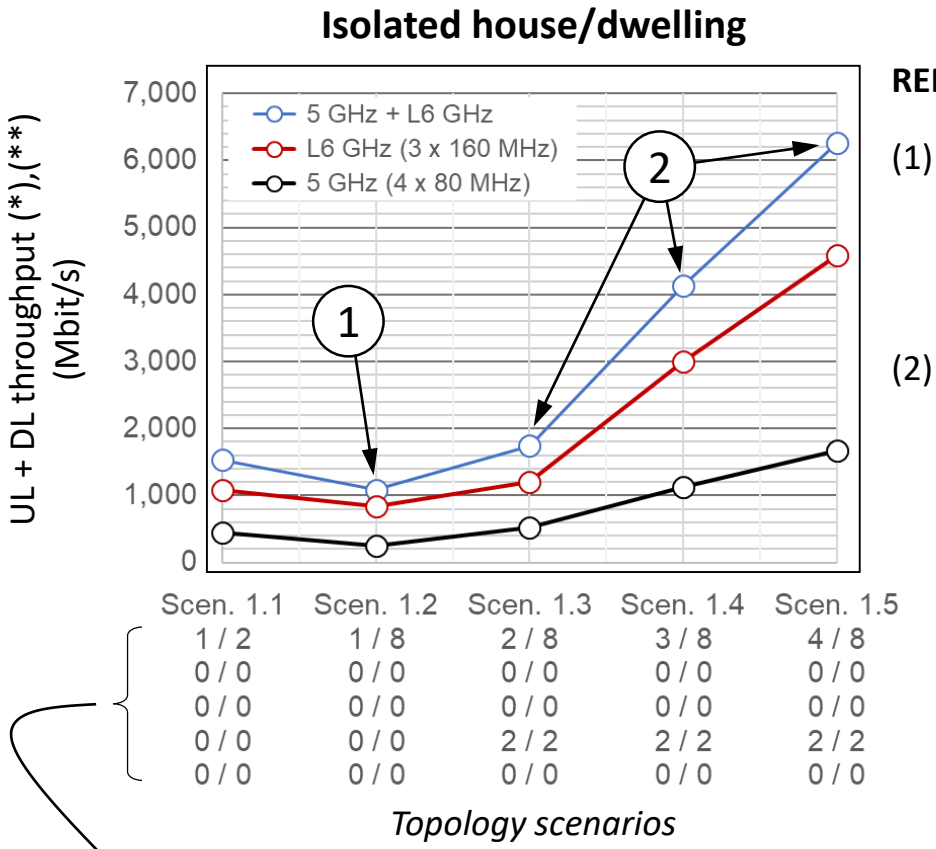
Results summary – UL + DL throughput (5 and L6 GHz)



X_a / Y_a: # APs / # STAs in the **target apartment**
X_1 / Y_1: # APs / # STAs interfering from **1st floor**
X_2 / Y_2: # APs / # STAs interfering from **2nd floor**
X_3 / Y_3: # APs / # STAs interfering from **2nd floor (corridor)**
X_4 / Y_4: # APs / # STAs interfering from **3rd floor**

REMARKS:

(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.

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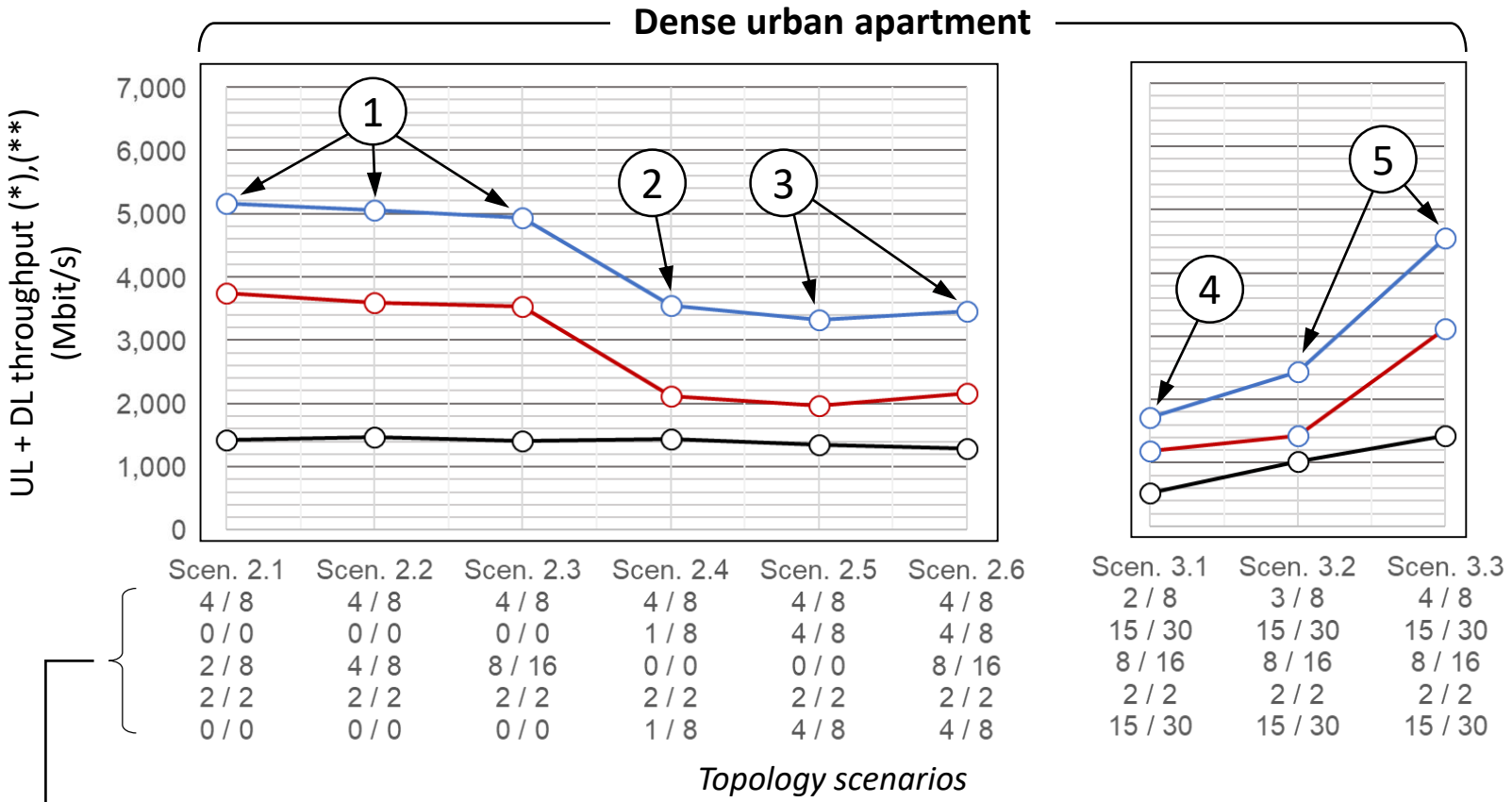
Results summary – UL + DL throughput (5 and L6 GHz)



X_a / Y_a: # APs / # STAs in the **target apartment**
X_1 / Y_1: # APs / # STAs interfering from **1st floor**
X_2 / Y_2: # APs / # STAs interfering from **2nd floor**
X_3 / Y_3: # APs / # STAs interfering from **2nd floor (corridor)**
X_4 / Y_4: # APs / # STAs interfering from **3rd floor**

REMARKS:

(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.

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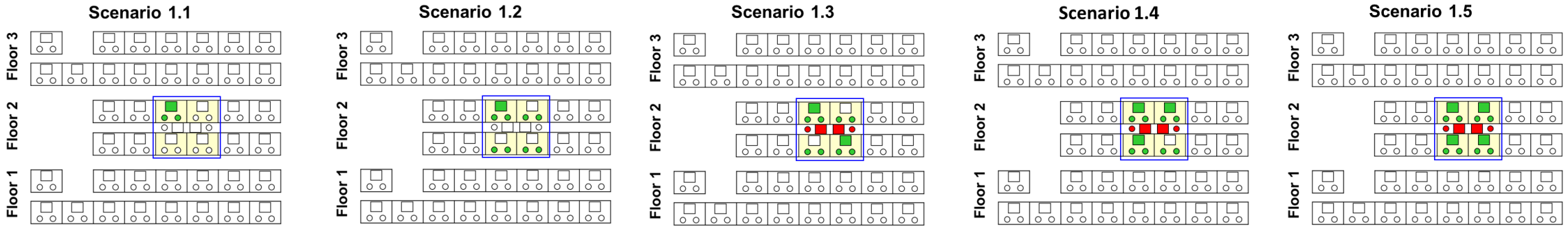
Results: AP densification – isolated house/dwelling



# APs / # STAs	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5
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%

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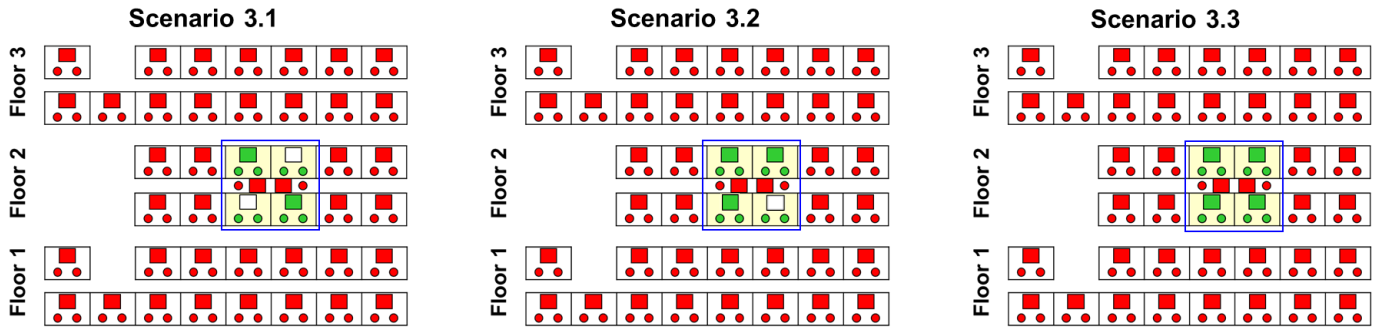
Results: AP densification – dense urban apartment



		Scenario 3.1	Scenario 3.2	Scenario 3.3
# APs / # STAs	In the **target apartment**	2 / 8	3 / 8	4 / 8
	Interfering from **1st floor**	15 / 30	15 / 30	15 / 30
	Interfering from **2nd floor**	8 / 16	8 / 16	8 / 16
	Interfering from **2nd floor (corridor)**	2 / 2	2 / 2	2 / 2
	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%

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Discussion of key features of the field tests

Conservative features

- **Measurements were performed in the rooms subjected to highest interference**
  - Interference was generated from a **high density of APs** which 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 made in the **middle rooms** of the middle floor (subject to greatest 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 . (their traffic was not considered within the measurements of the throughput in the target apartment)
- **High traffic load**
  - **1 Gbit/s (500 Mbit/s) FTP traffic in DL (UL)** was exchanged between all 44 APs and the served 86 STAs: 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.
  - The 8 STAs in the target apartment were also served with **4K video streaming traffic**: more than what would be expected in residential scenarios in the short- to medium-term future.
  - The hotel was equipped with a 100 Gbit/s wired LAN, with **10 Gbit/s Ethernet connectivity to each AP**.
- **Wi-Fi 7 features could not be exploited (e.g. the higher modulation and the multilink operation - MLO)**

"Optimistic" features

- **Advanced APs were used (Huawei AirEngine 8771-X1T)**

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Key learnings (1/2)

- **The L6 GHz band (5945-6425 MHz) provides an important contribution to the performance delivered by Wi-Fi under scenarios of extreme network traffic and interference.**

- **Indoor radio propagation for the 5 GHz and L6 GHz bands as compared with the 2.4 GHz band:**

  - Propagation across walls becomes more problematic in areas of an apartment that are further away from the AP, leading to a **more coverage-limited** environment.

  - In a dense urban apartment, the **measured interference** received from co-channel APs outside the apartment **reduces but is non-negligible.**

- **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 (*).**

(*) According to the Digital Economy and Society Index (DESI) 2023 indicators:
- 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.

Key learnings (2/2)

- **Using the available spectrum from 2.4, 5, and L6 GHz bands, a throughput of at least 1 Gbit/s 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 Policy Programme connectivity objectives for 2030 for all end users at a fixed locations.

Throughput recorded in the isolated "target apartment" (house/dwelling scenario):

- ca. **1.5 Gbit/s** (2 STAs/laptops and 1 AP / target apartment, with no external interference)
- ca. **6.3 Gbit/s** (8 STAs/laptops and 4 APs / target apartment, with no external interference)

Throughput recorded in the "target apartment" when severely interfered (dense urban apartment):

- ca. **1.7 Gbit/s** (2 STAs/laptops and 2 APs / target apartment, with 42 interfering APs)
- ca. **4.5 Gbit/s** (8 STAs/laptops and 4 APs / target apartment, with 42 interfering APs)

- **Going forward…**
  - The key constraint for Wi-Fi is coverage which can be effectivity addressed through **densification** of access points.
  - Once AP densification is applied, new RLAN technologies (e.g. Wi-Fi 8) will have the opportunity to exploit the large bandwidth available at **higher frequency bands (such as mmWaves)** to deliver higher throughput with lower latency, and in an interference-free manner (exploiting the higher wall penetration losses at high bands).
  - More efforts are needed to **extend high capacity fiber availability** for residential users and businesses.

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