Tampere University

5G Mobile Communications

COMM.SYS.700

5G Laboratory Project Work

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The Pre-lab

Q1.1
How 5G mobile identifies 5G cell?
How is this different between NSA and SA modes?

In 5G NR (5G New Radio), an UE (User Equipment) identifies a 5G cell primarily through a process called cell Search and Synchronization. This relies on detecting specific synchronization signals broadcast by the gNB (5G base station).

The core physical-layer identification mechanism is the same in both NSA and SA modes, based on the Synchronization Signal Block (SSB)

1) Frequency Scanning

The UE scans possible frequencies (using the Synchronization Raster defined in 3GPP for each band) and measures RSSI (Received Signal Strength Indicator) to find promising candidates.

2) Detects SSB (Synchronization Signal Block)

Each 5G cell periodically transmits SSBs containing:

- PSS (Primary Synchronization Signal) → Coarse Timing & Partial Physical Cell ID
- SSS (Secondary Synchronization Signal) → Frame Timing & Full Physical Cell ID
- PBCH (Physical Broadcast Channel) → carries the MIB (Master Information Block)



Figure 1: Transmission of Synchronization Signal Block (SSB) from gNB to UE

3) Reads MIB (Master Information Block)

By decoding the MIB from PBCH, the UE learns basic cell parameters:

- Subcarrier Spacing (SCS)
- System Frame Number (SFN)
- Location of SIB1 (System Information Block Type 1)

4) Reads SIB1 (System Information Block Type 1)

From SIB1, the UE learns:

- PLMN (Public Land Mobile Network) identity
- Cell Access Info
- Whether the cell is Barred or Reserved
- How to proceed with access

If the PLMN matches and access is allowed, the phone camps on the cell and begins the registration and connection procedure.

The Core Mechanism:

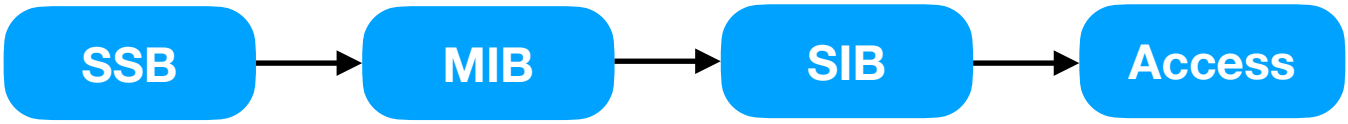


Figure 2: Sequence of 5G Cell Identification and Access Process

Complementary Notes:

Synchronization Raster
A predefined set of frequencies (defined by 3GPP per band) where the UE is expected to search for synchronization signals. It narrows down the scanning range so the UE doesn't have to check every possible frequency.

Subcarrier Spacing (SCS)
The frequency gap between adjacent subcarriers in the OFDM signal. 5G NR supports 15, 30, 60, 120, and 240 kHz options, allowing a trade-off between latency and coverage depending on the use case.

System Frame Number (SFN)
A 10-bit counter (0–1023) representing the cell's timing reference. It cycles every 10.24 seconds and allows the UE to synchronize to the cell's frame structure.

PLMN Identity
A unique identifier for a mobile network, composed of a Mobile Country Code (MCC) and a Mobile Network Code (MNC). The UE checks this to confirm the cell belongs to its home or an allowed roaming network before camping

Cell Barred / Reserved
Flags in SIB1 that indicate whether a cell is temporarily or permanently unavailable.
A barred cell must be skipped for a defined period; a reserved cell is restricted to specific operators or use cases only.

NSA (Non-Standalone, Option 3x)

In NSA, LTE is the anchor, and 5G NR is only added as a secondary carrier for data.

How cell identification works in NSA:

- Phone first performs normal LTE cell search
- Camps on an LTE eNB
- LTE broadcasts in its SIBs:
  - Whether NR is available
  - Which NR frequencies and bands to measure
- Phone measures NR cells and detects their SSBs
- Reports NR measurements to LTE
- LTE network decides which NR cell to add and configures the phone

NSA: You enter the building through the LTE door, then LTE opens a side door to 5G for faster data.

The phone does not independently select a 5G cell for access in NSA. It only discovers NR cells, but LTE decides if and when NR is used.

- Initial access = LTE
- Registration = LTE / EPC
- NR is just a secondary data pipe

SA (Standalone, Option 2)

In SA, NR is fully independent and connected directly to the 5G Core (5GC).

How cell identification works in SA:

- Phone scans NR bands
- Detects NR SSBs
- Reads NR MIB and SIBs
- Selects the best NR cell
- Performs RACH, RRC setup, and 5G registration directly with 5GC

SA: You enter directly through the 5G door, everything is 5G from the start.

Here, NR behaves like LTE does in LTE networks, fully autonomous.

Table 1: Comparison of key network parameters between NSA and SA

Aspect	NSA	SA
Initial cell search	LTE cell	NR cell
Who advertises NR cells	LTE SIBs	NR SIBs
Who selects NR cell	LTE network	UE
Core network	EPC (4G)	5GC (5G Core)
NR role	Secondary cell	Primary cell

Q1.2

What defines the maximum achievable throughput in the network in general?

The maximum speed (throughput) depends on the following factors:

- **Bandwidth:** This is the most important. If the channel is wider (like 100 MHz instead of 20 MHz), the speed is much higher.
  $C = B \cdot Log_2\,(1 + SNR)$

- **MIMO (Multiple Input Multiple Output):** This means using many antennas. If the phone and the tower use 4 antennas at the same time (4x4 MIMO), the data is sent in 4 streams. This multiplies the speed.

- **Modulation (MCS):** This is how dense the data is. Higher modulation (like 256QAM) packs more bits into the signal. This makes it faster but needs a very good signal.

- **Subcarrier Spacing:** In 5G, we can change the Subcarrier Spacing.
  Different spacing helps in different situations and can change the data rate.

- **Signal Quality (SINR):** If the signal is strong and clean, the network uses higher modulation. If the signal is bad, the network slows down to avoid errors.

Q1.3

What is the maximum theoretical throughput (Mbps) of the following 5G network specifications (DL):

- **Frequency band 1 (FR1), downlink, FDD**
- **60 MHz channel bandwidth with 30 kHz SCS**

  these define the maximum amount of Resource Blocks (RB)
- **1 Carrier (scaling factor is 1)**
- **2 × 2 MIMO (number of layers is 2)**
- **256QAM (defines how many bits per symbol we can transmit)**
- **Typical Overhead (OH) value for FR1 (= 0.14 or 14%)**

Please use the info available in 3GPP TS 38.306 for this calculation.

Note: All Formulas and Math symbols in this report are written in LaTex Language.

First, we have to define the numbers based on our description:

- V_{Layers} (MIMO Layers): 2 (given as 2 x 2 MIMO)

- Q_m (Modulation Order): 8 (for 256QAM, each symbol carries 8 bits)

- f (Scaling Factor): 1 (given as 1 carrier)

- R_{max} (Coding Rate): 0.92578 (standard constant 948/1024 used in specification)

- N_{PRB} (Number of RBs): 162
  (Note: Actually, the file TS 38.306 tells us to look at file TS 38.101 for this number so in that file, for a 60 MHz bandwidth with 30 kHz spacing (FR1), the standard maximum resource block count is 162)

- Numerology (μ): 1 (For 30 kHz Subcarrier Spacing)

- OH (Overhead): 0.14

- T_s^μ Factor:

This part of formula ($\frac{12}{T_s^\mu}$) calculates the number of resource elements per second.

For 30kHz SCS, symbol duration allows for 28,000 symbols per second per subcarrier

12 (subcarriers) $\times$ 14 (symbols) $\times$ $2^\mu \times 1000$

For $\mu = 1$, this equals 336,000

The standard formula for 5G data rate is:

$$\text{Data Rate (Mbps)} = 10^{-6} \cdot v_{Layers} \cdot Q_m \cdot f \cdot R_{max} \cdot \frac{N_{PRB} \cdot 12}{T_s^{\mu}} \cdot (1 - OH)$$

First, we have to calculate Peak Bits per Resource Block:

$$2 \text{ (Layers)} \times 8 \text{ (bits)} \times 1 \text{ (carrier)} \times 0.92578 \text{ (coding rate)} = 14.8125$$

Then, we have to calculate Total Resources per Second:

$$162 \text{ (RBs)} \times 336{,}000 \text{ (REs per second)} = 54{,}432{,}000$$

After that, we have to multiply them to get Peak Throughput (No Overhead):

$$14.8125 \times 54{,}432{,}000 = 806{,}274{,}000 \text{ [bits/sec]}$$

Finally, we also have to apply Overhead (14%):

$$806{,}274{,}000 \times (1 - 0.14) = 0.86806{,}274{,}000 \times 0.86 = 693{,}395{,}640 \text{ [bits/sec]}$$

To get Mbps, we divide by 1,000,000 (10^{-6})

Maximum Theoretical Throughput (Downlink) = **693.40 Mbps**

Measurements



Figure 3: Starting point of the measurements in Kampusareena, first floor near the main info

The actual measurements are performed in Kampusareena, starting from 1st floor near the main info in the area shown in above Figure 3. Perform the requested tasks in the lab and based on these answer the questions in the post-lab part.

You are mostly using Crosscall Stellar X5 phone for the measurements, as shown in Figure 4a, but also OnePlus 9 Pro, as shown in Figure 4b. Please be careful not to drop the phones, so handle it with care! You are using mainly different apps in phone:

- Bittimittari
- QualiPoc
- G-NetTrack Pro



(a) Crosscall Stellar X5



(b) OnePlus 9 Pro

Figure 4: Measurement phones.

Q2.1

At the starting location, perform five (5) speed test measurements with Bittimittari application (a speed test application by Traficom) with the following cases. For 5G connectivity, the network utilizes 60 MHz bandwidth at the n78 band together (as we use NSA) with two 4G carriers, band 1 (with 5 MHz carrier or technically only 4.8 MHz as we have had to suppress the last subcarrier) and band 3 (with 5 MHz carrier). All of these indoor network cells utilize 2x2 MIMO.

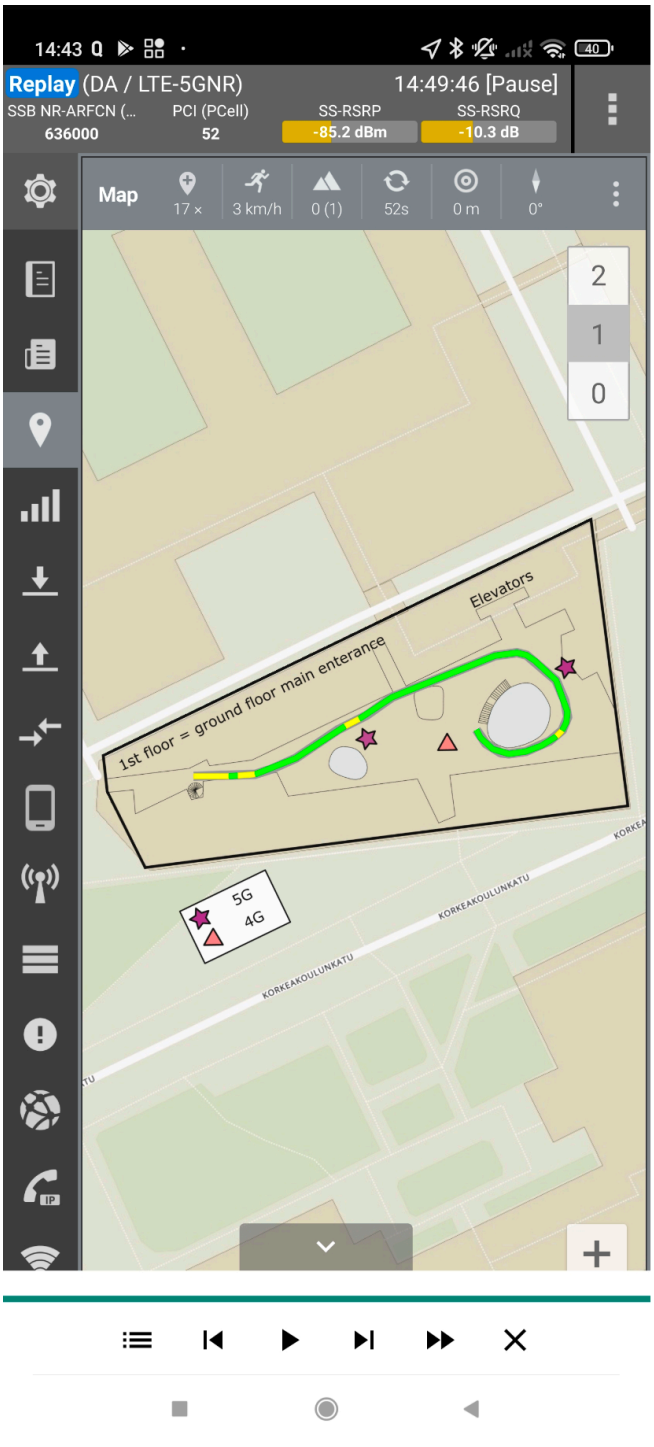
Q2.2

The second task is to visualize the signal strength of the indoor 5G network cells. Start a measurement in each floor with two phones and walk around each floor and add way points manually according to your location (rough estimations). You can decide what route to measure in each floor (no need to rake through all areas).

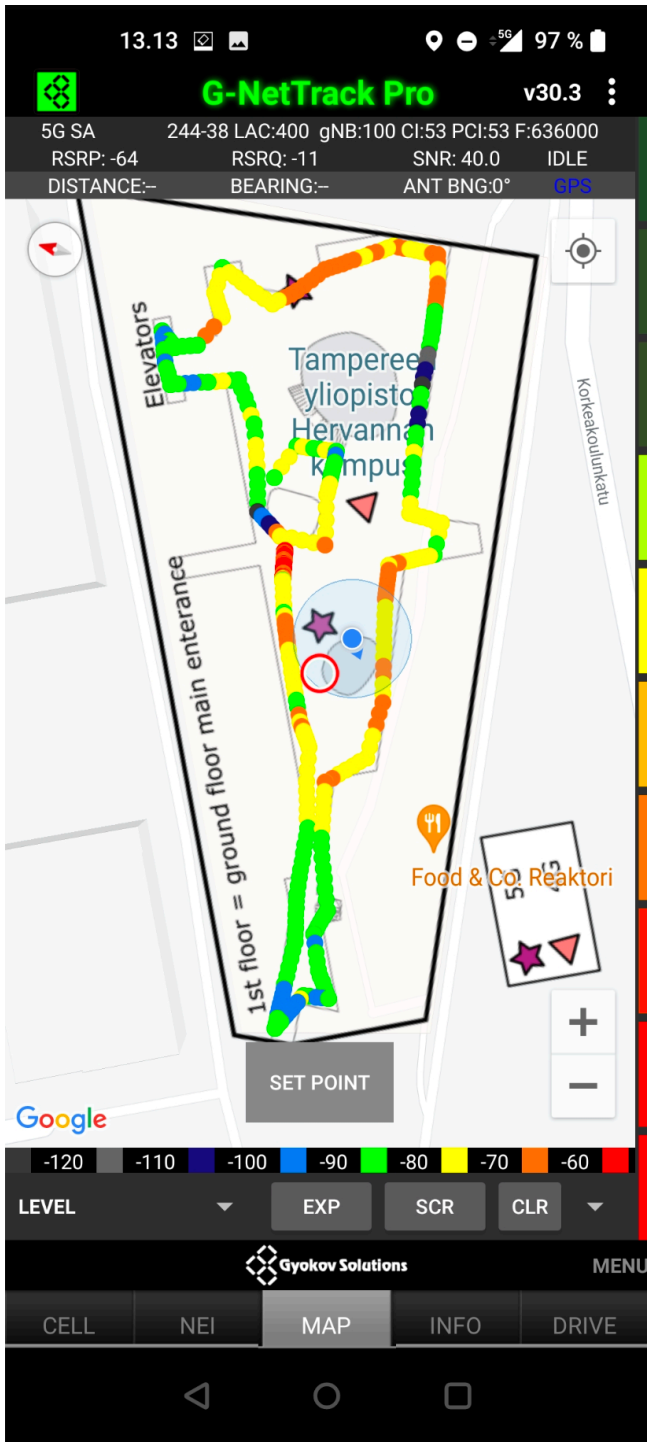
PLEASE NOTE

No need to go to the restaurant area (or other rooms), so try to avoid crowded areas as much as possible!
(in general you should not disturb others, keep this in mind)

After each measurement, save a screenshot from the measurement equipment (at least from the one with G-NetTrack Pro) for post-lab part. A simplified route of this is shown in Figure 5a for QualiPoc and Figure 5b for G-NetTrack Pro.
You can also find rough floor plans from last page of this document in Figure 11



(a) QualiPoc (Crosscall Stellar X5)



(b) G-NetTrack Pro (OnePlus 9 Pro)

Figure 5: Example from one measurement routes.

The Post-lab

Answer the questions presented here in your report. The questions here correspond to the tasks in the measurement parts (Q3.1 is about Q2.1 and both Q3.2 and Q3.3 are for Q2.2 results).

Q3.1 (analysis for Q2.1)
Show the mean values for each listed parameter in both (5G and 4G) cases. How much difference there are between these technologies? What are the things that can affect the achieved results in live networks?

a) 5G disabled

Table 2: Measured Performance Metrics in 5G NSA Mode

#	DL (Mbps)	UL (Mbps)	Latency (ms)	Jitter (ms)	Signal (dBm)
1	62.7	26	19	24	-100
2	58.6	24.2	20	22	-91
3	65.8	25.5	19	24	-97
4	65.2	25.5	20	22	-92
5	62.6	25.5	25	20	-93

The 4G connection offered consistent download speeds averaging around 63 Mbps with a latency of roughly 20 ms

b) 5G enabled

Table 3: Measured Performance Metrics in 5G SA Mode

#	DL (Mbps)	UL (Mbps)	Latency (ms)	Jitter (ms)	Signal (dBm)
1	510.4	50.9	14	4	-93
2	507.2	51.5	14	6	-101
3	520.9	50.1	10	4	-98
4	516.6	50.4	10	4	-102
5	512.3	53	10	4	-94

The 5G connection provided download speeds exceeding 500 Mbps (8x faster) and the latency of 10 ms

The following table summarizes the average performance of both 4G and 5G networks based on the five measurement samples recorded for each

Table 4: Comparison of Measured Average Performance in 4G and 5G Networks

Parameter	4G (Average)	5G (Average)	Improvement Factor / Difference
Download (Mbps)	**62.98**	**513.48**	~ 8.15x faster
Upload (Mbps)	**25.34**	**51.18**	~ 2.02x faster
Latency (ms)	**20.6**	**11.6**	44% reduction (-9 ms)
Jitter (ms)	**22.4**	**4.4**	80% reduction (-18 ms)

- **Throughput**: The 5G network is approximately 8 times faster for downloads compared to 4G. This is primarily due to the much larger bandwidth.

- **Latency and Jitter:** 5G nearly halves the latency and significantly reduces jitter. This provides a much more responsive experience for real-time applications like video conferencing or gaming.

- **Upload Speed:** While the upload speed doubled, the increase was less dramatic than the download speed, likely due to the configuration of the 5G NSA setup where 4G still plays a significant role in the connection.

Several technical and environmental factors can influence the actual throughput and quality achieved in a real world network:

- Bandwidth - MIMO (Multiple Input Multiple Output) - Modulation
- Signal Quality (SINR) - Subcarrier Spacing (SCS) - Network Load

Q3.2 (analysis for Q2.2)

Use your preferred software (e.g., Matlab) and import the measured files (.CSV) from each floor (0th, 1st, and 2nd floor). Visualize your results. Show SS-RSRP, SS-RSRQ and SS-SINR values. Analyze the indoor network average values for these parameters (per floor and over all floors). List all of the values into a table as well for a clear comparison. Based on the measurements, how does the signal strength appear to you across the floors? Show the screenshots from the lab in this part as well.

(Hint) Calculate the average values for logarithmic results correctly: you first have to convert the values into linear scale, then perform the averaging and finally convert the values back into logarithmic scale

Table 5: Indoor 5G signal quality measurements across different floors

Location	SS-RSRP (dBm)	SS-SINR (dB)	SS-RSRQ (dB)
Floor 0	-70.47	27.64	-10.81
Floor 1	-65.15	23.65	-10.83
Floor 2	-66.07	24.16	-10.95
Overall	-66.45	25.28	-10.86

Signal Quality (SINR)

The fact that Floor 0 has the best quality (27.64 dB SINR) while having the lowest strength is the most important finding of our measurement

Floor 0 (Cellular Isolation): This floor represents the basement level, where the thick foundation and surrounding earth act as a shield against external signals. While this reduces external penetration, the lower RSRP observed is also due to the measurement path covering a larger area, resulting in a greater average distance from the antennas. Additionally, the floor is not entirely isolated; interference is still present due to signal leakage through the large open spaces (holes) between floors, primarily originating from the same-cell-ID antennas on the opposite side.

Floors 1 & 2 (Interference Zone): These floors have large glass windows and are higher up. Even though they have strong local antennas, the environment differs from the basement. Since Tampere University operate on a dedicated frequency license, interference from external operators is negligible. Although there is potential interference from university's own macro cell, in practice, it does not significantly penetrate the indoor area. Therefore, the SINR observed here is determined more by the indoor propagation environment than by external noise competition.

Analysis of Signal Strength (RSRP)
Even though every floor has its own antennas, we still see a ~5 dB difference in signal strength between Floor 0 and Floor 1.

Floor 0 (-70.47 dBm): Despite having a local antenna, the Library environment contains high-density RF obstacles, like bookshelves and rows of books. These materials are highly effective at absorbing and scattering radio waves, causing shadowing. Additionally, if the antenna on this floor is positioned further from the specific measurement route used in the library, the path loss would be higher, resulting in the lowest average RSRP.

Floor 1 (-65.15 dBm): This floor serves as the main entrance and is an open, high-ceiling environment. Signal strength on this floor is higher because it's an open lobby with a line-of-sight (LOS) to the indoor antenna. The lack of interior walls and dense furniture (like bookshelves) allows the local antenna to provide the highest RSRP.

Floor 2 (-66.07 dBm): Similar to Floor 1, the restaurant floor is generally open. The slight drop compared to Floor 1 might be due to a slightly greater distance between the measurement path and the local antennas on this floor.

Table 6: Qualitative assessment of Signal Strength and Quality across different floors

Floor	Avg. SS-RSRP	Avg. SS-SINR	Qualitative Assessment
Floor 0	-70.47 dBm	27.64 dB	**Cleanest Signal:** Weakest power but highest quality due to shielding from external noise.
Floor 1	-65.15 dBm	23.65 dB	**Strongest Signal:** Best power due to open entrance layout, but more interference.
Floor 2	-66.07 dBm	24.16 dB	**Strong Signal:** High power, moderate quality.

Note:

Floor 0 has lower received signal power (RSRP) but higher signal quality (SINR). Floor 1 shows stronger received power but lower SINR. This illustrates that signal strength and signal quality should be interpreted separately.

Analysis of Signal Quality (SINR)

The inverse relationship between signal strength and signal quality across the floors is common in indoor Live network environments:

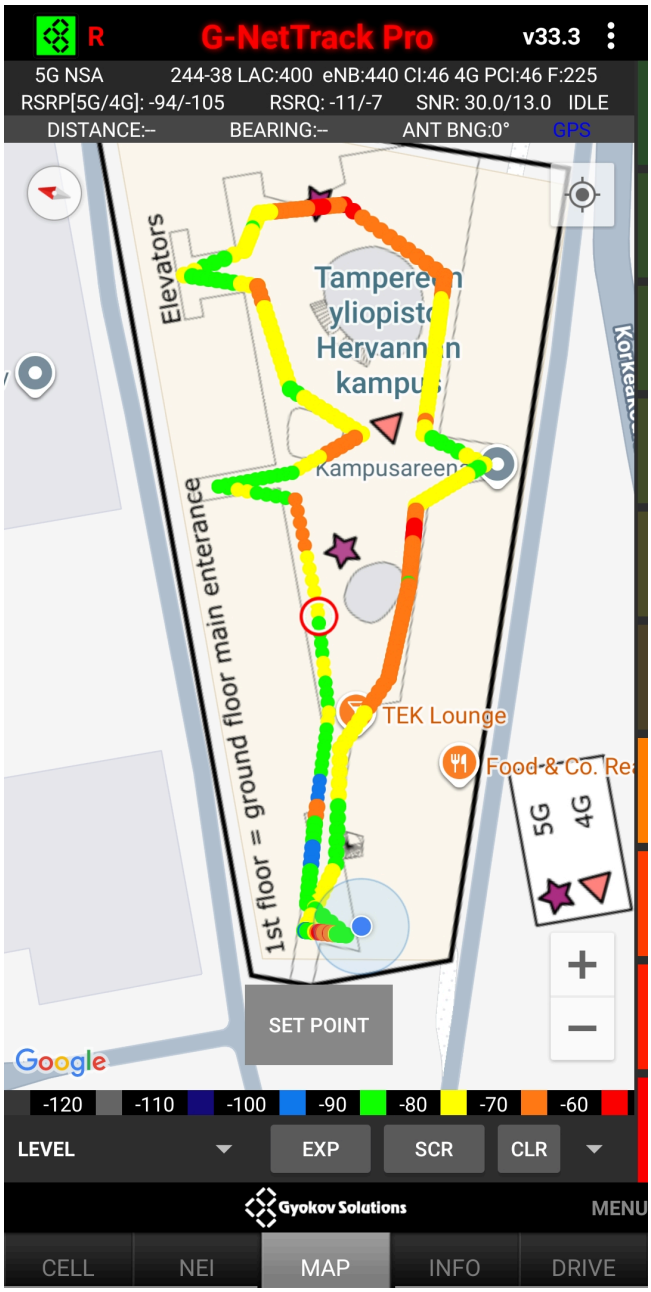
Floor 0 (High SINR - 27.64 dB): Although the RSRP is lower here, the SINR is significantly higher. Because the library is on the 0th floor (often partially underground or shielded by more walls), it is effectively isolated from external noise. The thick walls and floor slabs that weaken the primary signal also block interference from outside macro-cell towers. This results in a much cleaner signal environment.

Floors 1 & 2 (Lower SINR - 23.65 to 24.16 dB): These floors have higher RSRP but lower SINR. Being the main entrance and restaurant floors, these areas typically have large windows and open spaces. While this allows for a strong signal from the indoor 5G antenna, the SINR values are influenced by the specific physics of environment. It is important to note that the Noise floor is dependent on thermal noise power (temperature and bandwidth) and equipment characteristics, rather than external towers. Any additional reduction in SINR here is due to interference components rather than an increase in background noise.

Our Measurement Routes (G-NetTrack Pro)



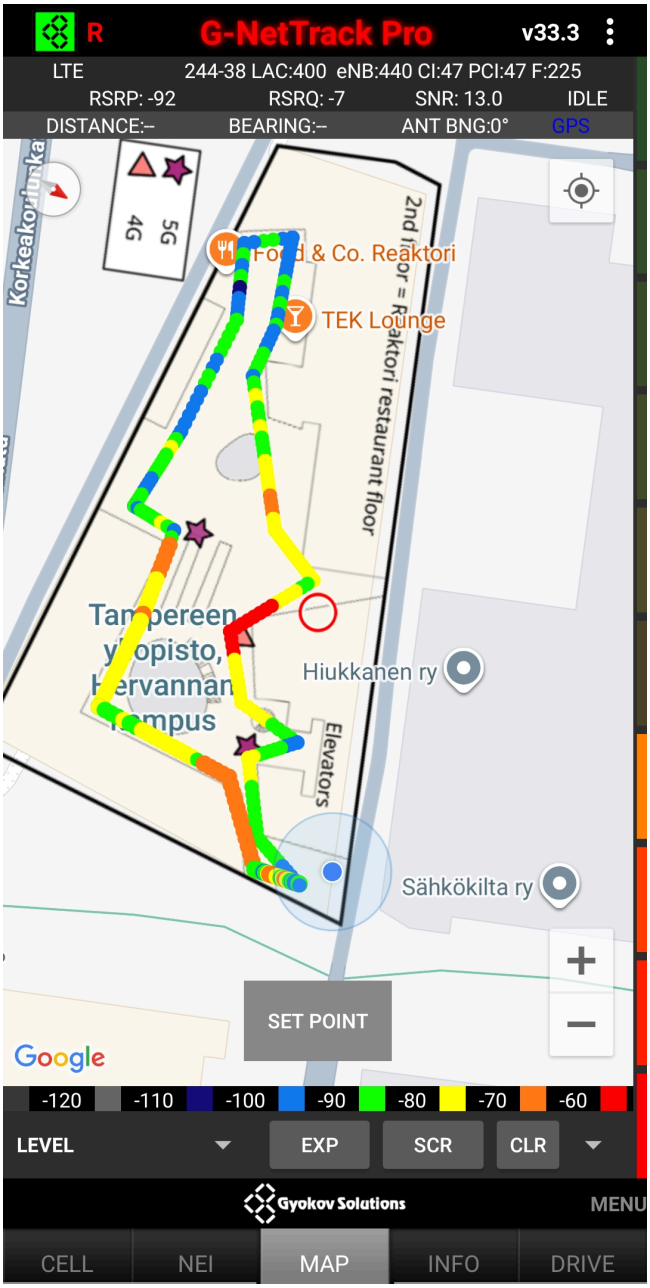
a) Floor 0



b) Floor 1

Figure 6: Measurement route coverage maps using G-NetTrack Pro

Our Measurement Routes (G-NetTrack Pro)



c) Floor 2

Figure 6: Measurement route coverage maps using G-NetTrack Pro

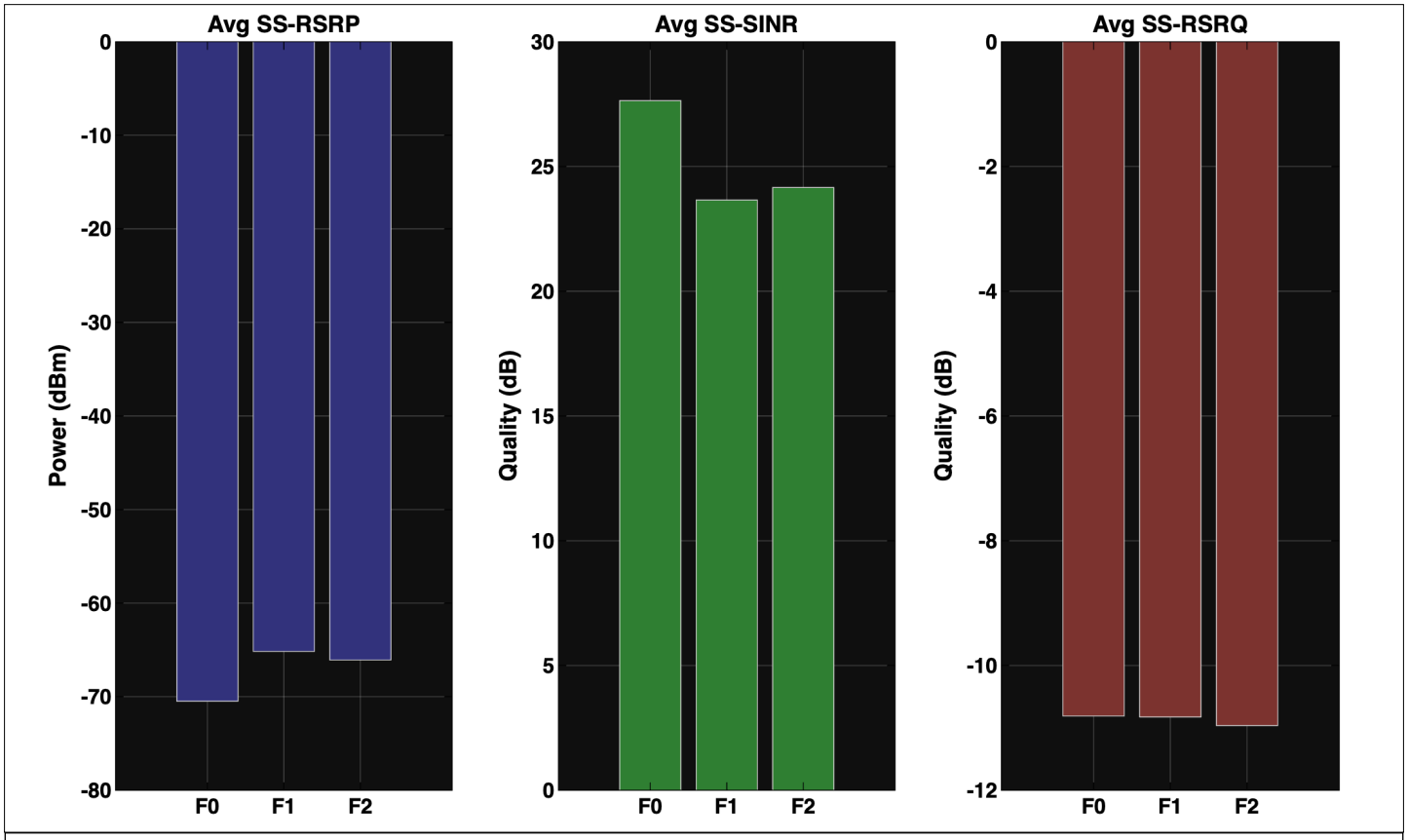


Figure 8: Comparison of Average SS-RSRP, SS-SINR, and SS-RSRQ across Measured Floors

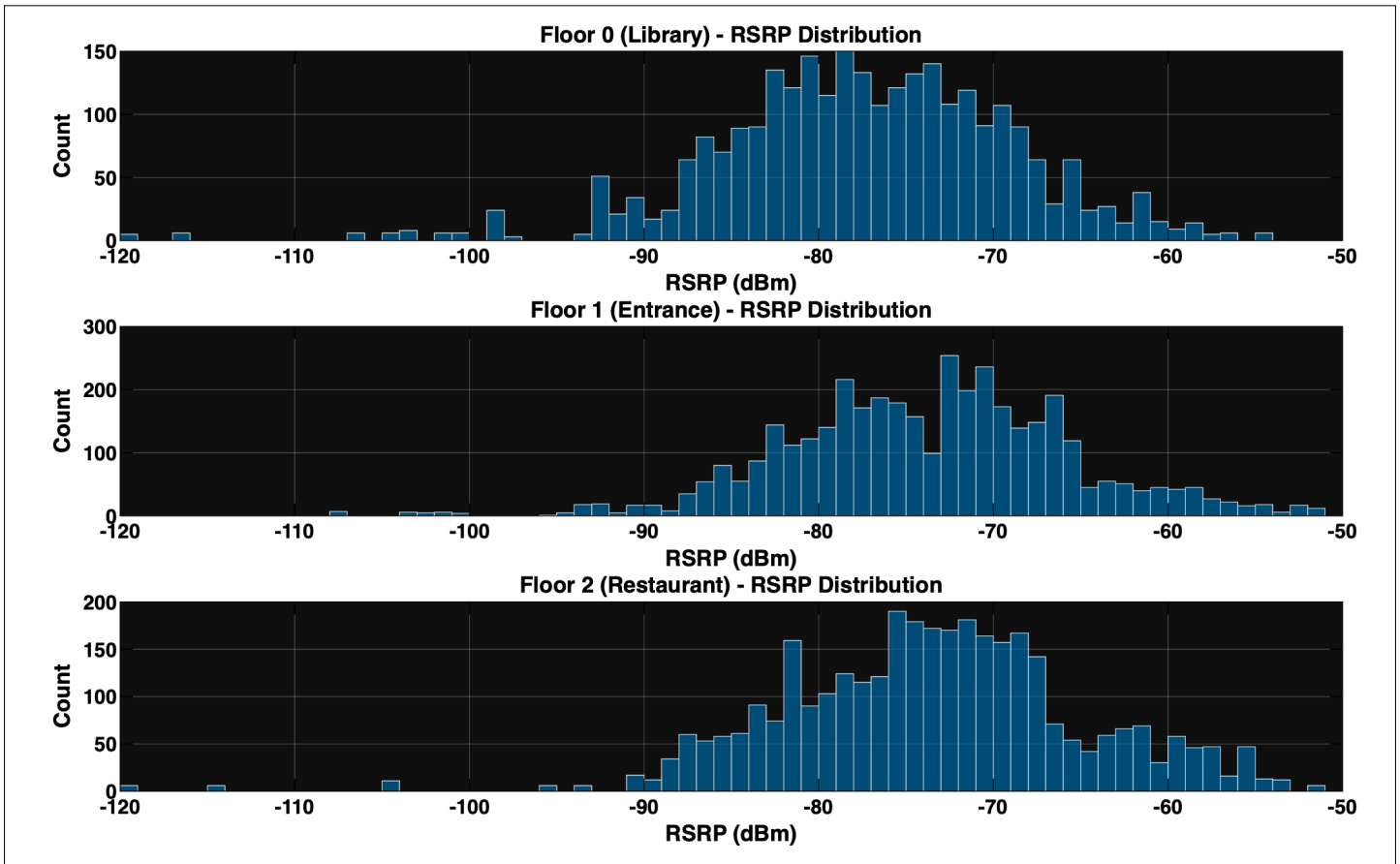


Figure 9: SS-RSRP Probability Distribution for Floor 0, Floor 1, and Floor 2

Q3.3 (analysis for Q2.2)

Similar to the previous question, analyze the performance of the network now by focusing on the throughput values. Show histograms of data rates for each floor separately and then a combination of all floors. Calculate and show also average values for each floors as well as all floors combined in a table for a clear comparison. Please analyze the results (i.e., what kind of differences are there between the floors and why might be the reason for that, where would you expect to get the best or worst data rates etc.)

Please Note

The script works such that there is first a 1 second test for ping to www.google.fi, then a 10 second DL test and last a 10 second UL test. This naturally affects the average values as you have different times for each test, which should be taken into account (not exactly as there is time gap between different tests). So please take this into account in the results as well as in the analysis part.

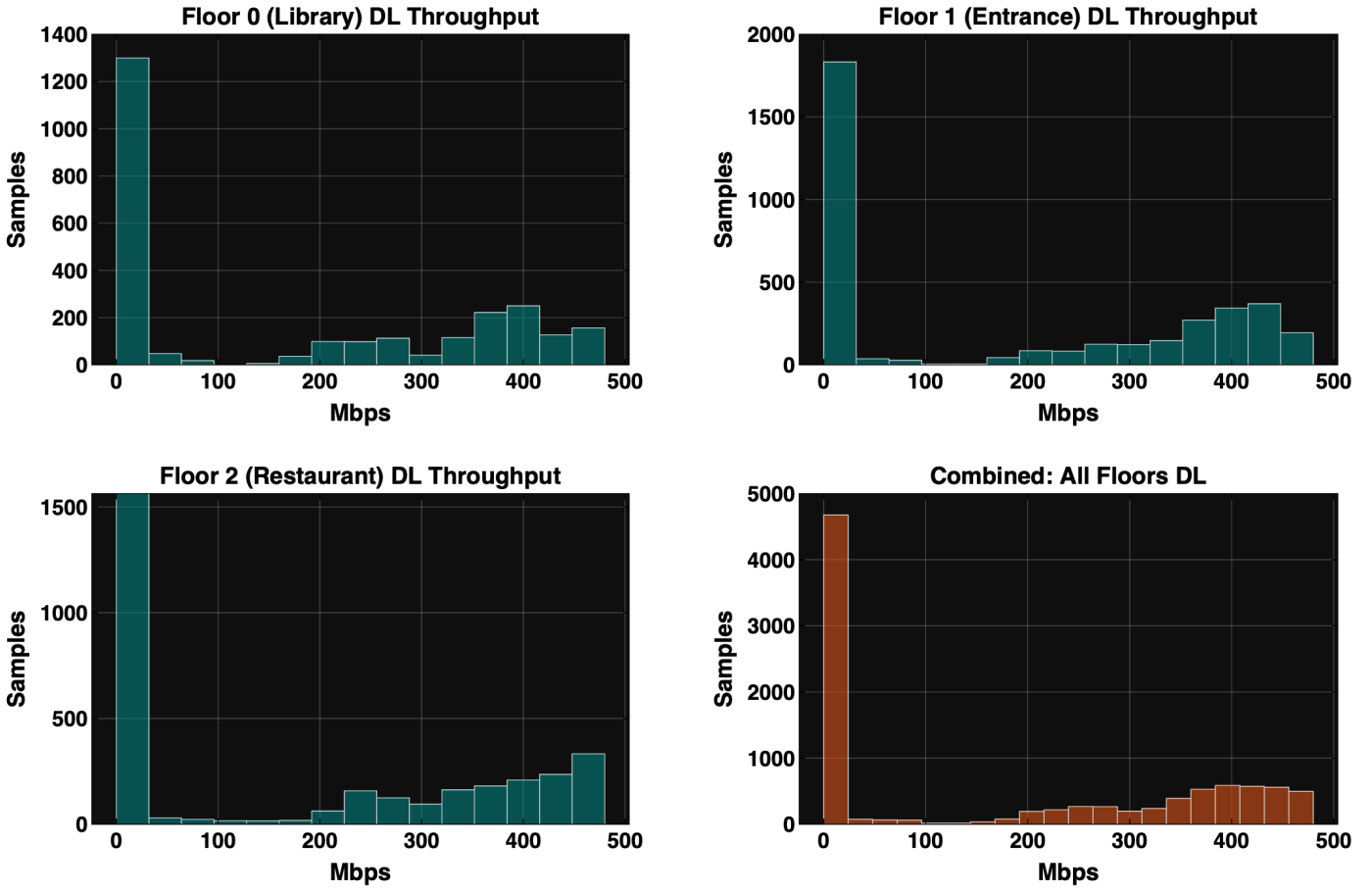


Figure 10: Histograms of Net PDSCH (Download) Throughput for each floor and the total combined dataset

Table 7: Average Downlink and Uplink throughput measurements per floor

Measurement Location	Avg DL Throughput (Mbps)	Avg UL Throughput (Mbps)
Floor 0 (Library)	170.77	6.62
Floor 1 (Entrance)	178.72	6.66
Floor 2 (Restaurant)	181.77	7.66
All Floors Combined	177.56	6.99

The highest average download throughput was achieved on Floor 2 (181.77 Mbps), while the lowest was on Floor 0 (170.77 Mbps).

Floor 0 (Lowest Average Throughput): The Library recorded the lowest average DL throughput (170.77 Mbps) despite the highest average SS-SINR reported in the signal-quality measurements (27.64 dB). This indicates that the throughput difference cannot be attributed to SINR alone. Route geometry, multipath, scheduling, instantaneous MCS selection, and the timing of separate measurement runs may also have influenced the result.

Floors 1 & 2: These floors recorded slightly higher average DL throughput (178.72 and 181.77 Mbps). The more open environment may have contributed, but the measurements do not isolate a single cause. The throughput results should therefore be interpreted together with the signal-quality data and normal test variability rather than as a direct consequence of one RF metric.

The Test Sequence Effect: It is important to note that the raw measurements include a 1-second ping and a sequential shift between DL and UL. In this analysis, the averages were calculated by filtering for active transfer periods (>0.1 Mbps). If the "idle" or "ping" periods were included in a standard average, the throughput would appear artificially lower (approx. half of the values above) because the DL is zero during the UL test phase.

Across the three floors, the average DL throughput differences were modest (170.77-181.77 Mbps). Floors 1 and 2 produced the highest averages in these runs, while Floor 0 produced the lowest. Because Floor 0 also showed the highest average SS-SINR in the separate signal-quality measurements, the variation likely reflects several interacting factors rather than a simple monotonic relationship with RSRP or SINR.

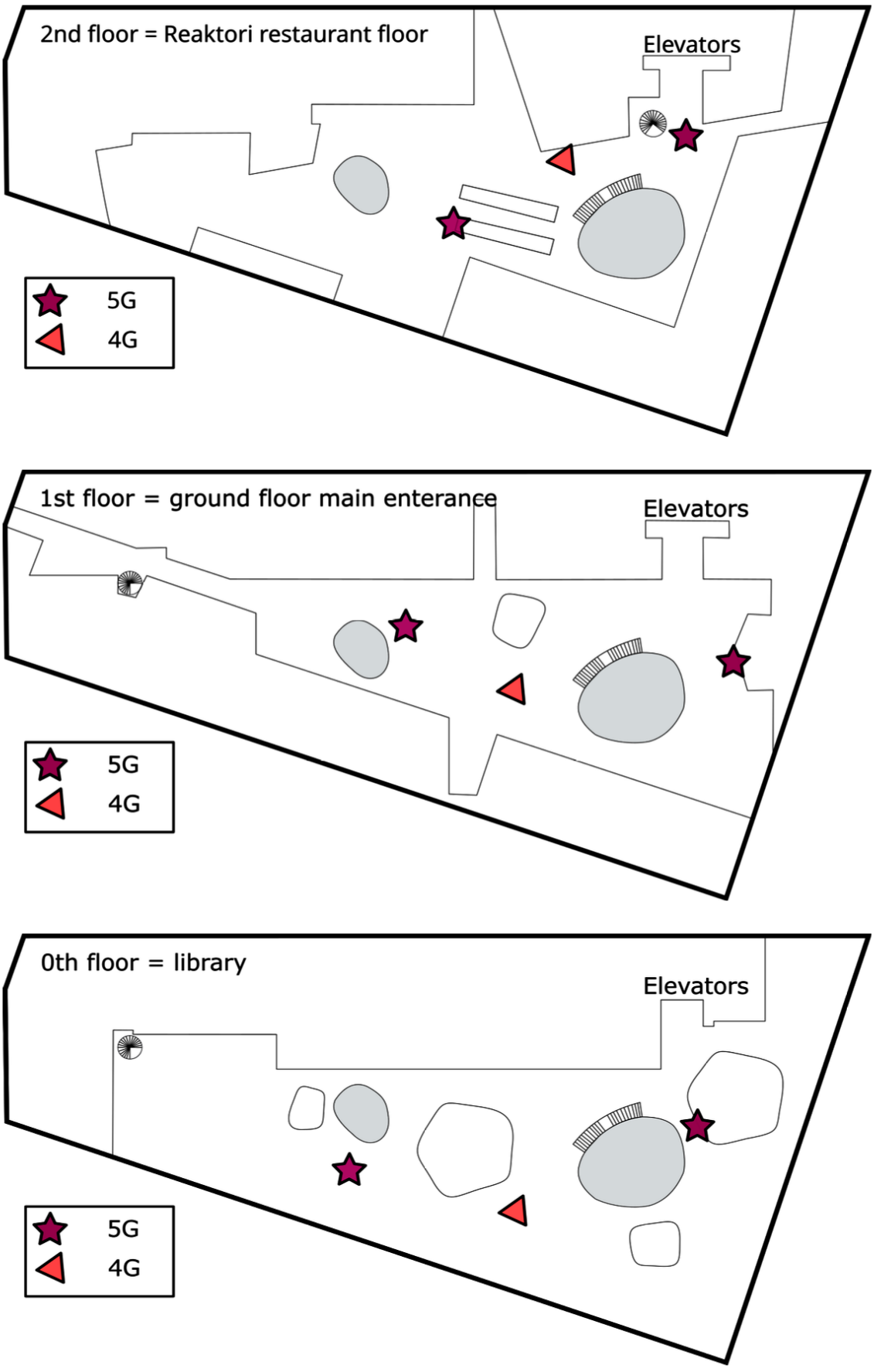


Figure 11: Kampusareena floor plans with rough locations for 5G and 4G antennas. Used as a background in the measurement app (QualiPoc)

References

These references support the technical background, standards, and tools used in this report.

[1] Tampere University, "5G Mobile Communications (COMM.SYS.700): 5G Laboratory Project Work," course material, 2026.

[2] 3GPP, TS 38.306, "NR; User Equipment (UE) radio access capabilities."

[3] 3GPP, TS 38.101-1, "NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone."

[4] 3GPP, TS 38.211, "NR; Physical channels and modulation."

[5] 3GPP, TS 38.215, "NR; Physical layer measurements."