5G Coverage and Performance

UiO **:** University of Oslo
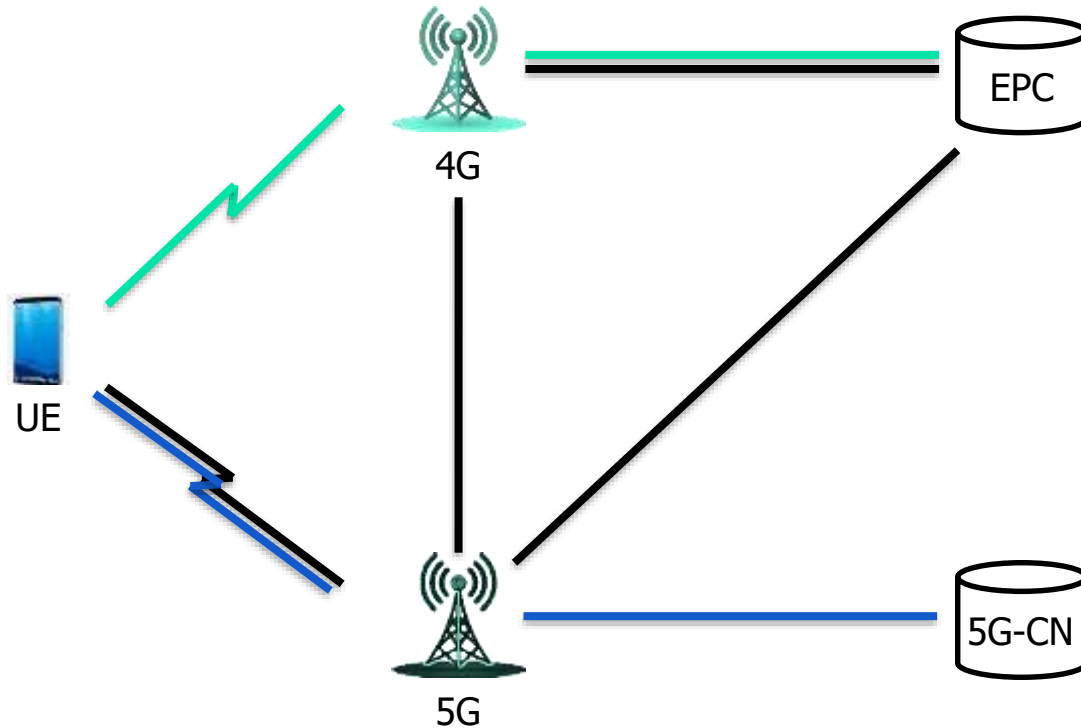
From 4G to 5G Transition

Today – 4G Access

Device attaches to LTE/4G radio and Evolved Packet Core (EPC)

Early 5G – Non-Standalone (NSA)

Device attaches to 5G-NR, which routes either via 4G Base Station to EPC, or direct to EPC

4G acts as control plane

5G Standalone (SA)

Device attaches to 5G-NR and 5G Core Network.

5G NSA field trials and testing

➢ 5G Non-Standalone (NSA) is being largely adopted for the rollout of 5G networks

➢ It is key to investigate how 5G NSA performs in the wild

➢ Large-scale measurement campaign on 5G NSA deployments in Rome, Italy

➢ Empirical analysis of the 5G **coverage** and **performance**

Measurement Setup and Campaign

➢ Four MNOs (Op1-Op4) offering 4G and 5G NSA connectivity in Rome, Italy

➢ Measurements period: 9 months (March 2023 - November 2023)

➢ Campaign organized in "sub-campaigns": different **days**, different **times** of the day and different **locations**

➢ Three mobility scenarios:
  ➢ <u>Indoor Static (IS):</u> measurements indoor
  ➢ Outdoor Walking (OW): measurements while walking outdoor
  ➢ <u>Outdoor Driving (OD):</u> measurements while driving a car

i. RF antenna
ii. GPS antenna
iii. R&S TSMA6 scanner
iv. two 5G capable UEs

For <u>network analysis</u>, <u>troubleshooting</u>, <u>visualization</u>, and <u>data exporting</u>,
we used the **R&S ROMES** software

Passive Measurements

➢ TSMA6 detects and decodes downlink control information

➢ Measurements 4G and 5G at each location

➢ Dataset features:

   ➢ Spatial (Latitude and Longitude) and temporal (Date, Time) information

   ➢ Carrier frequency identifiers

   ➢ Signal strength/quality indicators

Active Measurements

➢ Android application Qualipoc running on two Samsung S20 5G-capable devices

  ➢ **Throughput Test**: Speedtest by Ookla jointly with R&S Qualipoc to measure the end-to-end downlink (DL) and uplink (UL) throughput

    • **throughput (**donwlink, uplink**)**

  ➢ **Latency/Reliability Test:** Qualipoc interactivity test with i. eGaming real-time traffic pattern and ii. AR/VR cloud gaming traffic pattern.

    • **RTT**

    • **interactivity score**, i.e., combination of Round Trip Time (RTT), Packet Delay Variation (PDV), Packet Error Rate)

Carrier frequency identifiers

https://www.spectrummonitoring.com/frequencies.php?market=I
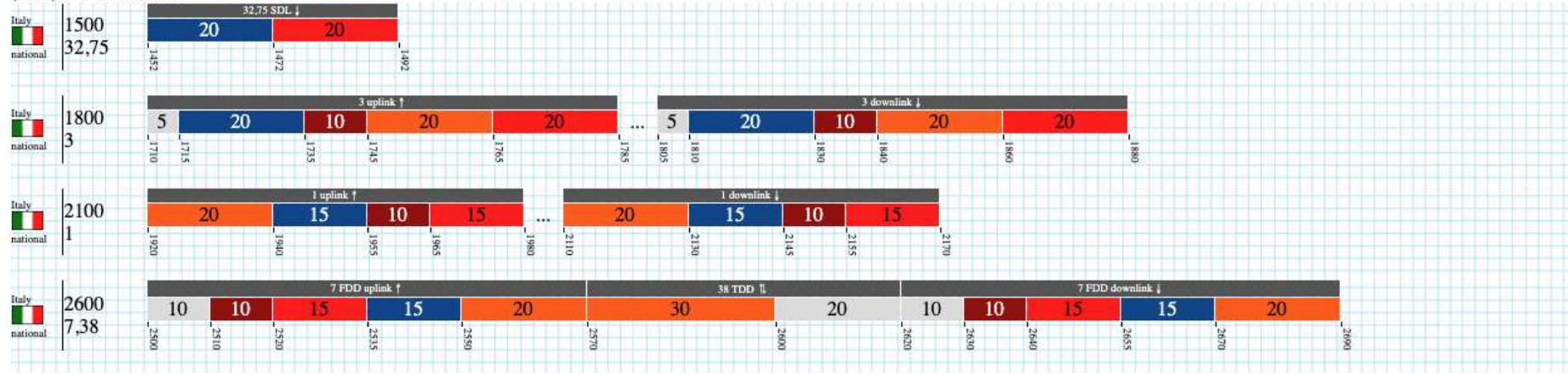
Signal Indicators

- **(SS-)RSRP:** Indicates the average power of the received reference signal spread over the full bandwidth. It is affected by distance, nearby buildings, walls, weather conditions, etc.
  - Range (in 4G): -140dBm (bad) to -44dBm (good)
- **(SS-)RSRQ**: Indicates the quality of the received reference signal. It is defined as RSRQ = N x RSRP / RSSI, where N is the number of Physical Resource Blocks.
  - Range (in 4G): -19.5dB (bad) to -3dB (good)
- **(SS-)SINR:** Indicates the signal-to-noise ratio of the received signal. In other words, it measures the ratio of the desired signal power to the sum of the power of the interfering signals and can be used to measure the quality of the connection
  - Range (in 4G): -20dB (bad) to 20dB (good)

- ❏ **These ranges slightly differ for 5G.**

Behind the Doors:
4G and 5G Datasets

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Data Sources

- **Passive dataset:**
  - Multiple **.csv** files (one for each sub-campaign)
    - The name of the file can be used for grouping data under the same location/area
    - Reports information such as Date/Time, signal strength for each detected neighboring cell
    - Other available information such as Frequency/Band and mobility scenario (IS, OW, OD) are also available
  - Structure of the dataset:
    - Time series - consists of '**frequency scans**'
      - 'batch' of samples sharing features such as Date, Time, Latitude, Longitude, and **Frequency**.

- **Active dataset:**
  - Multiple **.csv** files (one for each sub-campaign)
    - The name of the file can be used for grouping data under the same location/area
    - Indicators related to the radio and physical layers, as well as QoS and QoE indicators.
  - Structure of the dataset:
    - Time series but _event-based_ — the dataset was updated at millisecond-level granularity
    - Row records with '?' represent unaltered values.

Important: You can use the file name to isolate both passive and active data from a particular sub-campaign

Example (5G) – Passive dataset

Date	Time	UTC	Latitude	Longitude	Altitude	Speed	EARFCN	Frequency	PCI	SSBIdx	MNC	SSS.SINR	SSS_RSRP	SSS.RSRQ
28.05.2023	18:33:15.561	1687966394	41.89987	12.41834	93.74	0.07	152690	763450000	147	2	"Op"[3]	-3.82	-114.59	-15.75
28.05.2023	18:33:15.561	1687966394	41.89987	12.41834	93.74	0.07	152690	763450000	251	2	"Op"[3]	-8.62	-118.45	-19.61
28.05.2023	18:33:15.621	1687966395	41.89987	12.41834	93.59	0.04	152691	763455000	147	2	"Op"[3]	-6.35	-116.45	-17.75
28.05.2023	18:33:15.621	1687966395	41.89987	12.41834	93.59	0.04	152691	763455000	251	2	"Op"[3]	-8.82	-118.55	-19.86
28.05.2023	18:33:15.644	1687966395	41.89987	12.41834	93.59	0.04	368890	1844450000	102	3	"Op"[4]	-2.02	-109.90	-14.50
28.05.2023	18:33:15.684	1687966395	41.89987	12.41834	93.59	0.04	638016	3570240000	531	5	"Op"[4]	-6.91	-118.55	-18.33
28.05.2023	18:33:15.684	1687966395	41.89987	12.41834	93.59	0.04	638016	3570240000	531	3	"Op"[4]	-6.24	-117.86	-17.78
28.05.2023	18:33:15.721	1687966395	41.89987	12.41834	93.59	0.04	643295	3649425000	582	2	"Op"[2]	-4.93	-104.38	-16.42
28.05.2023	18:33:15.721	1687966395	41.89987	12.41834	93.59	0.04	643295	3649425000	584	1	"Op"[2]	-8.77	-112.79	-19.71
28.05.2023	18:33:15.722	1687966395	41.89987	12.41834	93.59	0.04	643295	3649425000	584	5	"Op"[2]	-3.37	-93.95	-15.40

Example - Active

```
     Date          Time GPS.Long GPS.Lat X5G..PCI LTE.PCI SS.RSRP SS.RSRQ SS.SINR RSRP  RSRQ  SINR RAT.Info X5G.PDSCH.Throughput LTE.PDSCH.Throughput
720 16.12.2020 10:55:08.071        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?    LTE              ?                    ?
721 16.12.2020 10:55:08.074        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?     ?               ?                    ?
722 16.12.2020 10:55:08.211        ?       ?        ?      68       ?       ?       ?  -96   -15    -1     ?               ?                    ?
723 16.12.2020 10:55:08.236        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?     ?               ?                    ?
724 16.12.2020 10:55:08.483        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?     ?               ?                    ?
725 16.12.2020 10:55:08.732        ?       ?        ?      68       ?       ?       ?  -96   -15    -0     ?               ?                    ?
726 16.12.2020 10:55:09.026        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?     ?               ?                    ?
727 16.12.2020 10:55:09.224        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?    LTE              ?                    ?
728 16.12.2020 10:55:09.232        ?       ?        ?       ?       ?       ?       ?    ?     ?     ?     ?               ?                    ?
729 16.12.2020 10:55:09.297        ?       ?        ?      68       ?       ?       ?  -96   -16    -1     ?               ?                    ?
    X5G..PUSCH.Throughput LTE.PUSCH.Throughput X5G..PDSCH.QPSK.Rate X5G..PDSCH.16QAM.Rate X5G..PDSCH.64QAM.Rate X5G..PDSCH.256QAM.Rate LTE.PDSCH.QPSK.Rate
720           ?                   ?                    ?                    ?                    ?                    ?                    ?
721           ?                   ?                    ?                    ?                    ?                    ?                    ?
722           ?                   ?                    ?                    ?                    ?                    ?                    ?
723           ?                   ?                    ?                    ?                    ?                    ?                    ?
724           ?                   ?                    ?                    ?                    ?                    ?                    ?
725           ?                   ?                    ?                    ?                    ?                    ?                    ?
726           ?                   ?                    ?                    ?                    ?                    ?                    ?
727           ?                   ?                    ?                    ?                    ?                    ?                    ?
728           ?                   ?                    ?                    ?                    ?                    ?                    ?
729           ?                   ?                    ?                    ?                    ?                    ?                    ?
    LTE.PDSCH.16QAM.Rate LTE.PDSCH.64QAM.Rate LTE.PDSCH.256QAM.Rate X5G..PUSCH.QPSK.Rate X5G..PUSCH.16QAM.Rate X5G..PUSCH.64QAM.Rate X5G..PUSCH.256QAM.Rate
720           ?             DQA.Result Cur..Num..Sent.Packets Cur..Num..Lost.Packets Cur..Num..Packets.not.Sent Cur..Channel.QoS.3GPP Cur..Round.Trip.Latency.Median
721           ?        720         ?                 ?                      ?                      ?                       ?                     ?                     ?
722           ?        721         ?                 ?                      ?                      ?                       ?                     ?                     ?
723           ?        722         ?                 ?                      ?                      ?                       ?                     ?                     ?
724           ?        723         ?               420                     0                      0                     0.000                   0.057
725           ?        724         ?                 ?                      ?                      ?                       ?                     ?                     ?
726           ?        725         ?                 ?                      ?                      ?                       ?                     ?                     ?
727           ?        726         ?                 ?                      ?                      ?                       ?                     ?                     ?
728           ?        727         ?                 ?                      ?                      ?                       ?                     ?                     ?
729           ?        728         ?              1177                     0                      0                     0.000                   0.055
             729         ?                 ?                      ?                      ?                       ?                     ?                     ?
                    Cur..Round.Trip.Latency.10th Cur..PDV.Median Cur..PDV.99.9th Cur..Interactivity.Score Num..Sent.Packets Num..Lost.Packets
             720               ?                       ?               ?                   ?                        ?                 ?
             721               ?                       ?               ?                   ?                        ?                 ?
             722               ?                       ?               ?                   ?                        ?                 ?
             723             0.047                   0.020           0.052               50.700                     ?                 ?
             724               ?                       ?               ?                   ?                        ?                 ?
             725               ?                       ?               ?                   ?                        ?                 ?
             726               ?                       ?               ?                   ?                        ?                 ?
             727               ?                       ?               ?                   ?                        ?                 ?
             728             0.046                   0.018           0.045               55.500                     ?                 ?
             729               ?                       ?               ?                   ?                        ?                 ?
```

Post-Processing challenges

- **Cleaning:** Remove metadata and measurement configuration details from raw data files
  - These were exports from a measurement software tool (ROMES)
- **Missing Data:** How to handle?
  - e.g., MNC missing - Action: insert it by using other features (such as Frequency)
  - e.g., GPS missing - Action: if indoor campaign, insert it manually
- **Mutate Data:** Add features useful for the analysis
  - e.g., location, mobility scenario, folder structure (for future segmentation), etc.
- **Invalid Data:** Requires domain knowledge
  - Look for outliers and extreme values
    - Determine either extreme (of interest) behavior or measurement error

A few numbers

- Additional information regarding the dataset available in our paper: 'The Chronicles of 5G Non-Standalone: An Empirical Analysis of Performance and Service Evolution' available here: https://ieeexplore.ieee.org/abstract/document/10753472

TABLE 1. Number of passive samples collected in Rome during the 2nd collection phase (2023), for each technology, scenario, and MNO.

	4G		5G	
	IS	**OD**	**IS**	**OD**
Op_1^I	1.878M	632.8K	701.8K	211.9K
Op_2^I	1.896M	533.8K	4.99M	2M
Op_3^I	672.7K	334.9K	2.163M	795.7K
Op_4^I	983.7K	410.2K	3.751M	1.307M

TABLE 2. Number of active sessions executed in Rome during the 2nd collection phase (2023), for each UE mode, MNO, test, and scenario. The total measurement duration for each test is provided alongside the test name (in hours). For *eGaming real-time* and *AR/VR Cloud Gaming*, we report the number of sessions executed against the server in Switzerland.

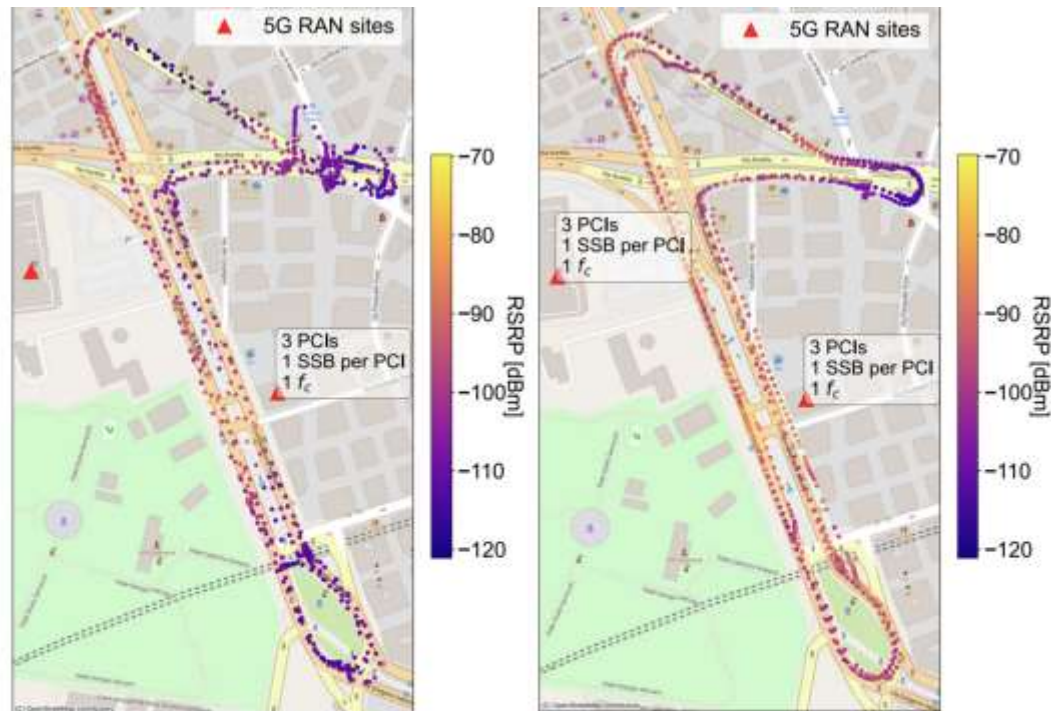|	4G				5G-enabled			
	Op_1^I	Op_2^I	Op_3^I	Op_4^I	Op_1^I	Op_2^I	Op_3^I	Op_4^I
ETSI Throughput Test (27 hr)								
IS	176	176	83	71	777	774	150	146
OD	77	76	17	17	167	179	66	78
eGaming real-time (26 hr)								
IS	111	110	95	95	768	770	85	83
OD	87	87	26	25	165	164	64	63
AR/VR Cloud Gaming (13 hr)								
IS	192	192	92	100	391	387	105	105
OD	41	42	N/A	N/A	127	127	70	70
Ookla (20 hr)								
IS	92	89	N/A	N/A	289	290	N/A	N/A
OD	17	20	N/A	N/A	48	50	N/A	N/A

FIGURE 2. Spatial-temporal characterization of 5G RAN deployment and coverage for Op_1^I in the OD location, in 2021 (left) vs. 2023 (right). Coverage is reported as the highest RSRP value (across the PCIs detected for Op_1^I) observed in the points traversed during the measurements.

5G Coverage map (2021)
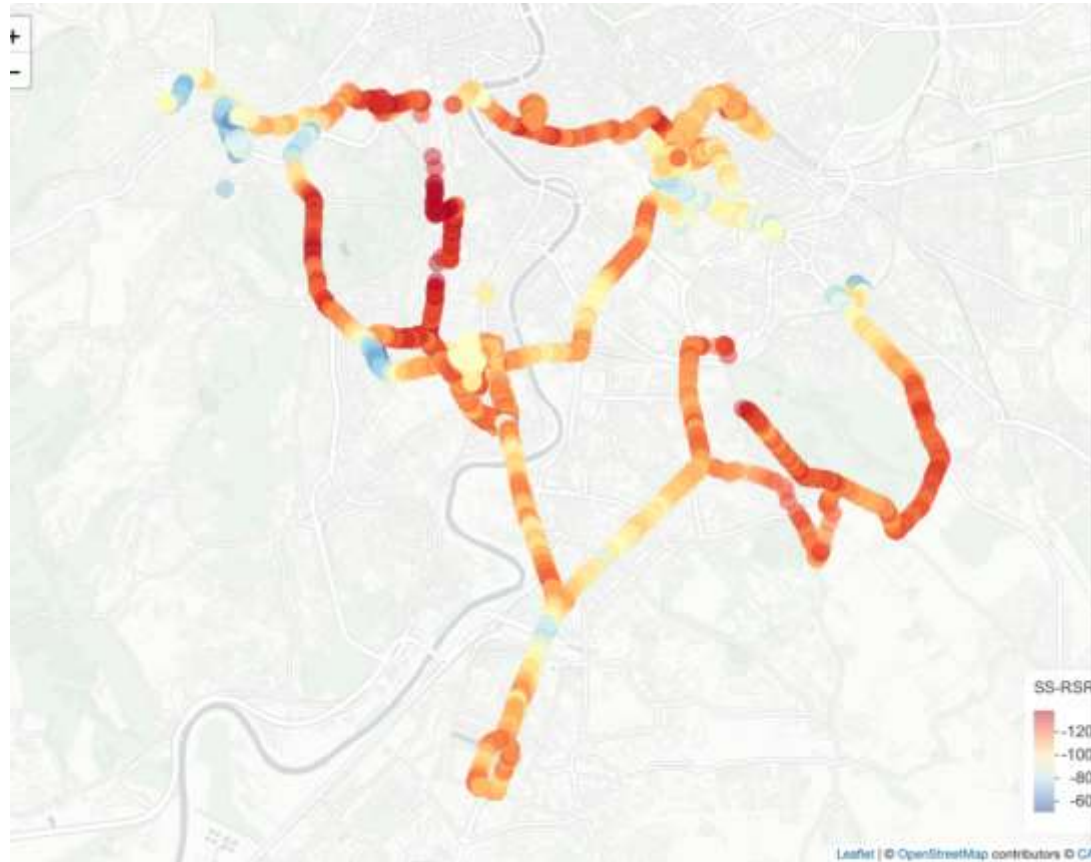
Highest SS-RSRP [dBm] measured across the 5G PCIs of Op1 detected at the locations traversed during OW and OD sub-campaigns.

5G Coverage (2021)
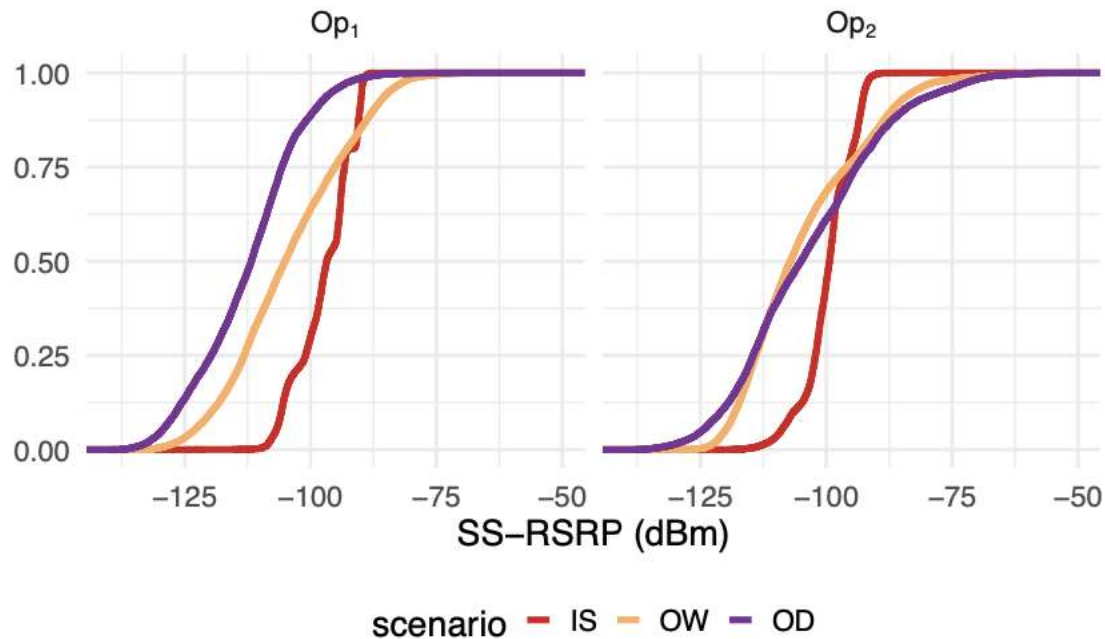
Distribution of 5G SS-RSRP [dBm] (in an ecdf format), for $Op1$ and $Op2$ and grouped by scenario.

Significance Tests

- Kruskal-Wallis (non-parametric): Determine statistical significance between the means of more than two independent groups

    Assumptions:
    - No assumptions
    - **Null Hypothesis:** The means across all groups are equal
    - **Alternative Hypothesis:** At least one group mean is different from the rest
        - if p-value is less than a significance level (e.g., 0.05), we can reject the null hypothesis

- Dunn's Test (non-parametric): If Kruskal-Wallis shows statistical significance, conduct Dunn's test to determine which groups are different (test each combination of groups)

Operator and Technology comparison

Technology	IS	IW	OW	OD
4G	0.2906	0.0274 *	0.2480	0.3581
5G	0.1594	0.00033 ***	0.1152	0.1439

Operator
comparison

Operators have significant differences especially for Indoor scenarios.

Operator	IS	IW	OW	OD
1	0.0021 **	2.3e-09 ***	0.0117 *	1e-05 ***
2	0.0133 *	1e-06 ***	0.00078 ***	1e-05 ***

Technology
comparison

Different technologies have significant differences for both operators.

Assignment

How to access the dataset

- Download the dataset here:
  https://zenodo.org/records/14073311 (active measurements)
  https://zenodo.org/records/17208871 (passive measurements)
- Important complementary material:
  - Article: G. Caso et al., "The Chronicles of 5G Non-Standalone: An Empirical Analysis of Performance and Service Evolution," IEEE Open Journal of the Communications Society(IEEE OJ-COMS), pp. 1-21, 2024
    (https://ieeexplore.ieee.org/document/10753472)
  - Check the description file for a complete list of all available features
  - Description of the features
    https://zenodo.org/records/8224890/files/description.pdf?download=1

What to evaluate

- Coverage and performance analysis
    - Given a selected number of different (sub-)campaigns, compare the coverage and/or performance of different operators (further dissect per frequency band)
    - Given two or more sub-campaigns at the same location (e.g., repetitions of indoor/outdoor campaigns), show how the coverage and/or performance changes over time.
    - Given a single operator, compare the coverage and/or performance across different locations or scenarios. HINT: Particularly interesting for OD campaigns
- Incorporate 2 of the 3 items above in your assignment

    Make sure to carry out statistically significance tests among different groups!

Contact Points

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