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***Abstract*—Long-term monitoring, measurement, and collection of key performance indicators (KPIs) for fourth and fifth-generation (4G and 5G) networks under various transmission conditions are essential for optimizing performance and ensuring seamless connectivity in dense environments. In this paper, we present a cost-effective, portable measurement setup with an intuitive user interface, designed for efficient cost-efficient measurements in diverse environments. This setup was used for large-scale measurement studies of 4G (Long-Term Evolution – LTE) and 5G (Non-Standalone – NSA) mobile networks conducted in Brno, Czechia, enabling the exploration of indoor and outdoor network coverage across different radio frequency (RF) bands and environmental conditions. Using this equipment, nearly 1,500,000 samples were collected with a time resolution of 1 second. To support the reproducibility of our study, the dataset is publicly available for download. The results demonstrate varying performance of 4G and 5G mobile networks across different scenarios and show the significant impact of network load fluctuations based on the time of day.**

***Index Terms*—4G and 5G mobile networks, coverage mapping, data analysis, interpolation, key performance indicators (KPIs).**

I. Introduction

The advent of fourth and fifth-generation (4G and 5G) mobile networks marks a significant leap in mobile communication technology, driven by the increasing demand for high-speed and reliable connectivity [1]. The effectiveness of 4G and 5G networks, particularly under varying transmission and environmental conditions (e.g., the time of day on network load) [2]–[4], depends heavily on a comprehensive understanding and continuous optimization of signal coverage, capacity, and reliability, especially in dense urban environments [5]. To achieve optimal network performance and seamless connectivity, it is essential to conduct long-term monitoring and detailed measurement of key performance indicators (KPIs) across various transmission conditions [6]. Such long-term measurements provide invaluable information for mobile operators, enabling them to optimize network deployment and resource allocation, enhance quality of service (QoS) for end-users, aid in regulatory compliance and spectrum management, and support the development of emerging technologies that rely on robust mobile connectivity [7].

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The study and empirical analysis of 4G/5G mobile networks have become increasingly critical in our interconnected world. In recent years, numerous studies have focused on exploring 4G/5G mobile signal coverage in various indoor and outdoor environments [8]–[15]. Raida et al. [8], [9] reported the results for indoor static (managed at TU Wien, Vienna, Austria) and rural outdoor measurements, conducted by a smartphone, in the LTE band 20 (800 MHz). The datasets are open and publicly available. The analysis of the results revealed the impact of various transmission conditions, such as weather conditions like rain, on the stability of certain KPI measurements.

Extensive 4G and 5G (NSA) mobile network measurements have been conducted in [10]–[12]. In [10], an empirical study was conducted on 5G NSA deployments for two mobile operators in various urban areas of Rome, Italy, focusing on KPIs, throughput, latency, and coverage. The study found that 5G provides significant downlink (DL) throughput gains compared to 4G. However, these gains remain unstable in the investigated scenarios. The measurement concept and setup used in the study do not allow for the online evaluation of the measurement data. The outputs of study focused on the 4G/5G cellular signal coverage in a complex factory environment was reported in [13]. Measurements were conducted in six different locations inside the factory. Among other findings, the results (openly accessible on GitHub) showed varying performances of 4G/5G mobile networks on weekdays and weekends, influenced not only by the heavy industry environment but also by temporal factors.

A comprehensive 3G/4G mobile coverage measurement study conducted in rural areas of Malaysia was presented in [14]. The dataset (not publicly available) was collected using modified Samsung Galaxy S6 smartphones. The observations confirmed stable and good 4G-based mobile connectivity and provided basic directions for the implementation of 5G networks in rural areas. An extensive measurement-based study (three-month-long) of a 5G mobile network, by the using of three smartphones, in a large public bus transit system in Madrid, Spain, has been provided in [15]. The measurement results (openly accessible) revealed different end-to-end user performances were observed on urban and suburban routes, reflecting the varying 5G deployments of the operators.

Contribution: Our contribution is twofold. First, we propose a cost-effective measurement setup comprising a 4G/5G module, a processing unit, and a custom-built application for controlling and configuring measurements. This setup, independent of any third-party applications, provides flexibility and allows for customized visualization and data manipulation. The equipment used is characterized by its small size, portability, and remote connection capability. Second, we present a KPI-based comparative analysis of 4G and 5G NSA networks across different transmission environments (e.g., a university dormitory, public tram transit) and conditions (static and dynamic) in various areas of Brno, Czechia. We have made the complete dataset and all source codes used to process the dataset publicly available [16] to promote the reproducibility of our analysis and to support future research in this area.

The rest of this paper is organized as follows: The created measurement system and the related software application, including the measurement tool and data visualization, are introduced in Section II. The measurement scenarios at the conditions in detail for that the the long-term measurement campaigns were conducted are described in Section III. The discussion of the obtained results is also involved in this section. Section IV concludes this paper.

II. Measurement Setup

Key considerations at the designing of the measurement setup include selecting appropriate methods, equipment, and tools for collecting accurate data are provided in this section.

A. Methodology

In this study, we adopted a methodology appropriate to collect data at various measurement scenarios (indoor / outdoor) and transportation modes (e.g., public transport, foot). Measured data are collected from the mobile site using a measurement device and stored in `log` files, which are then stored on the internal memory storage of the device. Subsequently, the data are retrieved for visualization, enabling users to analyze the data and deduce conclusions from the result of the measurement campaign. This approach mirrors practices used by mobile network operators and benchmarking companies, which typically divide tests by environment.

B. Measurement Setup

The hardware (HW) setup (see Fig. 1), consisting of a Waveshare 5G Module, Raspberry Pi 4 Model B, and a $40\,\mathrm{Ah}$ battery pack, enables seamless data gathering at various measurement conditions. The functionality of the measurement tool is inspired by network performance tools like InfoVista's TEMS Investigation and TEMS Discovery[1]. These commercial tools allow users to visualize data on a map, display KPI graphs, and provide insights into specific samples.

For independent and accurate KPI measurement, selecting of a 4G or 5G module with Global Navigation Satellite System (GNSS) support is essential.

[1]https://www.infovista.com/tems/discovery

Fig. 1. Measurement setup: (left) battery pack, (middle) measurement device, (right) equipment to visualize data.

In this work, the SIM8200EA-M2 5G module was selected due to a support of a wide range of RF bands and USB 3.1. It also support a set of AT commands, like `"AT+CPSI?"` and `"AT+CGPSINFO"`, for network signal measurements and to obtain GPS coordinates, respectively.

The Raspberry Pi (RPi) – a processing unit – was chosen for its balance of performance and cost. With a quad-core ARM Cortex-A72 processor, $2\,\mathrm{GB}$ of RAM, and USB 3.0 ports supporting up to $5\,\mathrm{Gbps}$, this model meets the requirements for high-speed network measurements. It offers the flexibility of open-source Linux and the ease of Python programming.

A battery pack with a $5\,\mathrm{V}$ output and a capacity of $\approx 148\,\mathrm{Wh}$ is employed. This capacity ensures prolonged operation, even without implementing energy-saving measures. Under the consideration that the setup consumes $\approx 8\,\mathrm{W}$ of power, the battery can sustain measurements for ≈ 18 hour for mobile outdoor measurements.

C. Measurement Tool

To ensure precise and consistent data collection, an additional tool was developed to manage and configure measurement settings. The tool, designed as a user-friendly application, leverages platforms that support graphical user interfaces (GUIs) and uses predefined tools and Python packages.

The core measurement script, written entirely in Python, uses the `pyserial` package to establish communication with the 4G/5G module, while other built-in Python modules manage data processing and storage. The flowchart in Fig. 2 illustrates the flow of this script. The script begins by allowing users to choose their preferred radio access technology (RAT) and RF band. After connecting to the module, an AT command initializes the system. The GPS status is checked, and the measurement name is either assigned automatically or input by the user. Once set, the script enters a loop to continuously collect measured values via AT commands. This loop runs until the specified measurement duration is reached.

To ensure scalability and simplicity the work with the measurement tool, the Python-based *Dash* framework, combined with *Plotly*, was adopted to develop a low-code, interactive web applications tailored for data analysis tasks.

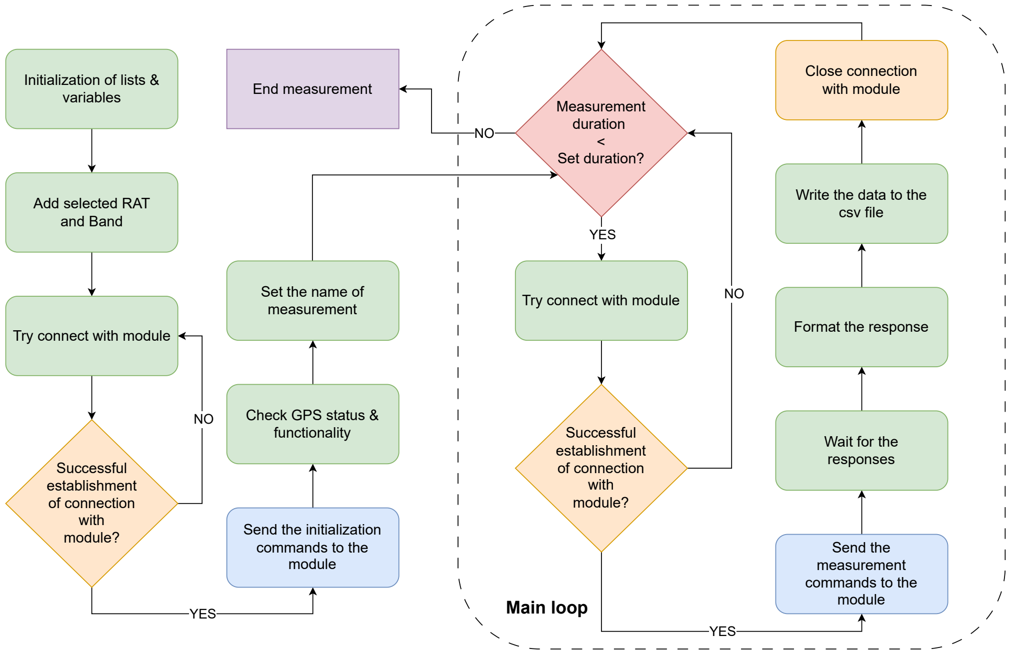

Fig. 2. Flowchart of the measurement script

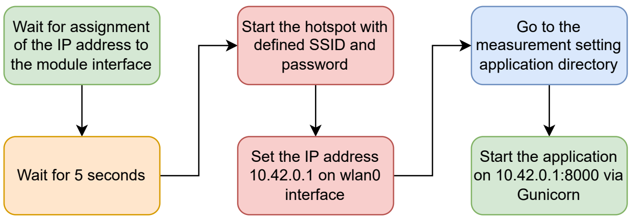

Fig. 3. Flowchart diagram of the startup bash script

The application runs locally for debugging, typically at `http://127.0.0.1:8050`, but can also be deployed to a local network using a web server like Gunicorn[2]. This allows users to interact with the system through a web browser, making the application platform-independent. The main components of the *Dash* framework, Layout and Callbacks, define the structure and functionality of the tool, enabling dynamic content updates based on user input.

Using the *Dash* framework, a user-friendly application was developed for configuring and controlling measurements on both a notebook and smartphone. Users can select the measurement name, duration, network technology, preferred band, and choose whether to enable GPS localization. Buttons labeled "START" and "STOP" control the measurement process. The application employs a background callback mechanism from *Dash*, which ensures that measurements continue to run without blocking the server. This allows users to terminate the measurement at any time by clicking the "STOP" button. Additionally, the real-time progress bar and data display help monitor the process during operation.

[2]https://gunicorn.org/

Deployment is managed by a bash script that runs at startup on the RPi. According to Fig. 3, the script checks if the module has an assigned IP address. If yes, it establishes a hotspot to provide internet access. Then we go to the *Dash* application directory to launch the app using Gunicorn. The application is hosted on the local network at `10.42.0.1:8000`.

D. Data Visualization

The developed visualization tool includes a navigation bar for accessing dynamic (mobile) and static data analyses. For mobile measurements, users can explore data on an interactive map, with color-coded KPI thresholds (e.g., green for strong signals, red for weak signals). Hovering over a sample reveals detailed information, and clicking on a point draws a line connecting the sample to the nearest cell tower (see GSMweb[3]), showing the calculated distance (see Fig. 4,).

The mobile measurement page provides a comprehensive analysis of data, incorporating data filtering, visualized on an interactive map, and graphed KPI values over time. Filtering and interpolation tools allows users to narrow data by radio access technology (RAT), band, or network operator, and estimate coverage maps based on KPIs, respectively. Users can adjust thresholds for signal quality metrics and explore relationships between samples and network KPIs. The static measurement analysis page mirrors the mobile page but focuses on indoor data without GPS functionality. Boxplots and histograms replace the map for data visualization. Rolling averages and data reduction options are available for analyzing large datasets with significant variability, facilitating the extraction of long-term trends while minimizing the load on the application.

[3]https://gsmweb.cz/

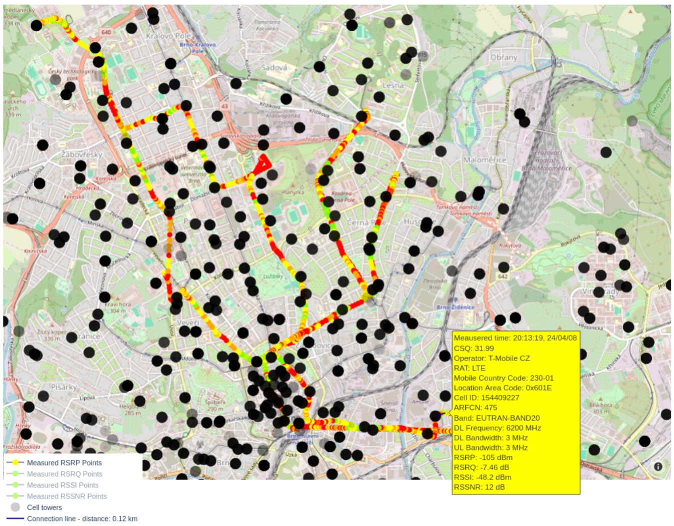

Fig. 4. Upper part of the application with navigation bar, dropdown data selector, and interactive map

TABLE I: 4G/5G NR NSA: Quality thresholds (determined through a combination of experimental measurements and objective assessments) for different KPI metrics and LTE bands

Metric	Excellent	Good	Moderate	Bad
RSRP (LTE Band 1)	> -90 dBm	-90 to -120 dBm	-120 to -140 dBm	< -140 dBm
RSRP (LTE Band 3)	> -90 dBm	-90 to -120 dBm	-120 to -140 dBm	< -140 dBm
RSRP (LTE Band 7)	> -95 dBm	-95 to -125 dBm	-125 to -145 dBm	< -145 dBm
RSRP (LTE Band 20)	> -80 dBm	-80 to -110 dBm	-110 to -130 dBm	< -130 dBm
RSRP (NR Band 78)	> -85 dBm	-85 to -95 dBm	-95 to -105 dBm	< -115 dBm
RSRQ	> -10 dB	-10 to -15 dB	-15 to -20 dB	< -70 dB
RSSI	> -65 dBm	-65 to -75 dBm	-75 to -85 dBm	< -85 dBm
RSSNR	> 10 dB	3 to 10 dB	0 to 3 dB	< 0 dB

The KPIs [13], namely Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Received Signal Strength Indicator (RSSI), and Reference Signal Signal to Noise Ratio (RSSNR), measured in this study and their quality thresholds are listed in Table I.

III. Experimental Measurements

In this study, we conducted large-scale static and dynamic (mobile) measurement campaigns for the operator T-Mobile, providing 4G/5G coverage in Brno, Czechia. The campaigns, spread unevenly between March and May 2024, consisted of several sub-campaigns, considering weekdays, weekends, different times of day, and various scenarios.

A. *Static 4G Indoor Measurement for BUT dormitory*

Static 4G indoor measurement campaigns were conducted at the Pod Palackého Vrchem dormitory on the Brno University of Technology (BUT) campus. At this location, T-Mobile provides coverage on three LTE bands, each with a 10 MHz bandwidth: Band 20 (800 MHz), Band 3 (1800 MHz), and Band 1 (2100 MHz). In this work, data collected for Bands 20 and 3 are analyzed. It must be note that Band 7 (2600 MHz) was unavailable at this location, so no static indoor measurements were taken for that band. The measurement device was positioned under a table in a second-floor room in block A04, aligned with the base station (Cell ID 606491), but with no line-of-sight (LOS) due to the building layout.

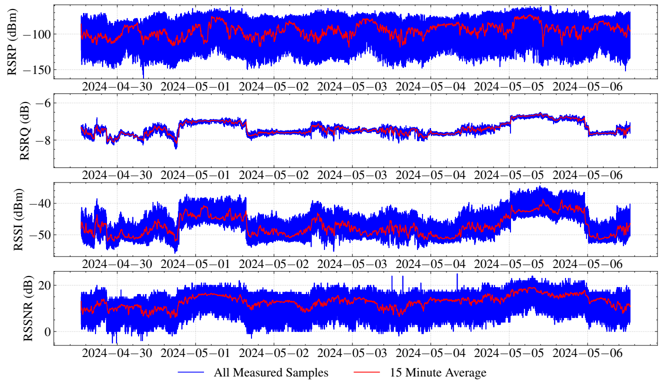

Fig. 5. Static indoor measurement conducted at Pod Palackého Vrchem dormitory on the BUT campus from April 29^{th}, 2024 to May 6^{th}, 2024 (LTE Band 20)

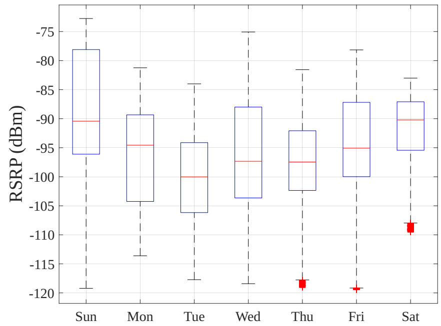

Fig. 6. Boxplots of the RSRP value distributions grouped by the day of the week representing the variability for a specific day of a static measurement conducted at dormitory on the BUT campus from April 29^{th}, 2024 to May 6^{th}, 2024 (Band 20, data averaged over a 15-minute window)

Measurements for Bands 20 and 3 were conducted over one-week periods (during normal college days, indicating significant user presence on weekdays, while fewer users were present during the weekend) as follows: April 29^{th}, 2024 – May 6^{th}, 2024 (Band 20), and March 22^{th}, 2024 – March 29^{th}, 2024 (Band 3). More than 736,000 and 600,000 KPI samples were collected during the measurement for Bands 20 and 3, respectively.

The one-week averages of the measured KPIs for the Band 3 are captured in Fig. 5. To represent the measured data in the time domain in an illustrative form in terms of data detail and presentation smoothness, a 15-minute interval was selected. The observed variability underscores the dynamic nature of network performance, influenced by factors such as time of day and network load. The periodic behavior of RSRP aligns with expectations, with values decreasing during peak periods of network congestion. An interesting insights to the distribution of RSRP values is shown in Fig. 6. The distribution of RSRP values grouped by the day of the week clearly demonstrates a strong correlation between RSRP values and the occupancy of the dormitory. This correlation allows for reasonable inference regarding the days when the dormitories are most occupied, based solely on network load indicators.

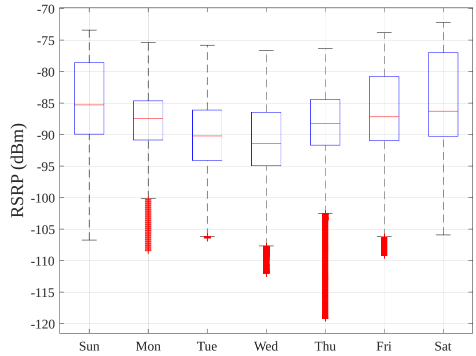

Fig. 7. Boxplots of the RSRP value distributions grouped by the day of the week representing the variability for a specific day of a static measurement conducted at dormitory on the BUT campus from March 22^{th}, 2024 to March 29^{th}, 2024 (Band 3, data averaged over a 15-minute window)

The distributions of RSRP values grouped by the day of the week is captured in Fig. 7. It is evident that the RSRP values strongly correlate with the occupancy of the dormitory. Based on this observation, we can reasonably infer the days when the dormitories are most occupied. This trend is particularly notable on Wednesdays, where the median RSRP metric is $-91.42\,\mathrm{dBm}$, the lowest value among all days of the week (the highest network load in Band 3). Is it visible, while Tuesday is as the busiest day for Band 20, Wednesday takes the lead for Band 3. Network planning and optimization strategies can be based on this understanding of band-specific network load variations. Hence, network operators can allocate resources more effectively, ensuring optimal performance and user experience during peak usage periods.

B. Mobile 4G Outdoor Measurement across the city of Brno

For the mobile 4G outdoor measurements, multiple campaigns were conducted using public transport to assess signal coverage across the city of Brno. The measurement device, locked to the LTE Band 20 and 3 being tested, was securely placed in a backpack. A total of 16,643 KPI samples were collected over 5 days (from April 2^{th}, 2024 to April 8^{th}, 2024) for Band 20, using trams as the primary mode of transport. Similar measurements were conducted for Band 3 in March 2024, when trams and buses were used for transport, resulting in 21,252 KPI samples collected over 5 different days. For the Band 20 and 3, the measurement route covered a distance of $157.6\,\mathrm{km}$ and $90\,\mathrm{km}$, respectively.

The boxplots in Fig. 8 provide a detailed breakdown of the distribution of KPIs across the observed days. The RSRP parameter shows a relatively stable median value around $-110\,\mathrm{dBm}$ to $-115\,\mathrm{dBm}$. This observation indicates that the RSRP metric remained relatively stable across all measured days. The consistent effect of the public transport methodology on all measured days is evident. Slight variations can be observed in the RSSNR values. On April 7^{th}, for instance, the median RSSNR value is $10\,\mathrm{dB}$, contrasting with the median values of $6.5\,\mathrm{dB}$ observed in the subsequent days.

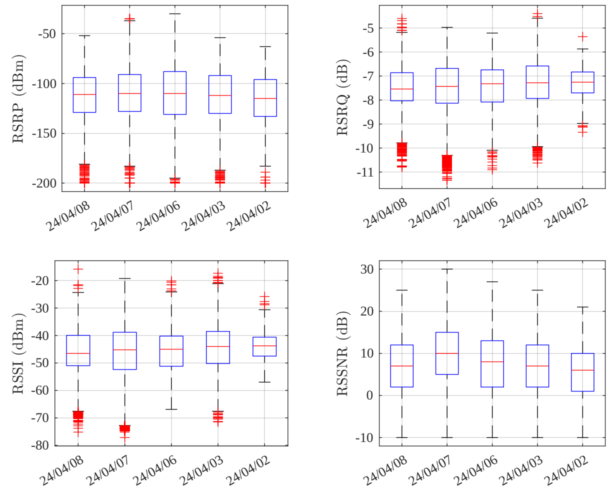

Fig. 8. Boxplots of signal metrics in a mobile measurement conducted at Brno city throughout April 2024 on LTE Band 20

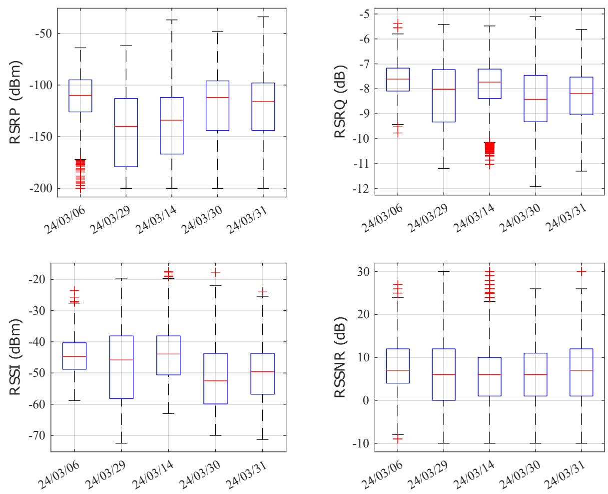

Fig. 9. Boxplots of KPIs in a mobile measurement conducted at Brno city throughout March 2024 on LTE Band 3

This discrepancy could be attributed to the conditions on April 7^{th} being a Sunday with favorable weather, resulting in fewer people in the city and consequently less interference.

Individual distributions of KPIs depicted through boxplots from measurements for Band 3 are shown in Fig. 9. The vast majority ($\approx 95\%$) of the measured data was obtained by the using of public transport. The median values of RSRP and RSSI reflect greater variability across different datasets compared to RSRQ and RSSNR. It is probably caused by different test types. On March 29^{th}, a notable decrease in the median RSRP value to $-140\,\mathrm{dBm}$ shows a relatively low signal strength. Conversely, some of the best results were recorded on March 6^{th}, characterized by a higher median RSRP value of $-110\,\mathrm{dBm}$. Datasets from March 30^{th} shown a comparatively high median RSRP value of around $-114\,\mathrm{dBm}$, despite other metrics such as RSSI and RSRQ showing relatively worse performance. A positive correlation between RSRQ and RSSI can be seen only from the point of view of distribution.

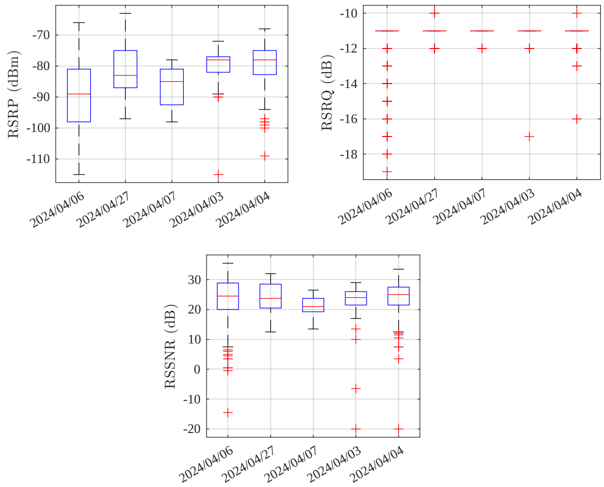

Fig. 10. Boxplots of KPIs in a mobile measurement conducted at street Skácelova throughout April 2024 on 5G NSA Band 78

C. *Mobile 5G Outdoor Measurement*

Due to limitations with the 5G module used and the unavailability of 5G standalone (SA) commercially in the Czechia, only one band was measured, namely Band 78, operating at a frequency of $3500\,\mathrm{MHz}$. While this band is not one of the most commonly deployed in Czechia, it provides valuable insights into its coverage in the city of Brno. This band is particularly relevant for operators deploying Fixed Wireless Access (FWA) to offer internet connectivity via mobile sites. Due to the unavailability of this band at the available locations for static measurement, only mobile measurements were conducted for Band 78, spanning over 10 hours of measurement conducted over 6 days in April 2024, covering a total distance of $15\,\mathrm{km}$. Over 852 KPI samples were collected at a mix of drive, bike, and walk-based measurements.

Statistical analysis of the measured KPIs in a form of boxplot is plotted in Fig. 10. Only RSRP, RSRQ, and RSSNR metrics were measurable. The RSSI metric is not supported by the utilized module in 5G NSA and thus not measured. The boxplot illustrates that while the RSRP values exhibit relatively high variability across the datasets, the RSRP medians are at a commendable level, not falling below $-90\,\mathrm{dBm}$ and even exceeding $-80\,\mathrm{dBm}$ on April 3^{rd} and 4^{th}, indicating a very strong signal. Minimum values and outliers are around $-110\,\mathrm{dBm}$, with none surpassing $-115\,\mathrm{dBm}$. This threshold corresponds to the minimum level at which the module remained connected to the 5G network, with disconnections occurring below this threshold. The variability in the RSRP metric across datasets is likely influenced by the measurement location and possibly the speed of movement.

The medians of the RSSNR metrics remain relatively stable and at a commendable level, ranging from $21\,\mathrm{dB}$ to $25\,\mathrm{dB}$, indicating a robust signal quality with ample distance between the signal and noise. Outlier values around $-20\,\mathrm{dB}$ suggest points where the measurement approached the cell edge, leading to disconnection.

IV. Conclusion

In this paper, a cost-effective and portable measurement setup for assessing both indoor and outdoor 4G/5G network coverage was presented. This setup was achieved using a HW components like the SIM8200EQ-M2 5G Module, the Raspberry Pi 4 Model B, and a $40\,\mathrm{Ah}$ power bank, at considering factors such as performance, cost-effectiveness, and power efficiency. A custom-designed application, built using the *Dash* framework, was also introduced to enable user-friendly control and configuration of the measurements. Additionally, a methodological procedure was outlined for the long-term collection and processing of measured data. Detailed information about the measurement setup, measurement methodology, source codes and dataset can be found in [1] and [16].

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