Assessing QoS and User Experience in 4G/5G Networks under Rapid Movement

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Original scientific article

***Abstract*—This paper presents an innovative measurement system and a methodology for assessing service quality and user experience in 4G/5G mobile networks during terminal mobility. We provide a guide for continuous mobile network measurements with minimal interruptions to signal or data connectivity, yielding complete, gap-free datasets across all communication layers, even in the presence of mobility-induced disruptions. The system integrates diagnostic and telemetry data collection from user equipment with active performance testing of standard Internet protocols. The presented methodology focuses on mitigating data loss during long-term measurements, with particular attention to terminal mobility. Its effectiveness is demonstrated through simultaneous measurements of three mobile operators in urban (Prague) and rural (Jeseník Mountains) areas of the Czech Republic, conducted while vehicles move along city streets, highways, and regional roads. The resulting gap-free datasets, including baseline measurements across key performance metrics, are publicly available in our GitHub repository.**

***Index Terms*—5G mobile communication, Drive testing, Mobile communication, Network performance evaluation, Quality of experience, Quality of service, TCP/IP, Wireless measurement.**

I. INTRODUCTION

This article is an extended version of the conference paper [1], in which we describe the testing methodology in much greater detail and expand on its conclusions. We focus more on describing the testing platform and its deployment for measurements in a mobile network. The article also describes, in greater detail, the problems associated with the movements of the terminal in mobile networks and the interconnection between the radio system and higher layers of communication. The main goal of this article is to present our methodology for measuring complex networks under rapidly changing external conditions. Our measurement approach is specifically optimized for drive-testing scenarios, where a single pass through a given area is performed in motion, closely mirroring the procedures used by regulatory authorities to verify mobile network performance in practice [2]. This single-pass measurement strategy is also widely used in large-scale measurement campaigns, where it is necessary to cover extensive areas within a very short time frame. We can expect to find such conditions when the user is connected via a mobile network, especially while in motion. As expected, with increasing terminal speed, changes in network conditions occur more often, requiring significantly more effort to maintain the connection in a functional state.

Furthermore, we present an open, anonymized, gap-free dataset collected during simultaneous measurements across three mobile network operators in the Czech Republic, stored at one-second intervals to enable fine-grained temporal analysis. The datasets were collected during a 4-hour drive test across several regions of the Czech Republic, including the capital city Prague, highway corridors, rural areas, and mountainous terrain in the east.

Our contributions are as follows:

- A novel measurement system, F-Tester® 4drive-box, is designed for comprehensive QoS and QoE assessment in 4G/5G networks under high terminal mobility conditions. This system integrates diagnostic data from user equipment with active testing of standard Internet protocols across OSI layers, ensuring continuous data collection despite mobility-induced disruptions such as handovers and IP address changes. The measurement approach is optimized for single-pass drive tests through a given area, closely reflecting how mobile networks are verified in practice.
- A publicly available, anonymized, gap-free dataset derived from simultaneous comparative measurements across three mobile operators in urban (Prague) and rural (Jeseník Mountains) environments in the Czech Republic is included. The dataset, stored in one-second intervals, contains baseline performance metrics such as throughput, RTT, one-way delay, SNR, CWND, jitter, and packet loss statistics and is accessible via a GitHub repository [3].
- A detailed measurement methodology optimized for mobile environments, featuring TCP/IP stack optimizations (BBR congestion control, reduced timeouts) and leveraging the well-established iPerf3 and FlowPing tools for active traffic generation and performance assessment, is presented. This design maintains uninterrupted data streams during drive tests and enables reliable, repeatable measurements during a single pass through each measurement route.

The remainder of this paper is structured as follows. Section II reviews relevant standards, commercial tools, and exist-

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ing approaches to TCP/IP and QoE measurement in mobile networks, highlighting their limitations under high mobility. Section III introduces the F-Tester® 4drive-box architecture, describes the hardware and software components, and details the configuration of FlowPing and iPerf3 for single-pass drive testing in rapidly changing radio conditions. Section IV defines the QoS and QoE-related indicators used in our study, including throughput, RTT, one-way delay, jitter, packet loss, SNR, and congestion window behaviour. Section V verifies the reliability of the proposed platform by comparing it with certified Rohde & Schwarz equipment. Section VI presents representative examples of signal coverage and radio conditions, and analyzes the observed TCP/IP performance and QoE-relevant behaviour across operators and across urban, highway, rural, and mountainous regions. Finally, the Conclusion summarizes the main findings and implications of our measurement campaign, while the Future Work section outlines planned extensions, including VoLTE/VoNR testing, more advanced cross-layer QoE modeling, and improved time synchronization mechanisms.

II. State of the Art

Current standards and recommendations are primarily focused on measuring communication network parameters in a stationary setting, where the terminal remains at a fixed location for the entire duration of the measurement [4], [5]. In contrast, mobile network measurements are typically carried out using commercial drive-test tools such as Nemo [6], R&S ROMES4 [7], or Enhancell Echo One [8]. These solutions are mainly optimized for detailed assessment of radio- and lower-layer performance, with support for higher-layer measurements (TCP/IP and application-level QoE) provided as an additional feature [9], [10].

Although these tools can perform higher-layer tests, the configuration and behavior of the applications used are often not fully transparent, making it difficult to verify whether the available transmission capacity is being effectively utilized, especially under high mobility. This limitation becomes critical in single-pass measurement campaigns, where only one traverse of a given route is available, and any gaps or suboptimal use of capacity cannot be compensated by repeated measurements [11], [12].

In parallel, a range of web-based speed test services has emerged, such as Ookla Speedtest [13], [14], RTR-NetTest [15], and other similar tools [16]. While useful as coarse indicators of user-perceived performance, their internal methodologies are usually proprietary and not fully documented, and they lack the fine-grained control over TCP/IP traffic and timing that is required for systematic, single-pass drive-test measurements.

Our work addresses these limitations by focusing on an IP-centric, fully transparent measurement approach explicitly designed for continuous, gap-free data collection during a single pass through the measurement area, while still capturing complementary radio-layer indicators. A comparison of the features of the technologies mentioned, and our proposed system is shown in Table I.

There is a wide variety of recommendations by the Internet Engineering Task Force (IETF) and the International Telecommunication Union (ITU). Unfortunately, the common web tester is not based on them, and there is a reason for this. Most of the recommendations are usable only under specific and rather stable conditions. The recommendations, such as RFC 6349 (Framework for TCP Throughput Testing) [17], are one of the most recent and useful RFCs. But even this specific RFC is already more than 10 years old and is still used in a number of commercial measuring instruments, as there is no suitable replacement. The problem with this specific RFC is that it introduces new metrics such as ”Transfer Time Ratio”, ”TCP Efficiency”, and ”Buffer Delay”, but does not literally say *how to measure* TCP throughput in this area. It also refers to other RFCs such as RFC 5136 [18] which further references RFC 7312 [19], but even these, and newer updates of these documents, do not give a satisfactory answer on how to proceed within the measurements, especially within the area of rapidly changing transmission conditions. The simple conclusion is that there is a lack of proper standardization in this area, making it rather challenging to measure key TCP performance metrics, such as throughput and RTT (Round Trip Time), in a comparable way across mobile networks. There are other, newer standards within the IETF or in RFCs, but the situation is no better, and nothing is specifically designed for mobile networks. This is specific to rapid changes in parameters over a short time window, especially when moving. There are also several standards within the ITU-T, such as Y.1540 [20], Y.1562 [21], Y.2617 [22], etc. Within the EU, various recommendations are also issued under the BEREC Group [23], [24]. These are mostly recommendations for fixed connections; the mobile environment is not addressed due to its complexity and variable parameters. Commercial mobile network measurement products use their measurement tools and procedures to make the measurement data available to users. However, the method of obtaining these data is mostly unknown. Several devices use iPerf [25] to measure TCP, SCTP, MP-TCP, and UDP. It is also worth noting that there are two versions, 2 and 3, which behave completely differently in the mobile environment, and each has its pros and cons.

Interpreting measurement results at higher layers is very complex, especially when measurements are in motion. During measurement, the network parameters constantly change, including switching between sectors or entire cells of the mobile network. We can also expect complete physical-layer connection failures, which cause delays or, more often, interruptions at higher layers. Changes in IP addresses are also very common, so TCP and UDP connections drop. This has a very negative impact on the completeness of the data obtained. Until recent versions of the tool, iPerf was not primarily designed to perform TCP tests in a mobile environment. Its main deployment is intended for high-speed wired and wireless networks without affecting the parameters of the communication channel due to the mobility of the subscriber [26]. However, over the last two years, iPerf3 has received updates that enable much faster reaction to changes in the physical channel. The tool now supports variables to specify send and receive timeouts. In this way, any problems during the transfer can be mitigated

TABLE I
Comparison of Existing Tools and the Proposed F-Tester® 4drive-box for Single-pass Measurements under Mobility

Tool / approach	RF-layer focus	Higher-layer metrics	Traffic configurability	Mobility behaviour
Nemo / R&S ROMES	Strong focus on detailed RF and protocol KPIs	Throughput, latency, and application tests as add-on features	Limited; predefined test jobs, TCP/IP stack behaviour mostly hidden in UE/OS	Mobility supported, but continuous, gap-free IP time series in a single pass are not an explicit design goal
Speedtest-like tools	No explicit RF metrics (only via device)	Basic DL/UL throughput and RTT only	None; traffic pattern and parameters are fixed and proprietary	Independent short tests, no continuous logging or session persistence across mobility events
RFC-based approaches	No RF metrics; protocol specifications only	Describe protocol behaviour (e.g., TCP, QUIC), not concrete measurements	High in principle, but no ready-to-use implementation for field drive testing	Do not directly address handovers or IP address changes; require additional system design
F-Tester® 4drive-box (this work)	Selected RF indicators from the modem as complementary context	Detailed IP/TCP statistics (throughput, RTT, OWD, jitter, loss, CWND, etc.)	High; fine-grained control of active traffic using iPerf3 and FlowPing (CC, timeouts, flows, patterns)	Designed for continuous, gap-free measurements and stable IP sessions during single-pass drive tests under mobility

much more quickly (in a matter of seconds rather than tens of seconds). That opens up a much more efficient way to test TCP behavior when terminals are in motion, without user intervention.

Another tool suitable for testing in a mobile network is our own FlowPing [27], which can inject specific data patterns into the network via the UDP protocol and then obtain current throughput, RTT, one-way delay, jitter, and packet loss. This tool can be used to effectively emulate user or device communication and its activities on the network.

The combination of these two tools can be used to probe, assess, and stress-test a dynamically changing transmission channel and obtain a comprehensive set of data from a moving measuring terminal.

III. Proposed Measurement Methodology

A. Measurement System Description

We used the F-Tester® 4drive-box, which is based on our four F-Tester® units, to collect the data. Three wireless measurement units (FTW1, FTW2, and FTW3) were used to measure the 4G/5G mobile network, and the fourth unit (FTO) was used as an orchestrator to control the measurements. The measurements were performed on a server located in the university's 10 Gbps backbone network. This setup can collect the dataset mentioned above, along with other benefits, such as the option to choose the TCP version (congestion algorithm) used for testing. For measurement in a real scenario, especially during a *single-pass* drive test, it is necessary to maintain communication under rapidly changing conditions, since there is no opportunity to repeat the same route under identical conditions. To prevent complete measurement failure, it is necessary to mitigate various connection issues. To do so, it is necessary to fine-tune the measurement tools with various timeouts, and it is advisable to have an infrastructure that automatically restarts tests after a connection failure. The whole measurement set is shown in Fig. 1.

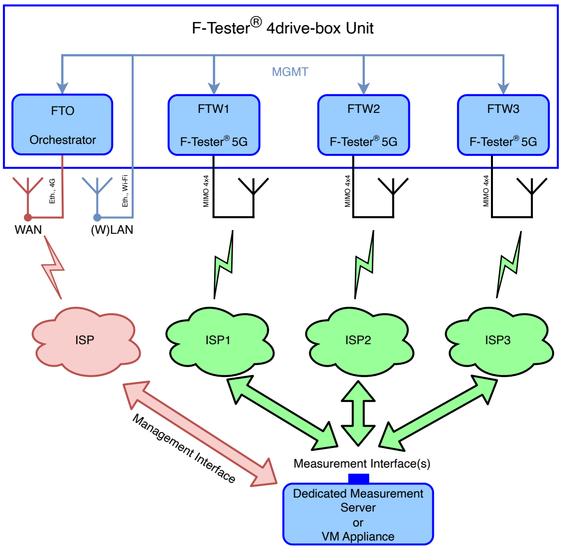

Fig. 1. Diagram of the F-Tester® 4drive-box setup for parallel measurements across three mobile operators' networks. The F-Tester® measurement system is highlighted in blue, the monitored mobile networks in green, and the independent configuration channel between the measurement device and server in red.

The hardware configuration of the F-Tester® unit measuring units is based on a reliable computer platform with sufficient computing power and the ability to operate as a mobile measuring device in cars and trains. The complete configuration and its features are described on the project webpage [28].

The interaction between the individual internal components of the F-Tester® 4drive-box is described in detail in Fig. 2. We obtain data from the measurement system at various layers of the RM ISO/OSI. The basis is data from the FlowPing and iPerf3 measurement applications. We supplement the information from the measurement data flows with data from the physical layer of the mobile network and information describing the behavior of the higher layers of L3 (IP protocol) and L4 (TCP or UDP protocols) of the operating system. All data is collected through a unit called the Orchestrator. This unit is also responsible for managing the launch and supervision of running tests, ensuring the maximum possible completeness of data. The interaction between the individual layers of the RM ISO/OSI described above is critical for reliable and precise measurements during user terminal movement.

The measurement and data collection process in the user terminal is performed by four key blocks in the infrastructure, which are described in detail in the following chapters.

1) FlowPing: First, we collect data from the FlowPing tool. It is used to generate a stable UDP stream in request/reply mode with minimal impact on the measured network. The expected output consists of upstream and downstream data transferred per interval, RTT, one-way delay, jitter, loss rate, and out-of-order packets. The FlowPing tool [29] can be used to determine the actual response of the measured network to a specific data flow. For measurements in mobile networks, we use this tool to analyze network response as a function of packet size and frequency. In this measurement, we take advantage of the fact that changes in RTT in the network signal change the behavior of buffers along the way [30]. Mobile networks are known for significant buffering with respect to handovers [31], [32]; therefore, even a low bit-rate flow can capture nuances in RTT changes.

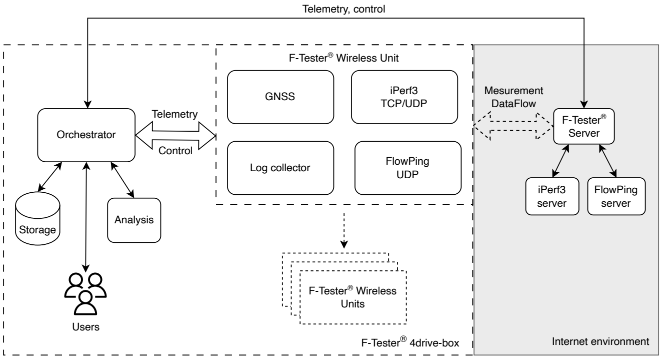

Fig. 2. Basic topological diagram of the interconnection of individual modules of the F-Tester® 4drive-box measuring system.

We also implemented a new feature to measure one-way delays, which is useful for distinguishing the distributions of communication delays between upstream and downstream directions. However, in the early stages of implementation, some problems remain unsolved, such as precise time synchronization between remote units, which can cause time drift, especially at the beginning of the measurement, as the convergence of common SNTPs is not fast enough [33]. The issue of accurate time transfer in wireless networks, including mobile networks, remains a pressing problem, as demonstrated by the measurements presented in this article [34].

A very powerful feature of the FlowPing application is the ability to set the reporting interval down to sub-second precision. Within the scope of the measurements, the reporting interval can also be reduced to the per-packet level, providing very detailed information about packet processing in the data network.

2) iPerf3: In the second block, we collect data from the iPerf3 tool. A tool for TCP or UDP measurement. It is used to fill the remaining network transmission capacity with multiple TCP or UDP streams. The TCP pressure on the network can be easily controlled by calculating the required number of streams and appropriate TCP window sizes based on the bandwidth-delay product (BDP). To get an idea, we recommend the study RFC 1072 [35], although some flow optimization is still necessary for network measurement under rapidly changing conditions. In addition, changing the default congestion avoidance (CA) algorithm used by TCP can be beneficial for measurements. The expected output consists of throughput in a specific direction, RTT, TCP window scaling, retransmissions, and other metrics.

Our settings align with the conclusions of [36] that using a smaller receive window size (RWND) leads to more efficient TCP transmission in networks with significant RTT fluctuations, typically in mobile networks when the terminal is in motion. Another significant factor affecting TCP efficiency in a mobile environment is the CA algorithm used. Commonly used, the Cubic algorithm is problematic in terms of loss occurrences, and much better transmission performance is achieved with time-based algorithms such as BBR [37]–[39].

TCP Cubic is currently the most commonly used TCP congestion algorithm [40]. Most Linux distributions use it as their default congestion algorithm. The BBR algorithm is also increasingly being deployed, mainly on Google's infrastructure. Both algorithms are now fully supported by the Linux/Unix ecosystem and the MS Windows environment. In terms of user experience measurement, TCP Cubic appears to be the more objective algorithm, and we use it in most comparative measurements.

The final choice of the congestion algorithm depends on whether you want to measure maximum throughput or prioritize the user experience, with settings similar to those of the user system. This topic is very well demonstrated by the results of TCP CA performance measurements in the Starlink network [41].

TABLE II
GNSS Samples per 50 m Distance

Speed	Update Rate		
	1 Hz	5 Hz	10 Hz
Walking (5 kmph)	36	179	357
City (50 kmph)	4	18	36
Rural (90 kmph)	2	10	20
Highway (130 kmph)	2	7	14
High Speed Train (230 kmph)	1	4	8

3) GNSS: The third block collects data from the Global Navigation Satellite System (GNSS). The Galileo and GPS constellations are activated by default in the measurement device. The system collects data on position and movement; this data is also used to obtain the exact time for synchronizing all measurement units. Data is collected using the NMEA-0183 protocol via a Universal Serial Bus (USB) modem interface. The interface supports position updates at up to 10 Hz. This update frequency enables position recording even at higher speeds and can capture measurements along high-speed train corridors with sufficient points. The number of measured points for drive tests correlates with the methodology used by the Czech regulator [2]. Table II shows the number of measured points for each individual velocity at a reference distance of 50 m.

If the measurement system consists of multiple measurement units, the GNSS block is active only in the device that orchestrates the measurements, ensuring a single, accurate time source throughout the system. The measurement units are synchronized with this source via Ethernet and the NTP/SNTP protocol.

4) Log Collector: In the last block, we collect telemetry data from the operating system runtime environment and all communication interfaces. A USB interface connects the modem to the computer, providing sufficient transfer speed and reliability. Several virtual channels used by individual applications/services are encapsulated in a single physical USB interface. The measurement data interface also has its own channel. The individual channels share a single physical interface, so it is crucial that they do not interfere with one another. Modern modems have USB version 3.0 and higher interfaces available. Even the basic version of USB 3.0 offers a speed of 5 Gbps on the physical layer, from which a throughput of up to 4 Gbps can be realistically achieved [42].

Information about the physical layer of the mobile network is available through the QMI (Qualcomm MSM Interface) and the Hayes AT command interpreter. The QMI interface enables higher-intensity data collection, but the basic open-source implementation of qmilib lacks the necessary functions for collecting diagnostic data. Using AT commands, the Qualcomm SDX family of chipsets can obtain detailed information on carrier aggregation, modulation, and MIMO (Multiple-Input Multiple-Output) configuration. If a more detailed analysis is required, the Qualcomm debug interface can be used. However, given the volume of data generated, this interface is not particularly suitable for use with measurements performed at higher layers. The large volume of data transferred significantly impacts the performance of both the measurements themselves and the collection of diagnostic data.

TABLE III
Log Collection Intervals [s]

Data Source	Minimum Collection Interval
Modem (QMI)	hundreds of ms
Modem (UART, AT)	lower units of second
Modem (UART, GNSS)	hundreds of ms
OS Environment (sysfs)	lower hundreds ms
FlowPing	per packet / miliseconds*
iPerf3	one second (sub-second unreliable)

The frequency of telemetry data acquisition is limited by the type of interface used. When reading data from the operating system, information is refreshed in the lower hundreds of milliseconds. If data is acquired from the QMI interface, a resolution of hundreds of milliseconds can be achieved. Data collection using the AT command is limited to units of seconds. For a large amount of information, sampling and subsequent averaging also occur directly in the system; therefore, more frequent data collection does not make sense. A number of parameters can also be obtained as events when they change; thus, it is not necessary to include them in the system loop. Typical data collection intervals in individual parts of the system and applications are listed in Table III.

Measurement during movement is a complex process that requires evaluating the behavior of higher layers. Very often, the modem appears to be connected at the physical layer, but the measurement does not take place. This is usually caused by a broken or frozen data channel. This event can be detected by collecting data at the TCP/IP stack level of the operating system. These conditions can be corrected during measurement by disconnecting and reconnecting the modem or by restarting it completely. Information about higher-layer behavior is obtained from the sysfs infrastructure and can be retrieved at intervals of hundreds of milliseconds.

After adding all the above, we create a comprehensive dataset. This is an output that we can obtain from the F-Tester® device [28], which is in development in our department. Due to its compatibility with the measurement methodologies of the Czech Telecommunication Office, it is also currently used to monitor the quality of mobile networks in the Czech Republic [2].

B. Reliability of Measurements During Movement

The TCP/IP protocol exhibits specific and dynamic behavior in mobile network environments, particularly during the movement of the measurement device. Movement significantly degrades signal quality, leading to instability in the data channel. These fluctuations affect physical layer parameters, increasing error rates, reducing overall channel capacity, and causing substantial changes in round-trip time.

This behavior worsens during motion: short signal outages extend into longer periods, potentially resulting in TCP connection interruptions or “freezing”—where the network interface remains active, but no data passes through the data channel. Another problem in mobile networks is the change of the IP address during a connection. The communicating counterpart is not informed of this change and therefore continues to send data to the original IP address; as a result, the connection is frozen. Restoring communication is usually straightforward (e.g., restarting the measurement application or reconnecting to the mobile network), but reliable detection remains challenging.

Default timeouts in operating systems and network applications range from tens of seconds to hours [43], which are unacceptable for drive tests — even the loss of short measurement intervals (1 s per ČTÚ methodology [2]) distorts results. Our system includes specialized routines that detect outages across all layers (1-4) with a response time on the order of seconds, ensuring measurement continuity even in dynamic mobile network environments. A comparison of default values and values optimized for mobile environments in the Linux operating system is shown in Table IV.

The problem with the above modification of TCP/IP stack parameters is their global effect on all established connections. This is not always desirable. Since version 3.10, the iPerf3 program has used the *snd-timeout* and *rcv-timeout* parameters to set timers for waiting for confirmation of sent and received data. Version 3.19 added support for detecting stuck control

TABLE IV
KEY LINUX NETWORK TIMEOUT PARAMETERS (STANDARD VS MOBILE OPTIMIZED)

Parameter	Default	Mobile Optimized
tcp_retries2	15 (∼13 min)	3 (∼30 sec)
tcp_fin_timeout	60 sec	10 sec
tcp_keepalive_time	7200 sec	20 sec
tcp_keepalive_intvl	75 sec	10 sec
tcp_keepalive_probes	9	3

connections via TCP keepalive and the *–cntl-ka* parameter. These parameters can thus effectively influence the robustness of TCP and UDP communication in a mobile network using iPerf3.

The proposed single-pass methodology and the F-Tester® platform are specifically designed for longer campaigns and larger-scale deployments. The system continuously logs all KPIs at 1-second intervals, supports simultaneous measurements across multiple operators, and is routinely used for multi-hour mobile drive tests, as demonstrated by datasets published on the Czech Telecommunication Office (CTU) measurement portal [44].

C. Measurement Configuration

1) Basic Setup Parameters: Since the measurement was carried out while driving a car, the details matter. The antenna system used was assembled from three identical multiband omnidirectional 4x4 MIMO antennas, which are designed for GSM/UMTS/LTE/5G. The frequency range is 698 MHz to 3800 MHz, with a gain of 3.5 dBi. The antennas were placed in the trunk of the car. This setup is suboptimal for achieving maximum network performance, but one should keep in mind that the typical car user faces similar conditions. An example of a measurement setup is shown in Fig. 3. The measurement took place on Wednesday, 6 September 2023, between 9 am and 4 pm.

Most measurements were taken while the car was moving. The measuring car was driven close to the speed limits in the corresponding areas (50/90/130 kmph). The visualized route passages are shown in Figures 4 and 5.

2) Detailed Configuration of Measurement Data Flow: The measurement data stream is constructed to verify the parameters of the dynamically changing communication channel as the user terminal moves. The constant data stream is generated by the FlowPing application (version 2.9.1) upstream and downstream, and transmitted over UDP. The error and delay measurements of the lightly loaded channel in both transmission directions are performed using a 512 kbps data stream with a constant packet size of 536 B. The amount of packets generated corresponds to a rate of 238 pps for each direction.

The TCP protocol with the Cubic congestion control algorithm fills the available downlink transmission capacity. The TCP window was set to 128 kB, and the maximum segment size (MSS) was 1200 B. The measurement was performed using three parallel streams. The chosen TCP stream configuration was rather restrictive. The bandwidth-delay product was calculated with a throughput of 25 Mbps per stream and an average RTT of 40 ms, corresponding to an unloaded real 4G/5G non-standalone (NSA) network. The measurement application used was iPerf3 (version 3.14).

Fig. 3. The image shows the F-Tester® 4drive-box measurement platform with three 4x4 MIMO multiband measurement antennas and one 2x2 MIMO antenna with an integrated GNSS antenna connected to the orchestration unit. The entire setup is located in the trunk of a car. This placement better reflects the user experience with the mobile network inside the vehicle.

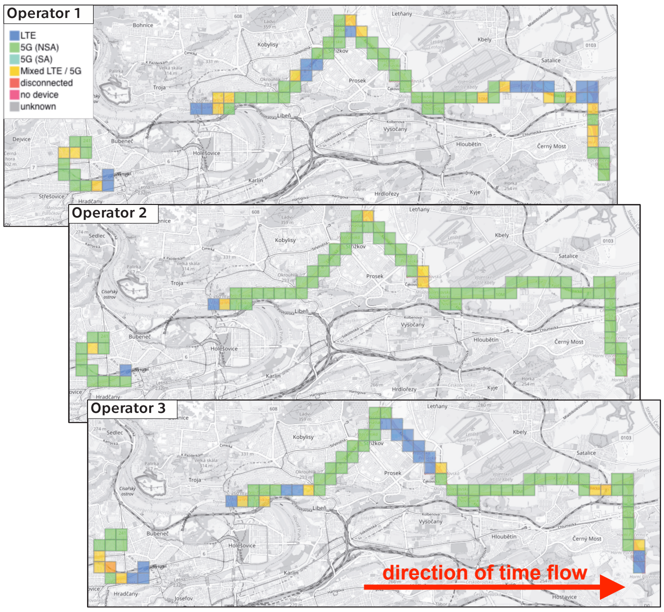

Fig. 4. Mobile network coverage of selected path part in Prague (Capital city). Square size set to 300 m. The arrow indicates the direction of movement corresponding to the flow of time.

3) Data Collection Interval: The data collection interval is set to 1 second, which corresponds to the data collection from the measurement applications setup. With the selected interval, we can cover all common measurement scenarios for walk and drive tests, as shown in Table II (1 Hz). The number of measured points for drive tests correlates with the methodology used by the Czech regulator [2] for car drive testing.

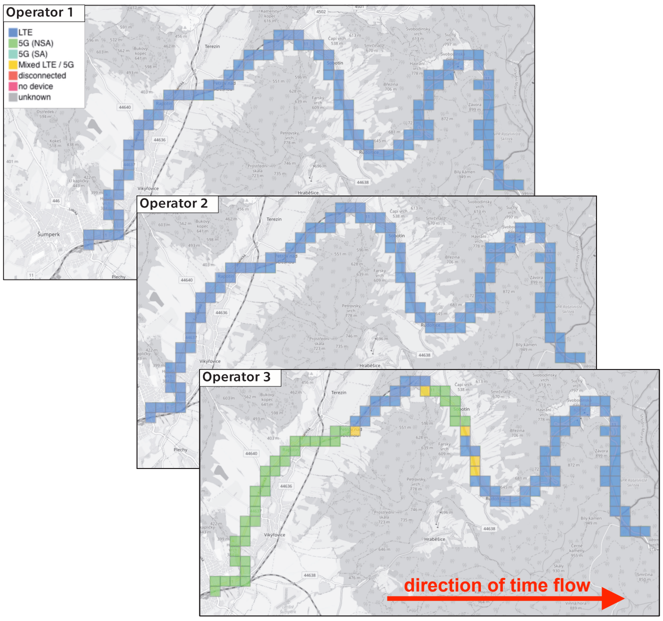

Fig. 5. Mobile network coverage of selected path part in Šumperk (town) and vicinity of Jeseník Mountains. Square size set to 300 m. The arrow indicates the direction of movement, corresponding to the flow of time.

IV. Network Performance

The data collection approach mentioned provides a detailed insight into mobile network performance in specific locations. This allows for a detailed analysis of how telecommunications operators compete with one another in both urban and rural areas.

A. QoS - Point of View

The measurement uses TCP and UDP protocols to inspect a broad spectrum of network behavior, including connection-oriented and connectionless data transmission, mirroring real-world Internet usage.

The study included downstream and upstream data throughput measurements, critical for understanding the network's capacity to support various user demands, from content consumption to content creation.

Measurements of signal strength and signal-to-noise ratio (SNR) between operators provide a direct comparison of network coverage and quality. These metrics are instrumental in assessing the clarity of the communication channel and the potential for data transmission errors.

The provided datasets enable the investigation of network performance using key indicators such as jitter and RTT. Jitter measurements highlight the network's stability, which is crucial for applications requiring consistent timing, while RTT provides insights into latency, which affects user experience in real-time communications.

Packet loss was monitored as a reliability metric to assess the network's reliability. The majority of TCP protocols (those with loss-based congestion algorithms) can suffer significant performance degradation when packet losses occur, making this metric a vital indicator of network health.

B. QoE - Point of View

Transmission speed, with reasonable responsiveness and stability, is crucial for the general public's understanding of network performance. These metrics serve as the basis for our analysis, providing clear insight into the perceived quality of telecom services. By focusing on transmission speed, we aim to present a straightforward metric that users can easily relate to and understand. On the one hand, the transmission speeds of higher-layer protocol payloads are what concern the common user the most. On the other hand, the user will not be fully satisfied with decent stability, as it is a crucial factor for a seamless online experience, ensuring that services like video calls and online gaming are smooth and uninterrupted.

V. Measurement Platform Validation

The reliability of the proposed measurement platform was verified at the radio layer by comparing modem-reported metrics with those from a certified Rohde & Schwarz TSMA6 mobile network scanner during an independent drive-test campaign along a 169 km railway corridor between Plzeň and Kolín. The datasets from both systems were paired using mobile network generation (4G/5G), PCI, and GNSS-based spatial bins of 50 m × 50 m, and then aligned in time by applying a small constant offset that maximized the correlation between samples while keeping the residual timing deviation in the order of 0.01–0.03 s.

Figure 6 shows a comparison of RSRP measurements between the R&S TSMA and data collected directly from 5G modems in F-Tester® units. The measurements were taken along the train corridor between Plzeň and Kolín on February 28, 2024, and illustrate the close agreement between both data sources over the entire route.

The correlation between RSRP (and related RF indicators) obtained from the TSMA6 and the F-Tester® modems was consistently high, confirming that modem-based RF telemetry is sufficient for assessing radio conditions in the context of QoS/QoE measurements. A more detailed description of the validation setup, pairing procedure, and statistical evaluation can be found in [5]. Based on these results, we consider the F-Tester® 4drive-box a suitable and trustworthy source of RF-layer information for the single-pass drive tests and demonstration presented in this work.

TABLE V
Distribution of 5G and LTE Coverage in Urban (Prague) and Rural (Jeseník Mountains) Environments.

Location	Operator	5G Coverage [%]	LTE Coverage [%]
Prague	1	64	36
Prague	2	71	29
Prague	3	69	31
Jeseník	1	0	100
Jeseník	2	0	100
Jeseník	3	12	88

VI. Results

The provided dataset offers valuable data for evaluating and comparing the mobile networks of the main mobile service

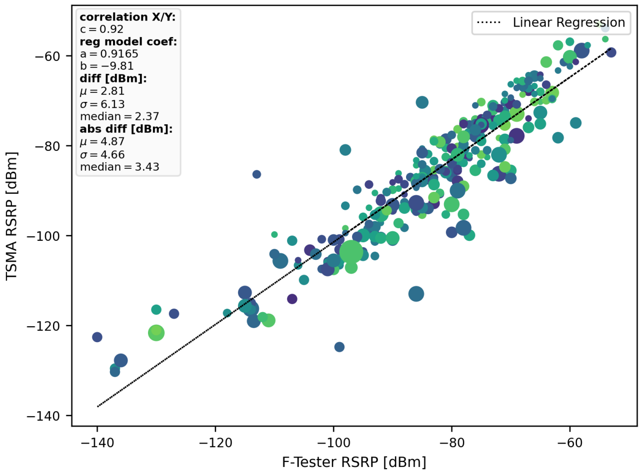

Fig. 6. Comparison of RSRP measurements between the R&S TSMA and data collected directly from 5G modems in F-Tester® units. Measurements were taken along the train corridor between Plzeň and Kolín on February 28, 2024.

providers in the area. It contains information on network throughput, RTT, and one-way delay. (The accuracy of one-way delay measurement depends on the quality of time synchronization among measurement units. Longer convergence time can be expected for synchronization methods based on the NTP protocol.) The dataset also includes jitter, loss, out-of-order packets, TCP window scaling, TCP retransmissions, Signal SNR, RSSI, RSRP, RSRQ, Cell information, MIMO, Bands, Bandwidth, GNSS coordinates with precision indicators, system load information, and more. Some of the available results are briefly described in the following sections.

It should be noted that our measurement campaigns are designed as single-pass drive tests along each route. In practice, this means that repeating the measurements under identical radio and traffic conditions is not feasible. This is especially true in urban and highway environments. As a consequence, our data processing is based on spatial and temporal aggregation, with a sampling and logging interval of 1 s. We do not use repeated trials, which are suitable for classical statistical inference, such as confidence intervals or hypothesis testing.

The primary objective of this work is not to provide an exhaustive statistical comparison of operators. Instead, we aim to demonstrate a methodology for continuous, gap-free data collection under high mobility. We also validate the completeness and usability of the resulting dataset. The dataset is made publicly available for more advanced statistical and cross-layer analyses in future studies, such as CDF-based evaluations and hypothesis testing across multiple campaigns.

A. *Signal Type*

Table V indicates a higher 5G coverage in highly populated areas, which is an expected result that shows the ongoing transition to 5G in cities and the dependence on LTE in less populated areas. Graphically, the signal coverage is shown in Figures 4 and 5 in a display mode with squares measuring 300 m on each side.

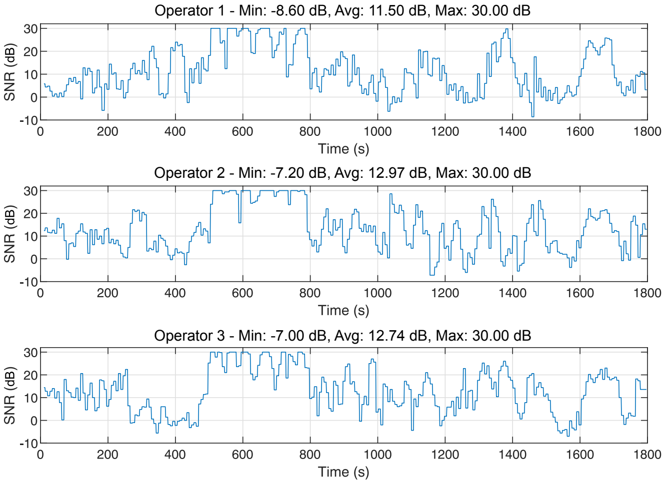

Fig. 7. Comparison of the SNR between operators in the Prague area.

B. *SNR and Other Signal Related Metrics*

The Signal-to-Noise Ratio (SNR) data illustrated in the accompanying graphs for Prague and the Jeseník Mountains region provide a compelling narrative about the signal quality of three major telecom operators.

Simple examples of SNR data processing for the Prague and Jeseník Mountains areas are shown in Fig. 7 and Fig. 8. Since GNSS coordinates are available, it is also possible to pinpoint signal data to exact locations. Other dataset metrics, such as SINR and RSSI shown in Table VI, as well as RSRP and RSRQ, can also be used to compare signal quality. These RF-layer observations are directly reflected in the higher-layer behaviour: regions with low or LTE-only coverage, as indicated in Table V and Figures 7 and 8, systematically coincide with reduced TCP throughput and increased RTT variability in the corresponding parts of the routes.

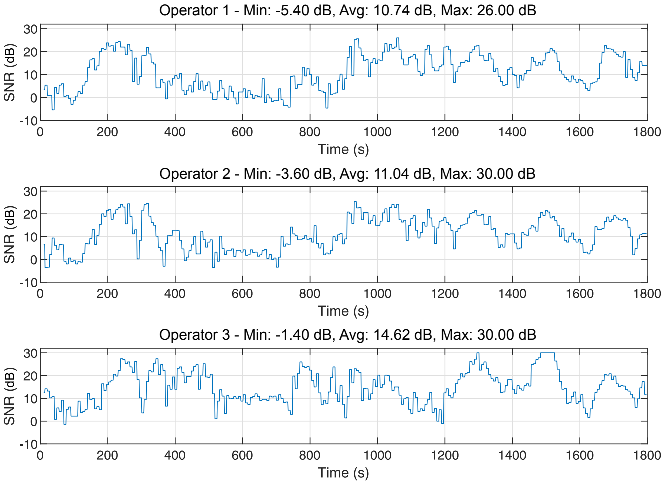

Fig. 8. Comparison of the SNR between operators in the Jeseník Mountains area.

C. *Round Trip Time*

As expected, our analysis revealed a significant difference in network performance between urban and rural settings, as

TABLE VI
RECEIVE SIGNAL SENSITIVITY PERFORMANCE COMPARISON IN URBAN AND RURAL SETTINGS.

Location	Operator	Min. [dBm]	Avg. [dBm]	Max. [dBm]
Prague	1	-78	-53	-27
Prague	2	-74	-51	-25
Prague	3	-78	-53	-27
Jeseník	1	-90	-60	-29
Jeseník	2	-86	-63	-31
Jeseník	3	-90	-60	-29

evidenced by TCP and UDP RTT measurements. The situation is clearly illustrated by the statistical data in Table VII. The actual evolution of RTT for the TCP protocol for all operators can be seen in Figures 9 and 10.

TABLE VII
MEASURED ROUND-TRIP TIME IN PRAGUE AND THE JESENÍK MOUNTAINS.

Protocol	Location	Operator	RTT [ms]		
			Avg.	5%ile	95%ile
TCP	Prague	1	34	20	72
TCP	Prague	2	53	28	109
TCP	Prague	3	66	27	203
TCP	Jeseník	1	132	36	371
TCP	Jeseník	2	115	36	326
TCP	Jeseník	3	102	30	375
UDP	Prague	1	38	21	85
UDP	Prague	2	58	32	128
UDP	Prague	3	70	28	208
UDP	Jeseník	1	150	38	396
UDP	Jeseník	2	133	37	330
UDP	Jeseník	3	246	33	571

As UDP RTT measurements better reflect the actual state of the network, we give them more credibility in network evaluation. The resulting RTT is calculated from the query-response relationship for each packet. With TCP, RTT is calculated from confirmed segments, which may not reflect individual packets; however, confirmation may be delayed and occur for larger blocks of data. Therefore, the measured RTT is higher than the per-packet calculation would indicate. In particular, pronounced RTT spikes often occur in segments where the SNR drops and the connection falls back to LTE, which is consistent with the increased buffering and more frequent handovers expected under such radio conditions.

The striking contrast in RTT, especially the elevated 95th percentile values in rural areas, highlights the varying reliability of network services by location and underscores the importance of optimizing networks in specific areas.

D. CWND/RWND

The Congestion Window (CWND), a TCP network protocol metric that regulates the number of packets sent before receiving an acknowledgment, provides information on network traffic management. Compared to CWND, the Receive Window (RWND) indicates the amount of data that the receiving side can receive and process. Examining CWND and RWND helps us understand how a network adapts to congestion, which in turn affects throughput and user experience.

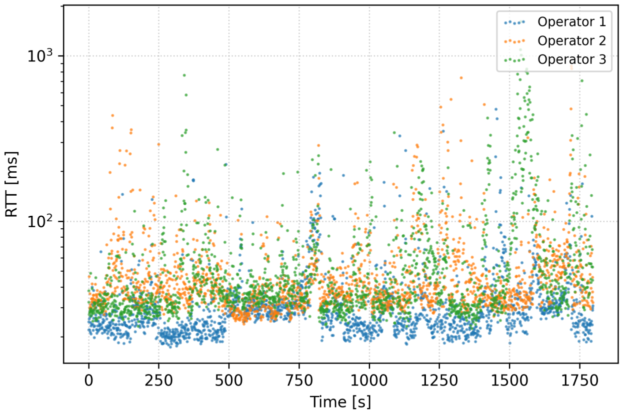

Fig. 9. Comparison of the RTT when moving a terminal between operators in the Prague area. (Logarithmic scale)

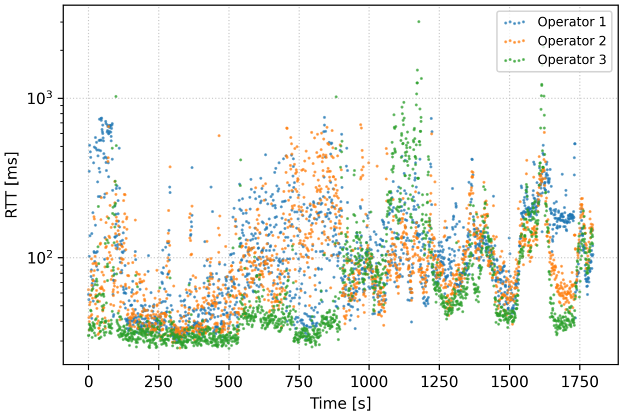

Fig. 10. Comparison of the RTT when moving a terminal between operators in the Jeseník Mountains area. (Logarithmic scale)

The dynamics of change in these indicators are crucial in assessing the availability of system resources for communicating parties and the parameters of the communication channel. Proper management of both windows significantly increases transmission efficiency.

The scaling behavior of the CWND for the measurement flows during the terminal movement is illustrated in Figs. 11 and 12. Correlated with the sufficient signal levels shown in Figs. 7 and 8, as well as network capacity, the CWND remains stable around the target value of 128 kB. As signal conditions degrade, the scaling of the CWND intensifies, with the most aggressive reductions occurring at the highest signal drop locations, which are subsequently reflected in the resulting throughput shown in Figures 13 and 14.

CWND values exceeding the target of 128 kB occur in locations with significant data transmission attenuation. Within the Fast Recovery and Fast Retransmit algorithms, larger bursts are required to compensate for losses. This phenomenon is most pronounced in the Jeseník Mountains, where signal levels are generally weaker, as shown in Fig. 12 around 50 seconds for operators 2 and 3.

The observed reductions and slow recovery phases of the

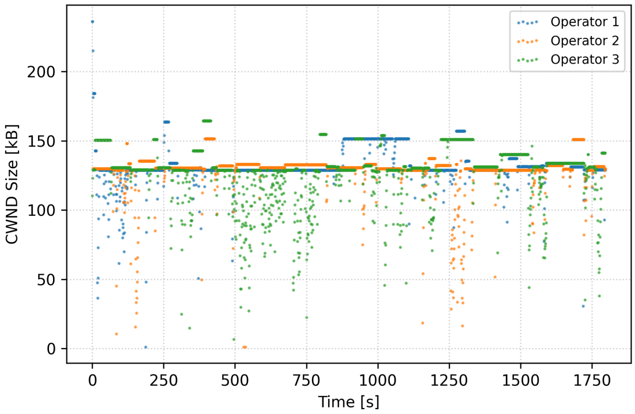

Fig. 11. Comparison of CWND scaling when moving a terminal between operators in the Prague area.

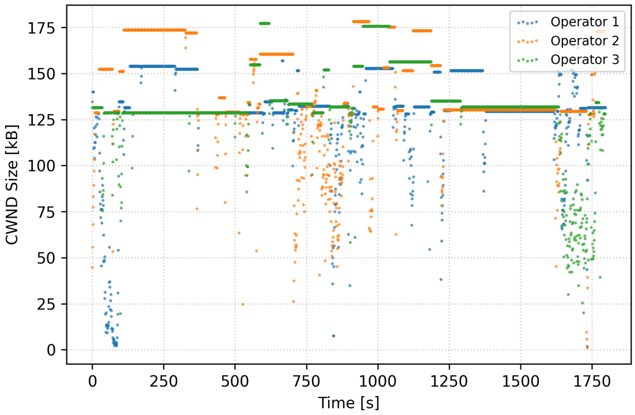

Fig. 12. Comparison of CWND scaling when moving a terminal between operators in the Jeseník Mountains area.

congestion window typically appear in route segments with degraded RF conditions or technology fallback, again illustrating how PHY-layer dynamics directly constrain TCP's ability to utilize the available capacity during mobility.

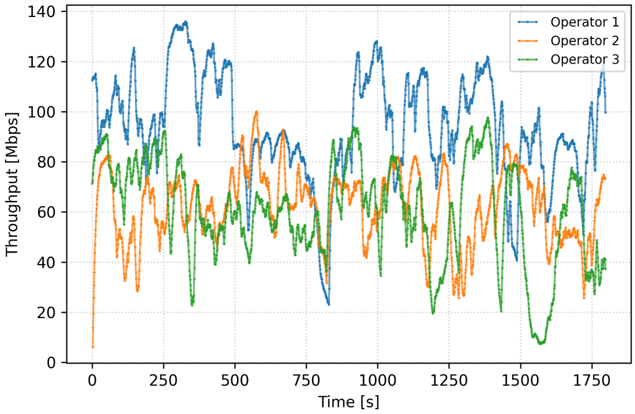

Fig. 13. Comparison of the TCP throughput when moving a terminal between operators in the Prague area.

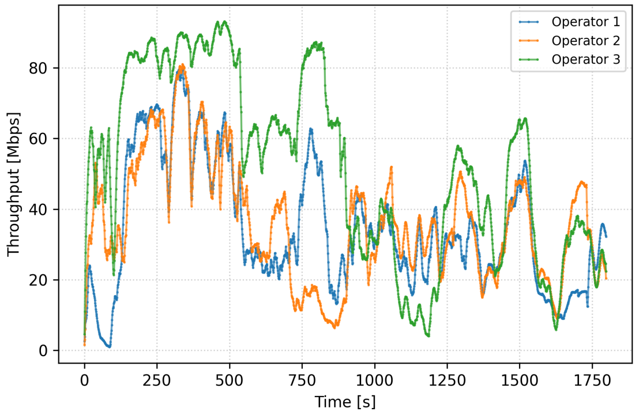

Fig. 14. Comparison of the TCP throughput when moving a terminal between operators in the Jeseník Mountains area.

E. TCP Throughput

Evaluation of single TCP throughput measurements and comparisons among different network operators provides an overview of network efficiency, as shown in Figures 13 and 14. Greater throughput variation typically indicates network inconsistencies or areas with weaker signal coverage.

When we pair the TP data with the GNSS coordinates, we can evaluate network throughput in a specific location. As expected, better service coverage, along with more up-to-date technology in more populated areas, brings higher network throughput.

Overall, the throughput traces confirm that good radio conditions with stable 5G coverage enable sustained high TCP rates, whereas low-SNR or LTE-only segments lead to noticeable throughput degradation, even though the IP-level measurement streams remain continuous and gap-free.

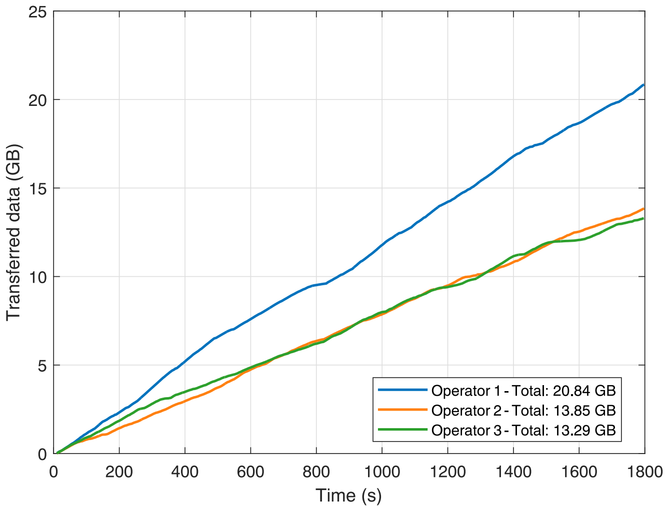

Fig. 15. Comparison of the amount of data between operators in the Prague area.

F. Data Transferred

The total amount of data transferred does not fully capture the complexity of network performance but reflects the current overall network capacity. It serves as a key indicator of user satisfaction, as shorter data transfer times clearly improve the experience. Due to the system's capability to continuously transmit data, the graphs Fig. 15 and Fig. 16 show the evolution of cumulative transmitted data growth over time (during the movement of the measuring terminal). The displayed graphs reveal distinct growth patterns for different operators at the same locations and times.

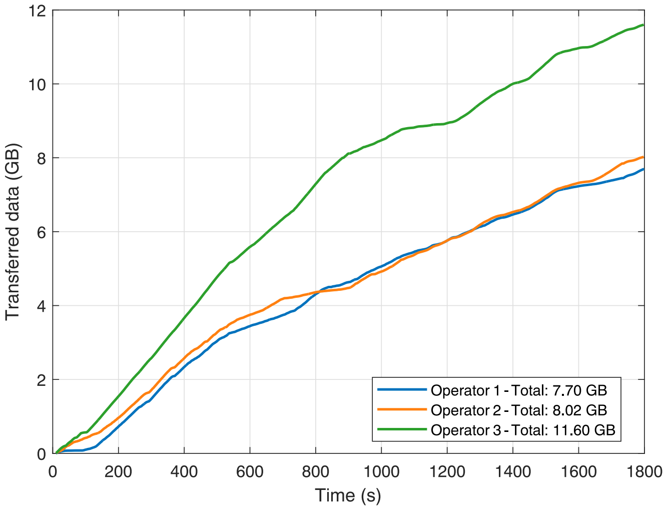

Fig. 16. Comparison of the amount of data between operators in the Jeseník Mountains area.

VII. Conclusion and Future Work

This paper outlined measurement methods for mobile networks using the iPerf3 and Flowping applications, along with techniques to maintain measurement reliability during signal outages and capacity drops. The proposed single-pass measurement approach enables consistent TCP/IP measurements in networks with rapidly changing parameters, such as mobile networks during terminal movement, while keeping configuration overhead low and avoiding repeated drives over the same route. By maintaining active TCP data flows during movement and correctly handling outages, the data provides valuable insight into user-perceived transmission quality.

The selected measurement methodology correlates data with specific locations and integrates information from physical and link layers with stress-testing tools, producing comprehensive datasets suitable for deeper analysis. Combined with the single-pass strategy, this makes the approach well-suited for large-scale drive campaigns where time, cost, and reproducibility are critical constraints. A device such as the F-Tester® simplifies data acquisition from complex setups and significantly reduces drive-test duration. The published open dataset [3], which features baseline comparative measurements across diverse terrains, supports the optimization of TCP/IP transmission properties and mobile network configurations.

The results presented here, gathered using F-Tester® , show the advantages of using complex data acquisition across different network layers. The gathered data allow researchers to distinguish between network generations deployed across the urban (Prague) and rural (Jeseník) areas. Datasets provide sufficient data to perform a comparative study of the state of network infrastructure for the three major Czech telecom operators in 2023. It is possible to highlight substantial disparities in coverage, radio conditions (SNR, RSSI), and end-to-end performance (throughput, RTT, CWND behaviour) between urban and rural areas, and across operators based on the provided data.

The results also enable operator-level comparisons at specific locations, helping both operators identify where to improve their networks and users select the most suitable network for their needs. Beyond standard performance metrics, it is possible to investigate the specifics of TCP congestion algorithms, revealing weak spots in networks. Exploiting CWND dynamics further shows different traffic management strategies: more aggressive congestion window growth in urban networks and more conservative behaviour in rural networks to accommodate higher latencies and lower capacities. Overall, the study's data confirm significant progress in urban network infrastructure, identify clear areas for improvement in rural networks, and underline the need for continued investment to bridge the urban–rural service gap.

While we demonstrate selected cross-layer effects by jointly interpreting RF indicators, TCP metrics, and throughput under mobility, a more systematic, quantitative cross-layer analysis is intentionally left for future work and is enabled by the publicly available dataset introduced in this paper.

This work opens several directions for future research. First, we plan to extend the measurement campaign towards the key function of mobile networks, namely voice services, by including VoLTE, VoNR, and popular OTT applications such as WhatsApp and Viber, with a focus on continuous QoE-oriented measurements. Second, we aim to automate the analysis pipeline on top of our publicly available dataset to gain deeper insight into correlations among individual data sources (physical and data channels, location, operating system state, and application-layer performance). Finally, a significant challenge lies in optimizing the temporal synchronization of measurement units to enable accurate one-way delay measurements in mobile networks. Our future work targets the deployment of high-precision synchronization methods, including the Precision Time Protocol (PTP) and GNSS-disciplined clocks, to overcome the limitations of NTP/SNTP and further improve the accuracy and usability of the collected datasets.

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