



Study of methods and techniques for assessing and verifying coverage by radio communication services

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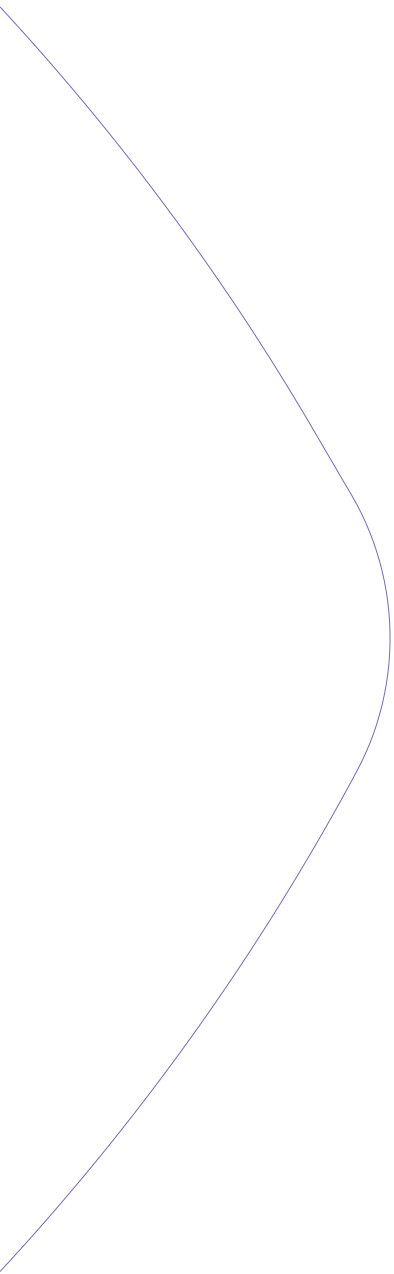
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Executive summary

Monitoring the radio spectrum and radio signal coverage of a geographical area is crucial for ensuring the efficient and safe use of radio frequencies. The radio spectrum is a limited natural resource that must be managed to prevent interference between the various services and applications operating within it. This is particularly important today, when many sectors rely on the long-distance transmission of information via wireless networks. These typically include industry, public safety, defence and, of course, meeting the communication needs of private end-users.

Monitoring radio signal coverage of a geographical area is, in principle, well managed today. Methodologies and adequate tools exist. However, the problem lies in the increasing number of monitored frequency bands, the demands for accuracy and speed of monitoring, and the growing volume of monitored parameters. These growing demands are leading to a search for new monitoring techniques that would build on existing ones or serve as a complement to them.

Based on the terms of reference and taking into account technological developments in this field, the study focuses on selected methods of determining and verifying coverage, which include the use of satellites and drones, the use of software tools, and the processing of large volumes of data. The study also examines the possibilities for determining the interdependence of monitored parameters for the evaluation of services provided according to new criteria. In preparing the study, the main focus was on mobile service coverage, particularly 5G services.

In the Czech Republic, monitoring is carried out primarily by measuring signal levels at various locations using portable measuring devices, by measurements using vehicles equipped with specialised measuring technology, by evaluation using software tools and mathematical models in the form of coverage level prediction, and also by monitoring the status and performance of the network in real time.

Within the framework of new techniques for hardware monitoring of mobile network radio signals, the study focuses on the use of satellites and drones. Satellites are currently proving to be practically unusable for radio spectrum monitoring. The reasons are primarily technical – minimising the radiated power from mobile base stations into the space segment – and economic – the development and operation of solutions deployed in the space segment of the communications network. However, in connection with the growing focus on the use of space, demands are also being placed on the development of space telecommunications. This will also lead to the need to develop and implement appropriate technical methods for monitoring the radio spectrum. Drones appear to be a viable means of monitoring in specific cases where monitoring via standard drive or walk tests is not possible in mobile wireless networks. Suitable measuring instruments are currently available on the market and measurement methodologies exist. However, the current legislation lacks exemptions for selected state authorities and institutions. A specific example is the Czech Telecommunications Office (ČTÚ), which is responsible for radio spectrum monitoring. The Office does not have an exemption to carry out measurement flights and must, for example, seek the landowner's consent to operate a drone where there is a source of radio interference on their land (e.g. an unauthorised transmitting station).

Verifying coverage of a geographical area using software tools is now a widely used method for the planning and operation of wireless/mobile networks. Practice shows that there are discrepancies between simulation results and measured values in real-world terrain and operational conditions. Given the differing calculation methodologies and input parameters used, there are discrepancies in the conclusions reached by individual mobile operators and, of course, in relation to the regulatory authority, the Czech Telecommunications Office (ČTÚ). It would be beneficial to standardise the initial conditions through appropriate amendments to the current legislation and, in cooperation with the Czech Office for Surveying, Mapping and Cadastre (ČÚZK), to create a publicly available 'reference' terrain model. Machine learning and elements of artificial intelligence are currently used in some software and simulation tools. The part of the study focusing on the use of more advanced technologies and software tools was, following discussions with the client, directed towards testing voice communication, where there is a current need for innovation in measurement equipment. Voice transmission quality testing is currently based on the same methodologies across various suppliers. Solutions for monitoring communication network parameters differ only minimally among renowned multinational manufacturers. Nor do tools for data acquisition, processing and visualisation differ significantly in terms of their functionality.

The study also examines ways of linking existing methodologies for monitoring mobile network radio interface signal parameters with new criteria for evaluating the services provided, which better reflect the end-user's perspective and their satisfaction with the service. As the analysis of a selected data sample has shown, simultaneous and correlated verification of radio parameters and quality of service parameters is possible, but requires the processing of large amounts of data from various locations to yield meaningful conclusions. Drive tests generate data with a wide dynamic range and variations along the measurement trajectory. In this case, data averaging plays a major role, which is currently performed on a reference grid of squares. From the relationship between data throughput (achieved transmission speed) and the level of the base station's transmitted reference signal, it is possible to broadly determine the threshold values of the parameters of interest, at which a significant percentage of end-users will achieve the required service level.

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Measuring the coverage of a geographical area by radio signals, and the continuous monitoring and evaluation of service parameters, are essential tasks associated with ensuring the operation of wireless electronic communications networks and the efficient use of the spectrum. Consequently, this also relates to consumer protection.

We recommend continuously monitoring developments in the field of methods and techniques for determining and verifying coverage by radio communication services, particularly international standards, measurement methods, evaluation techniques and simulations. In particular, focus on the following:

- In light of the growing importance of fixed LTE and fixed 5G, analyse measurement and testing requirements in this area, including in the context of VHCN networks and conditions.
- In connection with the growing development of private 5G networks, particularly in industry, analyse measurement and testing requirements in this area, including in the context of the expected use of the 26 GHz band.
- When using drones, strive to expand their usability, including by introducing exemptions in current legislation for conducting measurement flights.
- Initiate a more detailed analysis of simulation and measurement tools and their results among operators and the CTO with the aim of harmonising baseline conditions, methodologies and criteria.
- Analyse in greater detail and on an ongoing basis the relationships between radio parameters and quality of service parameters, leading to the validation and, where necessary, modification of coverage limits. For these purposes, optimise the methodology for measuring data transmission parameters.
- In connection with the growing focus on the use of space, address the issue of radio spectrum management in space telecommunications, taking into account the outcomes and study results of the WRC-27 and WRC-31 radio communication conferences, as well as the development of satellite technologies and support for their applications in science, research, industry and services.

Management summary

Monitoring the radio spectrum and the coverage of a geographical area by radio signals is a key factor in ensuring the efficient and safe use of radio frequencies. The radio spectrum is a limited natural resource that needs to be managed to avoid interference between the different services and applications that operate on it. This is particularly important nowadays, when many areas depend on the remote transmission of information via wireless networks. Typically, this includes industries, public safety, defence and, of course, meeting the communication requirements of private end users.

Monitoring the coverage of a geographical area by radio signals is, in principle, well managed at present. Appropriate methodologies and adequate tools exist. However, the problem lies in the increasing number of frequency bands requiring monitoring, the demands on the accuracy and speed of monitoring, and the higher volume of monitored parameters. These growing requirements are prompting a search for new monitoring techniques to build upon or complement existing ones.

Based on the terms of reference and taking into account technological developments in this field, the study focuses on selected methods of coverage detection and verification, including the use of satellites and drones, software tools and the processing of large volumes of data. Furthermore, the study examines the possibilities of establishing the interdependencies between monitored parameters for the evaluation of services provided in accordance with the new criteria. The study focused on mobile service coverage, particularly 5G services.

In the Czech Republic, monitoring is carried out mainly by measuring signal levels at various locations using portable measuring devices and vehicles equipped with specialised measuring equipment, followed by evaluation using software tools and mathematical models that predict coverage levels, and by observing the status and performance of the network in real time.

In the context of new techniques for hardware monitoring of radio signals in mobile networks, the study focuses on satellites and drones. Currently, satellites are considered practically unusable for monitoring the radio spectrum. The reasons are mainly technical – the minimal power emitted by mobile base stations to the space segment – and economic – the development and operation of solutions located in the space segment of the communication network. Of course, given the growing interest in the use of space, the development of space telecommunications is a legitimate requirement. This will necessitate the identification and implementation of appropriate technical methods for monitoring the radio spectrum. Drones appear to be a more practical tool for monitoring in specific cases where standard drive or walk tests are not feasible in mobile wireless networks. Currently, suitable measuring tools are available on the market and measurement methodologies exist. However, there are no exemptions for selected government authorities and institutions in current legislation. A specific example is the CTO (Czech Telecommunication Office), which is responsible for managing the radio spectrum. The office does not have an exemption to carry out measurement flights and must, for example, seek permission to operate a drone from a landowner who has a source of radio interference on their land (e.g. an unauthorised transmitting station).

Verification of geographical coverage using software tools is now a viable method for planning and operating wireless/mobile networks. Practice shows that there are differences between simulation results and measured values in real-world field and operational conditions. Given the different calculation methodologies and input parameters used, there are discrepancies in the conclusions drawn by various mobile operators and, of course, the CTO. It would be beneficial to standardise the initial conditions through appropriate amendments to current legislation and to create a publicly available 'reference' terrain model in cooperation with the ČÚZK (State Administration of Land Surveying and Cadastre). Some software and simulation tools utilise machine learning and elements of artificial intelligence. Based on discussions with the client, the part of the study focusing on the use of more advanced technologies and software tools centred on voice communication testing, where there is a current need to upgrade measurement equipment. Voice quality testing is nowadays based on the same methodologies across different vendors. The solutions for monitoring the parameters of communication networks vary only minimally between reputable international vendors. Even the tools for data acquisition, processing and visualisation do not differ significantly in terms of their functionality.

The study also examines the possibilities of reconciling existing methodologies for monitoring the parameters of mobile network radio interfaces with new criteria for evaluating the services provided, which more closely reflect the end user's perspective and satisfaction with the service. As the analysis of a selected data sample has shown, simultaneous and correlated verification of radio parameters and quality of service parameters is possible but requires the processing of large amounts of data from different locations to draw meaningful conclusions. Drive tests generate data with a wide dynamic range and variations along the measurement trajectory. In this case, data averaging, which is currently performed on a reference grid of squares, plays a major role. From the dependence of the data throughput (achieved data rate) on the level of the transmitted reference signal from the base station, it is possible to determine the threshold values of the parameters of interest for which a significant percentage of end-users will achieve the desired level of service.

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Measuring the coverage of a geographical area by radio signals, continuous monitoring and the evaluation of service parameters are essential tasks related to ensuring the operation of wireless electronic communications networks and the efficient use of the spectrum. Consequently, this also relates to consumer protection.

It is recommended to continuously monitor developments in methods and techniques for detecting and verifying the coverage of radiocommunication services, in particular international standards, measurement methods, evaluation techniques and simulations. Specifically, the following should be addressed:

- In the context of the growing importance of fixed LTE and fixed 5G, analyse the measurement and testing needs in this area, including in relation to VHCN networks and conditions.
- In the context of the increasing development of private 5G networks, particularly in industry, analyse the measurement and testing requirements in this area, including the anticipated use of the 26 GHz band.
- With regard to the use of drones, seek to expand their usability by introducing exemptions in current legislation for the performance of measurement flights.
- Initiate a more detailed analysis of simulation and measurement tools and their results from providers and the CTO to standardise baseline conditions, methodologies and criteria.
- To analyse fully and continuously the dependencies between radio and quality of service parameters leading to validation and possible changes to coverage limits. For this purpose, optimise the methodology for measuring data transmission parameters.
- In the context of the growing interest in space utilisation, address the issue of radio spectrum management in space telecommunications, taking into account the outcomes and study results of the WRC-27 and WRC-31 radiocommunication conferences, the development of satellite technologies and support for their applications in science, research, industry and services.

1 Introduction

1.1 The importance of verifying coverage of the territory by radiocommunication services

The survey and verification of coverage of the territory by radio communication services in the Czech Republic is carried out using commonly used methods and techniques (e.g. measuring signal levels at various locations using portable measuring devices, measurements using vehicles equipped with specialised measuring equipment that measure signal levels whilst driving, evaluation using software tools and mathematical models in the form of coverage level predictions, and real-time monitoring of network status and performance whilst simultaneously monitoring signal coverage).

As the aforementioned methods of determining and verifying coverage of the territory by radio communication services often contain inaccuracies, it is essential to identify and describe the most significant shortcomings in the study (in particular, under what conditions and at which locations these negative phenomena occur).

Consequently, there is a need to outline how to address these shortcomings and how to improve existing methods of determining and verifying coverage. Furthermore, it is necessary to propose and recommend the introduction of new methods and techniques, provided that such methods of determination and verification quantitatively and qualitatively improve the accuracy of coverage or, where appropriate, streamline the entire process.

Coverage verification is an important activity within the framework of spectrum management by the Czech Telecommunications Office, when assessing operators' compliance with development criteria for allocated frequency bands, but also from the perspective of consumer protection and monitoring compliance with contracts for the provision of electronic communications network services.

1.2 Objectives of the study

Based on the terms of reference and technological developments in this field, the study focuses on selected methods of determining and verifying coverage based on the following promising approaches:

- a) Spectral monitoring using satellites (obtaining results in real time).
- b) Use of drones for measurement (conducting measurements in hard-to-reach or hazardous areas).
- c) Using advanced simulation models (more sophisticated simulation models enable more accurate predictions for various scenarios).
- d) Techniques based on machine learning (automation of the coverage assessment process based on the analysis of large amounts of data).
- e) Using more advanced technologies (measuring and monitoring signal coverage with greater accuracy and sensitivity).
- f) Simultaneous and correlated verification of radio parameters and quality of service (QoS, or QoE) parameters.

The analysis focuses primarily on mobile service coverage, particularly 5G services. Alongside the analysis and technical aspects, the following information is summarised where available: countries in which the given survey method has been implemented, approximate implementation costs, other important facts and limitations (special hardware and software requirements, complexity of implementation, etc.).

1.3 Scope, focus and structure of the study

The study focuses on radio communication networks and radio communication services, primarily on LTE and 5G mobile networks. It is divided into key chapters, the first of which analyses the current state of affairs and sets out common starting points for the individual objectives of the study. These are then addressed in separate chapters with references to the common starting points. To ensure coherence, objectives c) and d) have been addressed in a single chapter. Specific issues and opportunities are outlined for each objective. Possible solutions and partial conclusions are proposed for these. The overall conclusions and proposed next steps are then summarised in the concluding chapter.

2 Analysis of the issue under consideration and general starting points

2.1 Monitoring of parameters in radio communication networks

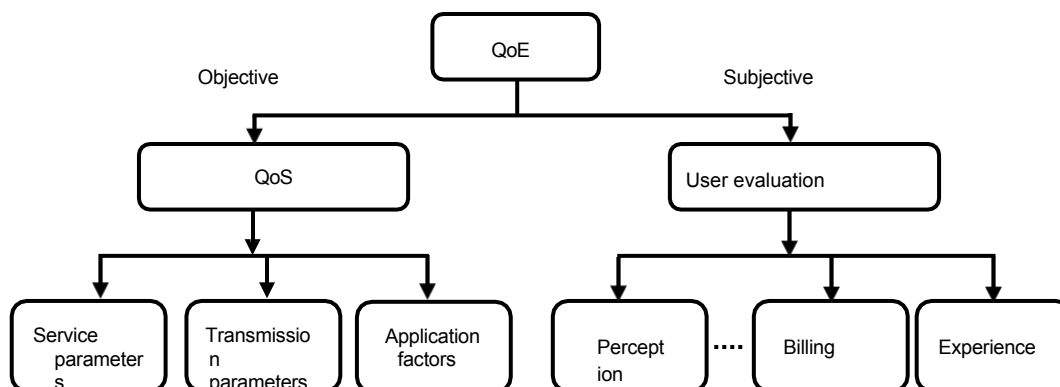
Radio communication networks represent a specific area of electronic communications networks. They utilise a radio channel in at least one segment (usually in the access part of the network) and signal propagation via electromagnetic waves through free space. The use of a radio channel carries a risk of communication outages and loss, exacerbated in many cases by the movement of users and the associated dynamic nature of the parameters. To ensure the required level of communication reliability, it is necessary to guarantee a sufficiently strong radio signal across the entire area of interest for moving users.

LTE and 5G technologies are key for modern mobile communication networks, significantly influencing the quality of services provided by public electronic communications networks as well as overall user satisfaction. LTE/LTE-A technology has brought a significant increase in data transfer speeds, reduced transmission latency and improved coverage compared to previous generations. It has also enabled technological convergence for various types of services, particularly data and voice (VoLTE, Voice over LTE). 5G NR (5G New Radio) technology, in turn, achieves even higher speeds, lower latency and the ability to connect many more devices simultaneously. These technological advances in mobile networks improve user satisfaction and have opened up new possibilities in previously undeveloped areas, such as private (campus) wireless networks.

2.1.1 Options for evaluating communication network and service parameters

An integral part of operating communication networks is the monitoring and verification of their operational parameters and the parameters of the services provided; for the radio parts of the network, this also includes signal coverage of the area of interest. It is possible to verify the relevant parameters using various methodologies, i.e. through defined principles and standardised procedures. Methodologies may focus on determining objective indicators, such as throughput, transmission delay, delay variation and bit loss. These parameters are essential for evaluating the level of service provided, i.e. Quality of Service (QoS). QoS parameters are a subset of the overall service evaluation by the end user and represent a technical perspective on network performance. The overall user assessment of the service – Quality of Experience (QoE) – includes not only objective QoS parameters but also the user's subjective assessment, which encompasses their perception of service quality based on personal experience. The subjective part of the QoE parameter is often measured through questionnaires and user feedback, providing valuable information on how users perceive network and service performance. The relationship between QoE and QoS is illustrated in the following figure.

Figure 1 – The fundamental relationship between QoE and QoS.



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The issue of QoS/QoE parameters in telecommunications is addressed by a number of International Telecommunication Union recommendations, starting with ITU-T Recommendation I.350 for ISDN networks. For transmission communication networks and facilities, QoS evaluation parameters are defined by ITU-T Recommendation G.1000. The follow-up ITU-T Recommendation G.1010 defines QoS parameters for connections in packet-switched networks, which provide a transmission environment for combinations of different types of services. From a QoS/QoE perspective, the following recommendations are important in telecommunications:

Table 1 – Table heading

Basic methodologies for IP-based services

G.1000	Communications Quality of Service: A framework and definitions
G.1010	End-user multimedia QoS categories
G.1011	Reference guide to quality of experience assessment methodologies
G.1020	Performance parameter definitions for quality of speech and other voiceband applications utilising IP networks
G.1021	Buffer models for the development of client performance metrics
G.1022	Buffer models for media streams on TCP transport
G.1028	End-to-end quality of service for voice over 4G mobile networks
G.1028.1	End-to-end quality of service for video telephony over 4G mobile networks
G.1029	Voice service diagnosis framework

Data and other services

G.1030	Estimating end-to-end performance in IP networks for data applications
G.1031	QoE factors in web browsing
G.1032	Factors influencing gaming quality of experience
G.1033	Quality of service and quality of experience aspects of digital financial services
G.1034	Quality of experience metrics for mobile telephony communication during rail travel
G.1035	Factors influencing the quality of experience for virtual reality services
G.1040	End-to-end network contribution to transaction time
G.1050	Network model for evaluating multimedia transmission performance over Internet Protocol
G.1070	Opinion model for video-telephony applications
G.1071	Opinion model for network planning of video and audio streaming applications
G.1072	Opinion model predicting gaming quality of experience for cloud gaming services
G.1080	Quality of experience requirements for IPTV services
G.1091	Quality of Experience requirements for telepresence services

From the perspective of the stakeholders, the issue of service evaluation can be divided into the following key areas:

- The access provider's domain – this refers to the entity providing the end-user's connection and transporting the service data. The relevant parameters can be divided according to individual communication layers – QoS evaluation.
 - Physical layer – signal strength, signal-to-noise ratio, bit or block error rate.
 - Higher communication layers – throughput (transmission speed), packet loss, transmission delay and jitter, etc.
- Service provider domain – the entity providing the requested service (application factors – video resolution, web service loading speed, etc.).
- Service user domain – this domain is assessed by Quality of Experience (QoE).
 - VoIP telephony – MOS parameter, E-model (R-factor according to ITU-T G.107 and related recommendations).
 - IPTV – MOS scale and other metrics (in accordance with ITU-T G.108x recommendations).
 - Web services – subjective evaluation (in accordance with ITU-T Recommendation G.1030).
 - etc.

2.1.2 MOS rating scale for QoE

The MOS (Mean Opinion Score) scale was originally developed for evaluating voice signal transmission services. Today, it is used for all available services and can be applied, for example, to the transmission of multimedia streams or the provision of web services, etc. Its use is important in the field of subjective evaluation of communication services. The rating scale is a point-based scale ranging from 1 to 5.

Table 2 – MOS scale for evaluating user perception of a service.

MOS rating		User-perceived quality
5	Excellent	Excellent
4	Good	Good
3	Fair	Average
2	Poor	Poor
1	Bad	Inadequate

In addition to its use for evaluating speech signals, ITU-T Recommendation P.800.1 defines MOS scales for:

- Interactive communication – supplementary symbol C (Conversational).
- Video (V).
- Audio (A).
- A combination of audio and video (AV).
- Values obtained by subjective evaluation – supplementary symbol S (Subjective).
- Values obtained by objective measurement – supplementary symbol O (Objective).
- Estimated quality based on a computational model – supplementary symbol E (Estimated).

In addition to MOS, other methodologies exist for evaluating services. Conversion relationships are defined between these and MOS (see E-model below).

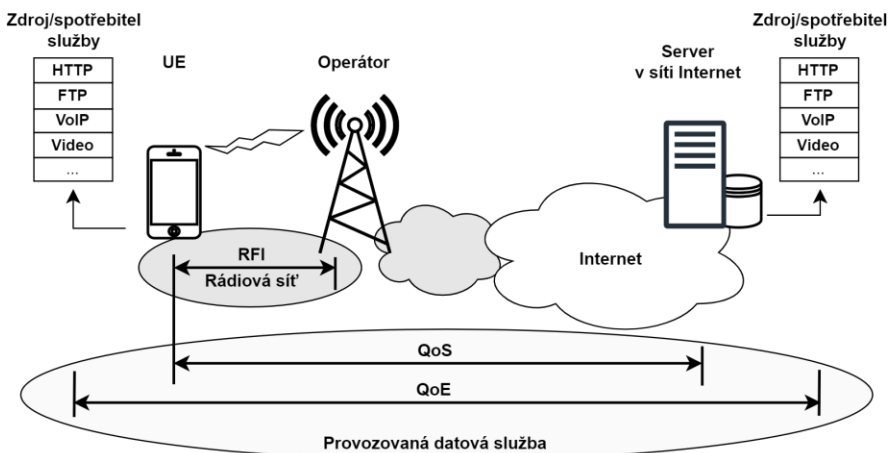
2.1.3 Network architecture and areas of parameter evaluation

Overall, the transmission chain in the provision of data and other digital services breaks down into a cascade of sub-segments (network components) and into communication layers (the RM-OSI communication model, or TCP/IP), as indicated in the following diagram¹. Mobile networks are characterised by a combination of a fixed part and a radio access network (RAN), where specific radio signal parameters (RFI) are measured.

¹ Document BoR (11) 53;BEREC ; A framework for Quality of Service in the scope of Net Neutrality; (<https://www.berec.europa.eu/en/document-categories/berec/reports/a-framework-for-quality-of-service-in-the-scope-of-net-neutrality>)

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Figure 1 – Schematic diagram of the network and areas of communication service evaluation.



LTE/5G NR technologies have, within their protocol architectures and control planes, implemented principles ensuring the monitoring and adherence to the required quality parameters of the transmission services provided. The end-user requires the provision of the service, i.e. requires the assurance of transmission parameters between both endpoints of the data link (end-to-end). Quality parameters are thus also influenced by the downstream network infrastructure. Monitoring of quality parameters must therefore be addressed in a broader context than, for example, just the radio interface of the mobile network. In this context, we distinguish between three levels of QoS evaluation² :

- QoS-1 – theoretical (expected, estimated) network performance – based on models and calculations.
- QoS-2 – measured by probes and elements excluding subscriber equipment.
- QoS-3 – measured including the subscriber part of the network.

2.1.4 Transmission parameters by communication layers

The complex problem of long-distance communication is simplified by breaking it down into sub-problems. One method, apart from dividing it into segments (sub-sections of the network, such as access, backbone, etc.), is to divide communication into sub-layers based on so-called layered communication models (ISO-OSI, TCP/IP). Nowadays, the TCP/IP layered model (or architecture) is generally used to meet the communication needs of end users. In accordance with the principles of the layered model, a number of methodologies for measuring relevant communication parameters at a specific communication layer have been established through historical development. It is therefore currently possible to determine the parameters of a given network communication layer using a specific methodology. Methodologies can also be classified according to whether they are applied whilst the network is in operation (In-Service, where the communication network also transmits data from regular users) or whilst it is not in operation (Out-of-Service, where the communication network transmits test data exclusively). Basic division into layers and examples of methodologies:

- The application layer – is the layer closest to the end user.
 - Speed meters are usually used to determine parameters at the application layer; these are often part of certain providers' and application servers' websites. They are also used to determine QoE parameters.
- Transport layer (L4) – TCP/UDP communication protocols are used.
 - TCP True Speed methodology RFC 6349.
- Network layer (L3) – the IP protocol is used.
 - In-Service mode – software tools such as IP Ping and Trace Route can be used.
 - Out-of-Service mode – software tools such as Iperf and Flowping can be used, as per ITU-T Recommendation Y.1540.

² Document BoR 20 (42); BEREC; Guidelines to assist NRAs on the consistent application of Geographical surveys of network deployments; (<https://www.berec.europa.eu/en/document-categories/berec/regulatory-best-practices/guidelines/berec-guidelines-to-assist-nras-on-the-consistent-application-of-geographical-surveys-of-network-deployments>)

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- Link layer (L2) – depends on the specific data transmission technology used at the lower physical layer. If, for example, Ethernet technology is used, the following can be utilised:
 - In-Service mode – monitoring in accordance with ITU-T Y.1731 (OAM – Operations, Administration and Maintenance, IEEE 802.1ag).
 - Out-of-Service mode – the RFC 2544 methodology supplemented by time-domain parameter measurements (e.g. delay jitter) and measurements enabling the generation of multiple concurrent flows.
 - Out-of-Service mode – SAM (Service Activation Methodology) in accordance with ITU-T Y.1564.
- Physical layer (L1) – ensuring bit-level data transmission at the physical layer is addressed depending on the type of transmission environment. For fixed networks, methodologies such as the following are used:
 - In-Service mode – monitoring of block error rates (e.g. from CRC protection) in accordance with ITU-T G.826.
 - Out-of-Service mode – BERT (Bit Error Rate Test) using PRBS (Pseudo-Random Bit Sequence) in accordance with ITU-T G.821.
- Transmission medium layer (L0) – signal parameters according to the type of transmission environment. For radio networks, these are RFI parameters.

The aforementioned standardised measurement methodologies for general monitoring of network and transport layer parameters can also be used in modern mobile networks with LTE/5G/5GNR technologies, as these methodologies are independent of the specific transmission technology used.

Methodologies for measuring physical (L1) and data link (L2) layer parameters are specific to the transmission technology used to implement the mobile network. Procedures for determining parameters are standardised in 3GPP (or ETSI) recommendations. For example, the determination of parameters at the data link layer is specified in:

- LTE – ETSI TS 136 314 (3GPP TS 36.314).
- 5G – ETSI TS 128 552 (3GPP TS 28.552).
- 5G NR – ETSI TS 138 314 (3GPP TS 38.314).

2.1.5 Radio interface parameters

As part of mobile network functionality testing, the physical layer parameters of the radio interface (RFI) can be monitored. The options for monitoring physical layer parameters depend on the transmission technology used (in accordance with the relevant standards). Typically, the following parameters are monitored:

- RSSI – Received Signal Strength Indication (signal power) (dBm) (2G, 3G and LTE).
- RSCP – Received Signal Code Power (signal power) (dBm) (3G only).
- RSRP – Reference Signal Received Power (signal power) (dBm) (LTE).
- RSRQ – Reference Signal Received Quality (signal quality) (dB) (LTE).
- EC/IO – Downlink carrier-to-interference ratio (signal quality) (dB) (2G, 3G and LTE).
- SINR – Signal-to-Interference-plus-Noise Ratio (signal quality) (dB) (LTE only).

In LTE networks, the parameters are linked to the CRS (Cell Specific Reference Signal). For 5G NR networks, SS (Synchronisation Signal) and CSI (Channel State Information) signals are used. The naming of LTE parameters is adjusted accordingly, for example to SS-RSRP/CSI-RSRP, etc.

2.1.6 Quality parameters at the network and transport layers

Given the TCP/IP architecture, the evaluation of data transmissions from the user's perspective takes place at the network and transport layers of the communication network. The fundamental basis for defining IP network parameters (L3) is ITU-T Recommendation Y.1540, which defines the following parameters:

- IP Packet Transfer Delay (IPTD).
- IP Packet Delay Variation (IPDV).
- IP Packet Error Ratio (IPER).
- IP Packet Loss Ratio (IPLR).

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- Spurious IP Packet Rate (IPSR).
- IPRR (Packet Reordered Ratio).
- IPDR (Packet Duplicate Ratio).

The transmission rate is calculated at the third layer, including the IP packet header:

- IP packet throughput (IPPT) and the corresponding IPRR ratio.
- Octet-based IP packet throughput (IPOT) and the corresponding IPOR ratio.

Recommendation Y.1540 also sets out a general methodology for breaking down parameters into individual parts of the communication chain, e.g. between individual parts of the backbone network and the access network, etc.

The measurement and evaluation of data transmission parameters at the transport layer are governed by RFC 6349 (Framework for TCP Throughput Testing), which defines a method also known as TCP True Speed. It utilises a suitable feature of the communication protocol, which employs the principle of acknowledging the delivery of data segments to the remote end of the link. The principle of acknowledgement also ensures regulation of the data flow according to the current state of the transmission network. A further advantage of measurement using the TCP protocol is that this communication protocol is used for communication by the vast majority of user applications, and the test results are therefore close to the user's actual perception of the service.

The following metrics and parameters are defined in RFC 6349:

- TCP throughput – the throughput/data flow rate measured at a specific point in the network during communication using the TCP protocol (in bits per second).
- RTT (Round-Trip Time) – the time difference between the sending of the first bit of a message to the recipient and the delivery of the last bit of the corresponding TCP segment acknowledgement (TCP Acknowledgment).
- BB (Bottleneck Bandwidth) – the lowest value of the transmission capacity of the entire measured route.
- BDP (Bandwidth Delay Product) – the product of the data link capacity (in bits per second) and the delay between the two ends of the link (in seconds).
- Send and Receive Socket Buffers – the size of the send and receive buffers.
- Minimum TCP RWND (Receive Window) – the size of the window for acknowledging received packets.
- MTU (Maximum Transmission Unit) – the maximum packet size usable for a data link (without the need for segmentation).

The transmission rate at the fourth layer (L4) is lower than at the lower layers (L3, L2, L1) due to the need to add additional service information for lower-layer communication protocols (packet and frame headers); it is also lower due to the application of TCP control mechanisms (gradual ramp-up of the data link's transmission rate) and is further reduced by error rates and the need to retransmit undelivered data, etc.

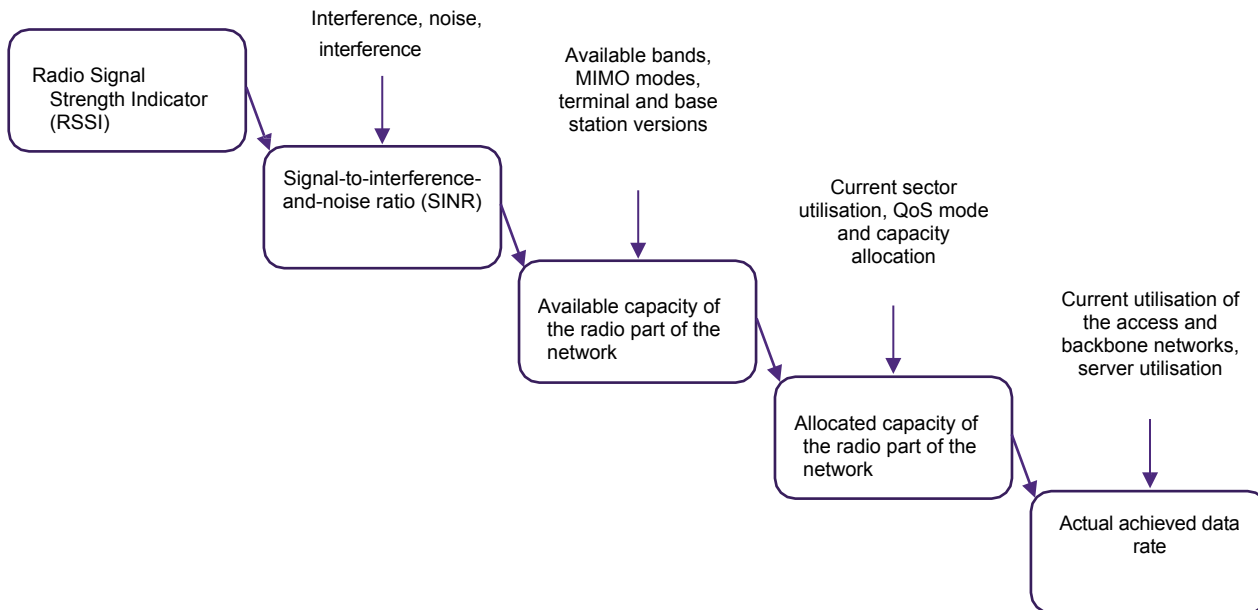
2.1.7 The relationship between radio parameters (RFI) and data transmission parameters (QoS)

The determination of parameters for radio communication service coverage is possible at various layers of the communication model, as mentioned above. Put simply, in radio communication networks we focus on the parameters of the radio physical layer (RFI), data transmission parameters and the service provided (QoS), or user satisfaction with the service provided (QoE).

In radio networks, and particularly in mobile networks, there are a number of factors that influence communication parameters. These are highly dynamic processes, whether in terms of changes at the radio interface (terminal movement, handover between base stations) or the load caused by concurrent traffic (sharing of resources at the radio interface, sharing of other parts of the network infrastructure). The following diagram illustrates the progressive accumulation of influences and factors from the radio interface to the network infrastructure.

It follows from the influences outlined that there are correlations between the parameters of the radio interface; however, it is necessary to take into account secondary influences and the nature of a multi-user environment with shared network resources, and to endeavour to identify the correct causal relationships.

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An important feature of LTE-A and higher-generation networks is the simultaneous use of multiple frequency bands (the 'carrier aggregation' method – CA). The resulting data rate is the sum of the individual data rates across multiple bands, and it is not possible to simply distinguish the individual transmission speeds. Each frequency band generally exhibits different RFI parameters. Terminals typically display the received signal strength for the primary band in which network registration and signalling take place. In rural areas, this is mainly the 800 MHz band, or possibly the 700 MHz band; in urban areas, it is also the 1800 MHz band.

2.1.8 Metrological considerations

When measuring radio networks and evaluating their quality parameters, it is important not only to select a suitable methodology, measurement and diagnostic equipment, but it is also necessary to include the possible error in the received data (measurement results) within the assessment or decision-making process. Whether it is a statistical error or a measurement error, it must be quantified and incorporated into the assessment or decision-making rules. In the case of measured data, this involves quantifying the so-called **expanded measurement uncertainty U** , which is assigned to the measured value X and, with sufficient probability (e.g. >95%, with a coverage factor $k = 2$), guarantees that the true value of the measured parameter lies within the interval $X \pm U$.

Another important aspect is the metrological traceability of measuring instruments and the parameters they control (measure). Metrology and measurement error are reflected in the rules for assessing the conformity of a network or service with the prescribed specification.

Metrological traceability is prescribed, for example, by the *ISO 9001 standard Quality Management Systems – Requirements*, which describes rules for quality control, metrological traceability and risk management measures. Metrological traceability, the balance of measurement errors and uncertainties, and decision-making rules when making statements of conformity with prescribed specifications are addressed in a number of documents available on the website of the Czech Accreditation Institute.

Metrological traceability of a measuring instrument is ensured by its calibration – comparison with a metrological standard. When measuring radio parameters, this essentially involves determining the amplitude of the received signal, i.e. measuring the alternating electrical voltage at a given frequency and at a reference input impedance. It is also important in the measurement process to account for the influence of the receiving antenna and its feedline.

When measuring data transmission parameters, the aim is to determine the value of the time variable, specifically in the case of delay measurement (the time difference between the moment of sending and receiving a data unit). When determining transmission speed values, the task involves counting units of information – bits per unit of time – so, once again, calibration of the meter's time base is a prerequisite (a sufficiently accurate oscillator for generating the reference frequency).

Another key point is that measurements in mobile networks are generally carried out whilst in motion, during which parameters change dynamically, and the results are then evaluated either as an average per unit of time, or as an average projected onto a geographical unit in the form of a square (e.g. measuring 100 x 100 m). Even when measurements are taken at a stationary point, the measured values fluctuate over time (typically due to changes in propagation, reflections, but also changes in network load and the network's internal regulatory mechanisms). It is therefore not possible to use the standard method of statistical evaluation, which assumes a stable measured quantity with fluctuations caused by measurement inaccuracies.

2.2 Methodologies and criteria for testing and evaluating coverage by radiocommunication services

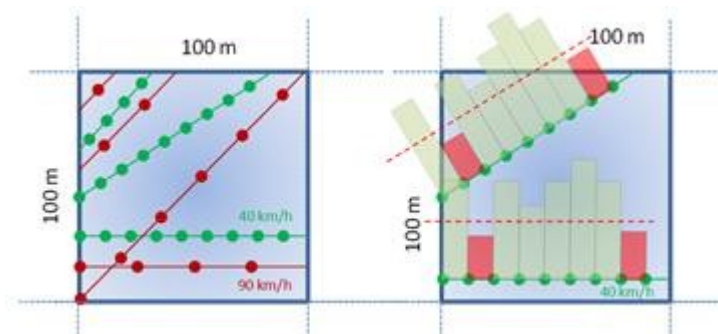
2.2.1 CTU methodologies and documents

In addition to communication standards and general quality assessment methods, methodological guidelines issued by the CTO exist for the area addressed in the study. Signal coverage is defined within the terms of auctions in the form of so-called 'development criteria', which form part of the relevant tender procedures for the use of radio frequencies. For LTE technology, this is the 2013 tender for the 800, 1800 and 2600 MHz frequency bands³ and the 2016 tender for the 1800 and 2600 MHz bands⁴. For 5G technology, this is the 2020 tender for the 700 MHz and 3400–3600 MHz frequency bands⁵. The methodology for measuring mobile networks is the subject of the CTU's 2013 document "Procedure for measuring data transmission speeds in mobile networks according to the LTE standard"⁶ and the CTU methodology from 2021 "Methodology for the measurement and evaluation of data parameters of mobile electronic communications networks" in version 2.3⁷. The basic procedures involve the measurement of radio parameters and data transmission parameters whilst driving and at a fixed point.

2.2.2 Grid method

The grid method is used to evaluate territorial coverage; this involves quantising the area into elements with a side length typically of 100 x 100 m or 50 x 50 m⁸. Standard coverage simulators provide their outputs in this grid, and measurement results are evaluated in the same grid. However, during on-the-move measurements, data is generated continuously, typically at 1-second intervals. The number of points measured in a specific square, and the number of values used to determine the average value for that square, therefore depend on the speed of movement. The path of movement during measurement may pass through a specific sub-section of a square, but the result is extrapolated to the entire area of the square. These aspects must be taken into account. Greater accuracy could be achieved by dividing the area into smaller squares; however, this would entail greater computational complexity for coverage simulations and the need to reduce speed during drive tests, which is undesirable not only in terms of measurement efficiency but also due to the potential disruption to road traffic.

Figure 2 – Schematic diagram of the evaluation of communication services.



³ Document ČTÚ-77 777/2013-613; Announcement of a tender for frequencies in the 800 MHz, 1800 MHz and 2600 MHz bands (2013); (<https://ctu.gov.cz/vyhlaseni-vyberoveho-rizeni-2013>)

⁴ Document Ref.: ČTÚ-1/2016-613; Announcement of a tender procedure for the award of rights to use radio frequencies to provide a public communications network in the 1800 MHz and 2600 MHz bands; (<https://ctu.gov.cz/aukce-2016-pasma-1800-2600-mhz>)

⁵ Document ČTÚ-38 426/2020-613; Announcement of a tender procedure for the granting of rights to use radio frequencies to provide electronic communications networks in the 700 MHz and 3400–3600 MHz frequency bands; (<https://ctu.gov.cz/aukce-700/vyhlaseni>)

⁶ Procedure for measuring data transmission speeds in mobile networks in accordance with the LTE standard; (<https://ctu.gov.cz/sites/default/files/obsah/ctu-new/ochrana-spotrebitele/kontrola-a-mereni/mereni-rychlosti-prenosu-dat-lte-2013-08-15.pdf>)

⁷ Document ČTÚ-10 330/2021-622; Methodology for the measurement and evaluation of data parameters of mobile electronic communications networks, ver. 2.3 ; (<https://ctu.gov.cz/sites/default/files/obsah/ctu-new/ochrana-spotrebitele/kontrola-a-mereni/metodika-pro-mereni-a-vyhodnoceni-datovych-parametru-mobilnich-siti-ek-2-3.pdf>)

⁸ Document BoR 20 (42); BEREC Guidelines to assist NRAs on the consistent application of Geographical surveys of network deployments (<https://www.berec.europa.eu/en/document-categories/berec/regulatory-best-practices/guidelines/berec-guidelines-to-assist-nras-on-the-consistent-application-of-geographical-surveys-of-network-deployments>)

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The relationship between grid cell size, measurement trajectory, measurement vehicle speed, number of measurement points, and the determination of average transmission speed during a drive test is evident from the figures for a measurement period of 1 second.

2.2.3 Limits for radio parameters

To objectively assess the coverage of an area by a radio signal, the RSRP and SINR values of the reference signal are measured. The limit values for the parameters vary depending on the frequency band and are based on the applicable ETSI and 3GPP standards. The specific conditions for verifying coverage of a geographical area and the population are set out in the tender documents for the use of individual frequency bands.

The conditions and procedures for verifying compliance with the required criteria when operating communication technologies are comprehensively set out in Annex No. 5 to "Announcement of a tender procedure for the granting of rights to use radio frequencies for the provision of electronic communications networks in the 700 MHz and 3400–3600 MHz frequency bands". The document summarises the method for evaluating population coverage, territorial coverage and linear infrastructure. From the perspective of RFI parameter measurements, it provides information on:

- Parameters of the measuring antenna and its location.
- Corrections and conversions of measured parameters (site power balance, measurements in border areas, corrections for conversion to in-building signal levels, etc.).

The table below provides a basic summary of the relevant parameters for individual site types and mobile reception, taking into account a 4 dB margin in RSRP reception.

Table 3 – Limit values for radio parameters

Frequency band	RSRP for uninhabited areas [dBm]	RSRP for populated areas [dBm]	RSRP for road corridors [dBm]	RSRP for railway corridors [dBm]	SINR [dB]
700 MHz	-118	-109	-118	-114	-5
800 MHz	-118	-109	-118	-114	-5
900 MHz	-118	-109	-118	-114	-5
1800 MHz	-118	-107	-118	-113	-5
2100 MHz	-118	-106	-118	-113	-5
2600 MHz	-118	-105	-118	-112	-5
3400–3800 MHz	-118	-100	-118	-109	-5

2.2.4 Limits for data communication parameters

The radio interface of the network infrastructure provides a data transmission service, i.e. it transmits bits in a wireless environment. Compliance with the specified criteria on the radio interface is therefore necessary (sufficient signal level and SINR), but not entirely sufficient to ensure end-user satisfaction with the data transmission service as a whole.

Just as the parameters of the radio interface are specified, the parameters of higher communication layers are also specified in individual tenders for the allocation of radio frequencies.

For the measurement of data transmission parameters at higher communication layers in mobile networks, a measurement methodology exists – the CTU document: Methodology for the Measurement and Evaluation of Data Parameters of Mobile Electronic Communications Networks, version 2.3.

For networks based on LTE technology, the CTU document "Procedure for measuring data transmission speeds in mobile networks according to the LTE standard" sets the minimum value for downlink data transmission speed per mobile device and per SIM card at 5 Mbit/s.

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For 5G technology, operating in the 700 MHz and 3400–36020 MHz frequency bands, Annex 5 of the tender sets the maximum transmission delay between the terminal and the peering centre at RTT = 25 ms (round-trip time).

At European level, the BEREC document 'Guidelines on Very High Capacity Networks'⁹, BoR (23) 164, 5 October 2023, which also covers wireless networks connecting fixed terminals and defines data communication parameters for these cases (criterion 2 – base station connected via optical fibre, criterion 4 – other cases of wireless networks where the base station is not connected via optical fibre).

⁹ [https://www.berec.europa.eu/system/files/2023-10/BoR %2823%29 164 FNE WG_Draft BEREC Guidelines on VHCNs.pdf](https://www.berec.europa.eu/system/files/2023-10/BoR_%2823%29_164_FNE_WG_Draft_BEREC_Guidelines_on_VHCNs.pdf)

3 Spectral monitoring using satellites

In accordance with its terms of reference, this section of the study focuses on a basic assessment of the possibilities for using satellite technologies to measure the coverage of the ground segment of mobile radio communications.

Given the development of space-based telecommunications, attention is also paid to the potential use of satellite technologies across the full range of requirements for radio spectrum monitoring tasks in the field of satellite radio communications.

Radio spectrum monitoring is one of the key sources of information and data for managing the spectrum at a global level in accordance with the Radio Regulations of the International Telecommunication Union (RR ITU¹⁰) and for its implementation at regional and national levels. It is therefore a source of information necessary for the development of plans for its effective use and for monitoring to ensure non-discriminatory access by terrestrial and space-based radio services to allocated portions of the radio spectrum, including orbital positions, undisturbed radio transmission of radiocommunication services, and for the drafting of relevant national legislation.

Therefore, this section of the study goes beyond the scope of the assignment to focus on trends in the use of satellites in the near future for the comprehensive task of radio spectrum monitoring within the activities of the ITU and the European Space Agency (ESA¹¹) and an example of satellite application in the Hungarian SMOG-P project, which focuses on monitoring space radio pollution generated by terrestrial radio equipment in the UHF band, is also described.

3.1 Basic characteristics of satellites and their applications

3.1.1 Classification of satellites

Depending on flight altitude, the following classification of orbits is used:

- a) Low Earth Orbit (LEO): 160–2000 km, used by small satellites (CubeSat, Orbcomm, meteorological satellites, Earth observation satellites, etc.). Their lifespan ranges up to 3 years, depending on their purpose.
- b) Medium Earth Orbit (MEO): 2,000–35,786 km, telecommunications (Inmarsat, Iridium, Global Star mobile networks), navigation (GPS, Galileo, Glonass, Beidou), sensor monitoring. The lifespan of satellites ranges between 5 and 6 years.
- c) High Earth Orbit (HEO): the apogee is always greater than 35,786 km, rarely used,
- d) Highly Elliptical Orbit (HEO): the farthest point in the satellite's orbit (apogee) is greater than 35,786 km, but the perigee is lower; used predominantly by Russian Molniya telecommunications satellites,
- e) Geostationary orbit (GEO) – more than 35,786 km, telecommunications (TV and radio broadcasting, fixed satellite data services – Internet, etc.). Lifespan ranges from 11 to 15 years.
- f) Lunar orbit: over 384,401 km (probes and missions to the Moon and planets). The lifespan corresponds to the duration of these missions.

¹⁰ source: <https://www.itu.int/en/publications/ITU-R/Pages/default.aspx>

¹¹ source: <https://www.esa.int/>

3.1.2 Frequency bands for satellite operations

Frequency allocations for satellite services range from 2.5 MHz to 3000 GHz, including orbital positions and technical radio parameters for individual satellite services (fixed, mobile, inter-satellite, space research, etc.), which are contained in the ITU Radio Regulations (RR) and the relevant ITU Recommendations¹². Coordination, notification and administration of satellite services are handled by the Satellite Department of the ITU Radiocommunication Bureau (Space Dept. ITU-R¹³).

To give a basic idea – the frequency bands used for satellite communications are: L (1–2 GHz) for mobile communications, S (2–4 GHz) for meteorology and maritime transport, C (4–8 GHz) for television broadcasting, X (8–12 GHz) for military use, Ku (12–18 GHz) for direct-to-home television broadcasting, Ka (26–40 GHz) for high-speed internet, and V (40–75 GHz) for ultra-high-capacity communications.

Within the ITU, the issue of radio spectrum monitoring in relation to satellite use is addressed by the study groups SG-1 Spectrum Management in Working Party 1C (WP 1C) – Spectrum Monitoring¹⁴, SG-7 Science Services¹⁵ and SG-4 Satellite Services¹⁶.

Satellite operations consist of a ground segment (ground satellite station) and a satellite segment (individual satellites or a network of satellites). Depending on the type of satellite service, two to three radio channels are used; these are intended for controlling the operation of the satellite's own systems and for transmitting data from the equipment and systems constituting the payload. In the case of radio communications, this payload consists of transmitting and receiving equipment for scientific experiments, measured data from various sensors, transponders for radio and television programmes, transponders for amateur radio services, etc.

The operation of a satellite or a network of satellites requires, in addition to the technical aspects themselves, administrative processes such as coordination and notification within the ITU, registration with the United Nations Office for Outer Space Affairs (UN OOSA¹⁷) and also the existence of and compliance with the requirements of relevant international and national legislation, given that satellite services are a commodity on the telecommunications market.

3.1.3 Satellite investment and operating costs

The use of a satellite for a specific purpose within a given project (mission) requires, among other things, an assessment of the economic aspects (investment, operational and potential additional costs) of the satellite itself throughout its entire life cycle (the figures given are rough estimates for LEO satellites).

The following costs must be taken into account:

- a) technical design – tens of thousands of euros,
- b) satellite development and construction (in-house or purchase of a kit) – from a few thousand to tens of thousands of euros,
- c) pre-launch tests (in-house provision, sharing as part of a kit purchase or other projects) – thousands of euros,
- d) launch and placement of the satellite into orbit (leasing, sharing, use of a specialist firm) – hundreds of thousands of euros,
- e) ground segment (construction or lease) – from a few thousand to tens of thousands of euros,
- f) decommissioning and clean-up at the end of its service life – thousands of euros,
- g) fulfilment of administrative and legislative obligations (ITU-R, UN OOSA) – in the thousands of euros,
- h) forecasting of unexpected costs (e.g. legal services and the consequences of damage caused by a collision with other satellites or by the satellite itself to ground-based objects or people, or the consequences of a failed launch or placement of the satellite into orbit), etc., which can run into hundreds of thousands of euros.

In addition to the total costs mentioned above, the costs of developing, manufacturing and operating the project's own content must also be taken into account. The costs of the GEO satellite itself will be a multiple of the amounts stated.

¹² Source: <https://www.itu.int/rec/r-rec/e>

¹³ Source: <https://www.itu.int/en/ITU-R/space/Pages/default.aspx>

¹⁴ Source: <https://www.itu.int/en/ITU-R/study-groups/rsg1/rwp1c/Pages/default.aspx>

¹⁵ Source: <https://www.itu.int/en/ITU-R/study-groups/rsg7/Pages/default.aspx>

¹⁶ source: <https://www.itu.int/en/ITU-R/study-groups/rsg4/Pages/default.aspx>

¹⁷ source: <https://www.unoosa.org/>

For the preparation of a financial plan, financial models such as Aerospace DS¹⁸ are used in the case of LEO satellites.

Even assuming that small LEO satellites appear promising for radio traffic monitoring, the costs of such projects are currently substantial, ranging from tens to hundreds of millions of euros. However, the clearly indicated dynamic development of the market for the use of small satellite technologies will lead to a reduction in these costs and thus also to the possibility of research into the implementation of applications in the field of radio spectrum monitoring within the remit of telecommunications regulators. Another way to reduce the financial costs of such projects is through the use of joint consortia of telecommunications regulators, as will be described further.

3.2 Frequency spectrum monitoring using satellites

3.2.1 Monitoring the terrestrial sector from satellites

Initial studies on this topic focused on assessing the feasibility of measuring the signal coverage of the terrestrial segment from satellites in geostationary and non-geostationary orbits in accordance with the provisions of the Radio Regulations of the International Telecommunication Union (ITU) and related national legislative documents – the Frequency Allocation Plan (national frequency table) – Decree No. 105/2010 Coll.¹⁹ to Act No. 127/2005 Coll., on Electronic Communications) and in a measure of a general nature issued by the Czech Telecommunications Office in the Radio Spectrum Utilisation Plan²⁰.

The studies carried out conclude that the use of satellites to measure signal coverage from terrestrial service transmission equipment, not only in real time, is practically unusable from the perspective of the requirement to measure terrestrial segment coverage.

The main reasons are:

- a) Monitoring of radio signals directed towards outer space can be measured spectrally in the case of LEO satellites at altitudes of at least 300 km above the Earth's surface; consequently, any geometric projection of coverage onto the Earth's surface is meaningless, even with regard to the use of this terrestrial mobile service. These measurements represent a form of monitoring the radio smog emissions from terrestrial transmitters of radio communication services into outer space (see the SMOG-P experiment described below).
- b) The radiation patterns of antenna systems for base stations of mobile and fixed services (for example, mobile networks mostly use panel-type structures²¹) are oriented in the horizontal plane to maximise the utilisation of transmitted power at and near the Earth's surface. In the vertical plane, these antennas have radiation angles of up to 15°. In the case of signal propagation into space, after passing through the Earth's atmosphere, it is possible, in addition to the signal's own spectrum (and possibly its content), to identify the geographical location of the signal source with a certain degree of probability.

3.2.2 The SMOG-P Project

The SMOG-P project⁽²²⁾ carried out in 2020 by the Budapest University of Technology and Economics²³ with the support of the National Media and Infocommunications Authority⁽²⁴⁾, serves as an example of the use of satellites in radio spectrum monitoring.

¹⁸ source: <https://pdfs.semanticscholar.org/2654/787f913203f58ac40e01243b6b88715e20c5.pdf>

¹⁹ source: <https://ctu.gov.cz/sites/default/files/obsah/stranky/539/soubory/nkt2021p.pdf>

²⁰ source: <https://ctu.gov.cz/plan-vyuziti-radioveho-spektra>

²¹ source: https://svjfilipova.cz/files/brozura_-_zakladove_stanice2.pdf

²² source: https://gnd.bme.hu/smog/files/publikaciok/smogp_spectrum_measurement.pdf

²³ Source: <https://www.bme.hu/en>

²⁴ source: <https://english.nmhh.hu/>

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The aim of this project was to confirm and map the electronic pollution caused by radio smog surrounding the Earth in the 460–860 MHz frequency band, generated by terrestrial TV transmitters and mobile networks, at an altitude of 350 km using the small SMOG-1 satellite²⁵.

The small SMOG-1 satellite, measuring 5 x 5 x 5 cm (the size of a Rubik's cube) and weighing 175 g, carried a spectral analyser capable of scanning in the specified range with a bandwidth of 800 kHz. Given that the bandwidth of digital TV broadcasting is 8 MHz, the resulting values were amplified by +10 dB. Its antenna covered a footprint with a radius of 4,000 km. The 70 cm UHF amateur radio band was used for communication with the satellite.

A weather balloon at the meteorological station in Gilica, Hungary, was used to verify the satellite's functionality, spectrum measurement capabilities and flight software.

The satellite's six-month lifespan reflected its size, which limited, in particular, the possibility of achieving sufficient energy self-sufficiency. The relatively low altitude of the flight path also resulted in a greater effect of gravitational forces and led to a gradual descent into the upper layers of the atmosphere and eventual destruction by burning up.

The result of the six-month measurement was a 3D interactive map²⁶ of radio smog and a map estimating radio smog at altitudes of 320 km to 420 km. The range of measured values was between -100 dBm and -60 dBm.

The results of the experiment were provided to the ESA and the ITU for use primarily in compatibility studies in the field of satellite services. An interesting finding is that signal levels from mobile systems (810–950 MHz) are almost identical to those emitted by large television transmitters operating in the 500 MHz to 600 MHz frequency band.

3.2.3 Trends in the use of satellites for radio spectrum monitoring

At present, in light of a number of initiatives in the field of space utilisation, there is a clear trend towards the significant emergence and development of the space telecommunications sector. The dynamic increase in the number of satellites in all orbits (see, for example, the Starlink network, OneWeb in LEO orbits) and the plans of satellite operators and manufacturers are also reflected in increasing pressure for the allocation of further frequency bands for fixed and mobile satellite services and their interference-free operation in accordance with the ITU Radio Regulations and its technical and regulatory measures. This can be inferred, among other things, from the planned agenda items and study groups relating to satellite services at the upcoming ITU World Radiocommunication Conference in 2027 (^{WRC-27}). It is therefore clear that, in this context, these trends will also be reflected in the use of satellites for these study and regulatory needs in radio spectrum management, including the acquisition of valid data using satellites.

Small satellite technologies in LEO orbits are proving particularly promising in the field of radio spectrum monitoring; these can be utilised primarily in the Earth-to-satellite (upload) segment and for identifying disruptive and illegal sources of radio signals penetrating into space, and potentially also in the monitoring of inter-satellite communications.

The trend towards using satellites for radio spectrum monitoring tasks is also reflected in the European Space Agency's (ESA) plans for the ARTES FPE 1B.129 programme – Spectrum monitoring mission feasibility assessment⁽²⁸⁾ – and in the activities 'Ensuring access to radio spectrum' and 'Supporting standardisation activities'. The development of a new plan of activities within the ARTES 4.0 programme is also included in ESA's programme calls. As a member of ESA, the Czech Republic has access to these activities involving 25 EU countries and Canada. This also creates an opportunity for deeper involvement of the Czech public administration, academia and industry in the design and implementation of projects focused on the needs of radio spectrum management in space telecommunications. This is primarily through membership of the relevant consortia for such projects.

Plans regarding the use of satellites and support for Czech projects and participation in ESA programmes for the period 2020–2025 are set out in the government document 'National Space Plan'²⁹ and will also be included in its amendment for the subsequent period.

²⁵ source: https://gnd.bme.hu/smog/files/publikaciok/levi_com/PID3627859.pdf

²⁶ source: <https://gnd.bme.hu/mb/site/>

²⁷ source: <https://www.itu.int/en/ITU-R/study-groups/rcpm/Pages/wrc-27-studies.aspx>

²⁸ source: <https://connectivity.esa.int/funding/spectrum-monitoring-mission-feasibility-assessment-artes-fpe-1b129>

²⁹ source: <https://www.czechspaceportal.cz/narodni-strategie/narodni-kosmicky-plan/>

3.3 Partial conclusions

The research described focused on assessing the possibility of using satellites for radio spectrum monitoring, i.e. the need to measure signal coverage, primarily of mobile networks, in real time in the terrestrial segment. The use of satellites for this purpose appears to be impractical. In cases where the radiation patterns of terrestrial transmitters allow the signal to propagate into space, it is possible, after the signal has passed through the Earth's atmosphere, to identify with a certain degree of probability the geographical location of the signal source, in addition to the spectrum of the propagated signal (and possibly its content). In this way, it is also possible to monitor the emission of radio smog from terrestrial transmitters of radio communication services into outer space.

In connection with the growing focus on the use of space, demands are also being placed on the development of space telecommunications. This will also lead to the need to develop and implement appropriate technical methods for monitoring the radio spectrum.

At the same time, it is necessary to focus on the preparation and development of appropriate national legislative and regulatory measures for both the use and management of the radio spectrum. Therefore, this section of the study includes an overview of the fundamental aspects and trends in satellite technologies, with a view to their potential applications in the field of radio spectrum monitoring.

This issue will undoubtedly require a separate study that comprehensively addresses the topic of radio spectrum management in space telecommunications, taking into account the outcomes and findings of the WRC-27 and WRC-31 radio communication conferences, as well as the development of satellite technologies and the promotion of their applications in science, research, industry and services.

4 The use of drones for measurement

The use of drones for measuring mobile networks is not a novelty, as it is in fact an alternative to the long-established 'drive tests'. Until now, these tests have been carried out on roads using vehicles, or within railway corridors using special measurement vehicles; in the past, conventional helicopters were also used for measurement.

However, drones enable measurements to be carried out more efficiently, more economically, more quickly and with a much higher density of measurements than a standard drive test, which is limited to existing road or rail transport routes. Furthermore, it is of course possible to carry out all measurements even in hard-to-reach terrain and in hazardous areas.

However, the legislative aspect is a drawback that is slowing down the deployment of this progressive technology. This aspect will also be described in the following chapters.

4.1 Specifics of 5G NR network measurements

5G New Radio, in particular, poses a challenge for testing infrastructure equipment due to the increasing complexity of MIMO and beamforming, higher bandwidths, and new bands extending into the mmWave range. The ever-increasing diversification and complexity of mobile network infrastructure equipment is often combined with requirements such as cost-effectiveness and rapid time-to-market. These requirements must be taken into account in innovative and flexible test and measurement solutions.

Testing 5G networks presents unique challenges that require strategic solutions. The main challenges associated with testing 5G networks include:

- 5G network coverage – the initial roll-out of this advanced technology is concentrated in limited areas. Regulatory bodies now take into account both received signal strength reference point (RSRP) and expected data throughput.
- Achieving optimal 5G network performance – the high degree of flexibility in 5G requires thorough performance tuning during network deployment to achieve the intended performance. It is essential to verify handover between locations, cells and clusters to ensure maximum network capacity.
- Interference – the use of time-division duplex (TDD) mode in 5G networks raises concerns about interference. Precise network synchronisation is required to prevent interference between base stations and between networks of different operators.

5G New Radio is a radio access technology for the next-generation mobile communications standard. It differs from LTE in the following respects:

- Globally, the FR1 and FR2 frequency bands are reserved, with priority given to the 3.3 to 4.2 GHz and 26 to 44 GHz bands.
- Support for beamforming for synchronisation signals / transmission and data channels in combination with 5G NR with MIMO for data channels.
- Wide flexibility of physical radio parameters, such as channel bandwidth, subcarrier spacing and symbol length.

These characteristics affect signal propagation and quality, which increases the need for accurate measurement of 5G NR networks.

4.2 Legislation and rules governing the use of drones in the Czech Republic

The operation of drones / UAS within the European Union is regulated by the EASA (European Union Aviation Safety Agency). As an EU Member State, the Czech Republic actively participates in the work of the EASA and subsequently adopts and enforces the rules governing the use of drones within its territory.

From a legal perspective, this falls within the remit of several authorities and ministries:

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- Ministry of Transport – this is the parent body of the Civil Aviation Authority (UCL).
- Civil Aviation Authority (UCL/CAA) – this authority is responsible for aviation safety and is the main authority that approves flight plans.
- Czech Telecommunications Office – this office is responsible for the administration and management of the entire frequency spectrum in the Czech Republic.

Unmanned aircraft (drones) have become an increasingly popular tool in the European Union for a variety of applications, ranging from commercial activities to recreational flying. Harmonised rules apply to the operation of drones in the EU, which were introduced under the European Regulation on unmanned aircraft systems. These rules are now applied in all EU Member States. The rules for operating drones are divided into basic categories:

OPEN Category

The OPEN category is intended for low-risk drone operations, which includes most hobby flying and some commercial applications. The following rules apply to operations in this category:

- Drone weight:** Drones must weigh less than 25 kg (with the exception of certain specific conditions).
- Flight altitude:** The maximum flight altitude is 120 metres above ground level.
- Visibility:** The pilot must always have the drone within direct visual line of sight (VLOS).
- No flying over people:** Flying over gatherings of people is prohibited, which means the pilot should maintain a safe distance from people and buildings.
- Mandatory training:** Pilots of drones weighing less than 250 grams (up to 2 kg for certain models) must complete an online course and obtain a pilot's licence.

The Open category also includes subcategories, divided according to the drone's weight and the pilot's qualification.

Where it is not possible to apply the rules and restrictions of the OPEN category, but aerial work still needs to be carried out, the SPECIFIC category may be used.

SPECIFIC category

The SPECIFIC category is intended for drone operations that pose a higher risk and require additional authorisation and access to a Specific Operations Risk Assessment (SORA). The challenges of this category include:

- Complex approval process:** Every planned flight must be officially approved, which may involve preparing a detailed risk analysis and operational documentation.
- Financial and time costs:** The process of obtaining authorisation can be costly and time-consuming, which may deter smaller businesses from using unmanned aerial vehicles.
- Experience and knowledge:** The pilot must have sufficient experience and knowledge of drone operations, which may involve more complex training and certification.
- Location restrictions:** Certain locations (e.g. near airports, military zones, etc.) may have additional restrictions, which complicates flight planning.

This category also includes flying in densely populated areas (HOP)

Operating drones in densely populated areas presents further complications:

- Regulatory restrictions:** Stricter rules on privacy and safety apply in these areas. Drone flying, even in the OPEN category, is restricted.
- Risk to people and property:** The main issue is the high risk to residents and property. Strict requirements to minimise risks must be adhered to.
- Air traffic:** Heavy air traffic over cities may require additional approvals or coordination with the authorities to prevent collisions with other aircraft or helicopters.
- Technical equipment:** Drones may require advanced technologies, such as obstacle avoidance systems or parachute systems, to ensure safe flight in such areas.

Overall, the operation of unmanned aircraft in the European Union is a complex issue that requires knowledge of regulations and a responsible approach to safe flying.

From the perspective of flight plan approvals and flight operations themselves, the location where the measurement is to be carried out is of great importance. The territory of the Czech Republic is divided into geographical zones, which include, for example: the aforementioned densely populated areas, protected landscape areas, national parks, airport grounds and heliports, military areas, prisons, the electricity grid, and the road and rail networks. If a request is made to conduct flights in a zone that overlaps with a geographical zone, it is necessary to comply with the rules for each zone and to adjust the operation of the unmanned aircraft in accordance with the restrictions of each zone. The SPECIFIC operation category (described above) and the Civil Aviation Authority, which carries out supervision, serve precisely this purpose of coordination.

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Furthermore, drone operations affect land and property managers and owners. Their consent is required to conduct flights. It follows from this logic that the most advantageous use of drones is in locations that are difficult for a human technician to access, as there are usually no other zones in such locations.

It is worth noting that the legislative situation regarding the operation of unmanned systems has improved significantly over the years. Limits that were previously insurmountable are now surmountable. There is now a Europe-wide system in place with clear rules, which is undoubtedly a good thing. It is also important to realise that if there are any restrictions, they are solely for the sake of safety. And provided all safety requirements are met to a high standard, it is possible to operate unmanned systems even in areas that were previously inaccessible.

Ministry of Transport

The Ministry of Transport is the founding body of the Civil Aviation Authority and, as such, is the authority's superior body. It exercises control and supervision over the operation of all aircraft and drones through this authority.

Civil Aviation Authority

The Authority notes that drones using frequencies other than those allocated for protected aviation use fall under Directive 2014/53/EU on radio equipment. When operating such drones, frequencies may only be used on the basis of a general authorisation or an individual authorisation for the use of radio frequencies issued by the Czech Telecommunications Office (ČTÚ).

At the end of 2023, Article 22 of Commission Implementing Regulation (EU) 2019/947 will cease to apply, and only Article 20 will remain in force for UAS placed on the market before 1 January 2024. This means that aircraft not bearing a 'C' label and placed on the market by the end of 2023 will continue to be operated under operation subcategories A0 for aircraft weighing less than 250 g and under subcategories A1–A3 for aircraft weighing more than 250 g.

Furthermore, on 1 January 2024, the provision of point UAS.SPEC.050(1)(l)(ii) of the Annex to the Implementing Regulation will enter into force. This means that, when operating within the SPECIFIC category, the operator is required to equip the unmanned aircraft with an active and up-to-date remote identification system. An overview of currently available remote identification systems is available on the EASA website. In the SPECIFIC category, it is now also necessary to equip the unmanned aircraft so that it meets the requirements of 2.5.3 AMC1 to Article 11 for *'enhanced containment'*.

Czech Telecommunications Office

The CTU has a dual role in relation to drone operations, namely:

- Administrator of the frequency spectrum used, among other things, for remote control of drones:
 - Frequencies allocated for model aircraft, radio-controlled toys and drones.
 - Frequencies allocated for protected aviation use.
- The spectrum administrator may be a drone operator or the client commissioning a service that produces measured data demonstrating network quality. The data collected may indicate both network quality and the level of network interference.
- The Czech Telecommunications Office (ČTÚ), as the state institution responsible for spectrum management, should have certain exemptions for conducting measurement flights. For example, it is inappropriate to seek permission to operate a drone from a landowner who has an unauthorised transmitting station on their land (or a station transmitting outside the allocated bands). Practice shows that such inspections are then pointless.

4.3 Technical requirements for drones / UAS

In general, the technical requirements for drones can be summarised as requirements for maximum flight time, maximum weather resistance, maximum payload and minimum cost.

- Flight time and maximum range. Flight time and maximum range have a direct impact on the volume of data collected, or on the area that can be covered by the measurement. This parameter also affects the cost-effectiveness of individual measurement tasks, or entire projects.
- Flight speed range.
- Drone payload and wind load profile.
- Weather resistance. Given that the aim is to utilise modern robotic technology, it is desirable for it to be as weather-resistant as possible. It is now common for unmanned aerial vehicles to have an IP XX rating. In some cases, it is possible

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use unmanned aerial vehicles even in situations where helicopters or human personnel cannot be deployed (fog, icy transmitters, etc.).

- Computing power of the drone's control unit(s).
- The computing power of processing units (usually mini-PCs) is readily available today. Over the last 1–2 years, there has been a reduction in the size of computing units. This is a common trend in the IT sector. This reduction in size, or rather weight, then provides a weight allowance that can be utilised for additional systems enhancing flight safety.
- Area of application. Within the telecommunications infrastructure, it is possible to measure objects located in inaccessible areas with low population density, such as border transmitters, without major problems. Alternatively, measurements can be carried out in populated areas with higher population density. However, these areas impose higher safety requirements. These requirements are now set by the Civil Aviation Authority (CAA). Meeting these higher safety requirements, for example through parachute systems or tethered solutions, is possible and practicable. However, these higher requirements do affect other drone parameters, such as total weight versus payload, flight time, wind resistance, etc. It is therefore necessary to assess operational areas both individually and comprehensively.

Current practice shows that for aerial tasks involving frequency spectrum measurement, drones with a payload capacity of at least 2.5 kg are required. Flight times of around 30 minutes are now commonly available for both large and small drones. It appears that this duration is currently sufficient for carrying out measurements. For more time-consuming applications, it is no problem to change batteries and repeat flights as required.

For measuring so-called linear structures, the use of aircraft systems, or VTOL (Vertical Take-Off and Landing) systems, is more suitable.

Figure 3 – Example of a drone equipped with a frequency spectrum measurement system.



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Figure 4 – Example of a drone prepared for a frequency spectrum measurement system.



4.3.1 Technical requirements arising from 4G and 5G network coverage measurement tasks

In the following text, we will limit ourselves solely to the FR1 frequency band, which ranges from 40 MHz to 6 GHz. The FR1 band is the focus of attention given the massive development of 5G networks and the associated terrestrial services, as well as the planned non-terrestrial services – FR1 and FR2.

In 3GPP⁽³⁰⁾ the 5G NR bands for NTN UE³¹ communication with satellites are/will be defined in the table:

Table 4 – 5G NR bands for communication with satellites.

REL	WI	NR band	Uplink (UL) operating band Satellite Access Node receiver / UE transmit <small>FUL,low – FUL,high</small>	Downlink (DL) operating band Satellite Access Node transmit / UE receive <small>FDL,low – FDL,high</small>	Remarks
REL-17	NR_NTN_solutions	N256	1980–2010 MHz	2170–2200 MHz	FR1, FDD, S-band
REL-17	NR_NTN_solutions	N255	1626.5–1660.5 MHz	1525–1559 MHz	FR1, FDD, L-band
REL-18	NR_NTN_LSband	N254	1610–1626.5 MHz	2483.5–2500 MHz	FR1, FDD, LS-band
REL-18	NR_NTN_enh	N512*, N511*, N510*	27.5–30.0 GHz 28.35–30.0 GHz 27.5–28.35 GHz	17.3–20.2 GHz 17.3–20.2 GHz 17.3–20.2 GHz	FR2, FDD, Ka-band

Source: 3GPP

Given the wide range of measurement tasks, it is essential to integrate various types of measurement instruments into unmanned aerial vehicles – from scanners and spectrum analysers to data stream analysers and measurement receivers for the frequency bands under test. A full range of measurement antennas is also available. These are categorised by frequency band, mode of operation and radiation pattern. Antennas are an essential part of the measurement equipment.

It is possible to hire unmanned aerial vehicles. The same applies to individual pieces of measurement equipment. This option is based on the operational and economic merits of the individual solutions. Ready-made products are now available – Unmanned Aerial Vehicle + measurement equipment + Software – which are declared to be mutually compatible (see the description of Deviser and NOKIA Drone Networks below). Given that these are still new methods and technologies even today, it is common for the combination: unmanned aerial vehicle + measuring instrument

³⁰ 3GPP (The 3rd Generation Partnership Project) – Cooperation agreement in the field of mobile communications.

³¹ NTN (Non-Terrestrial Networks) – Non-terrestrial network (other than a terrestrial network, e.g. a network with a space segment); UE (User Equipment) – User terminal/user's end device.

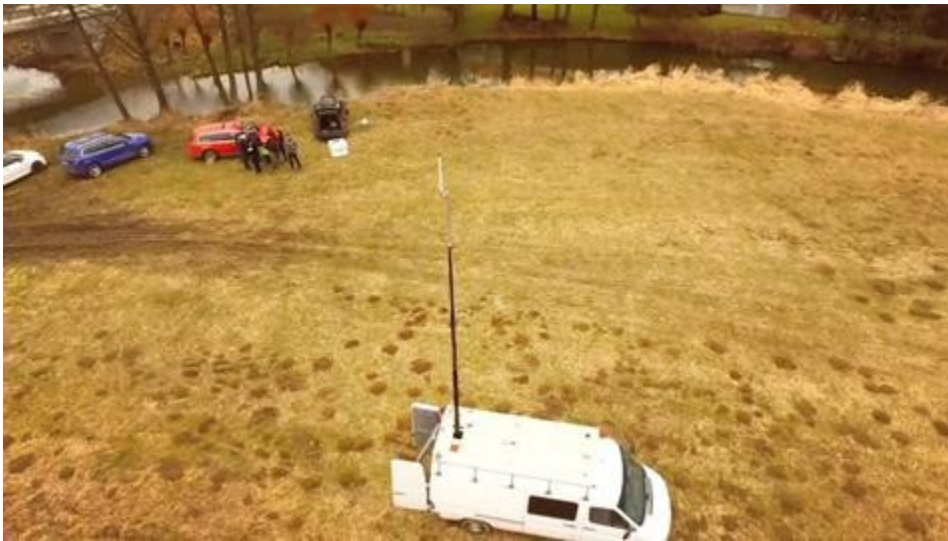
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assembles. Or even builds to order. In such cases, special attention must be paid to mutual compatibility, as mutual interference may occur. The measurement itself may then be affected and the measured data rendered irrelevant.

The main requirement for mutual compatibility is to prevent interference from drone systems from penetrating into measuring instruments and interfering with the measured frequencies, or affecting measured parameters such as data services. Recently, the need to monitor GPS/GNSS³² data in connection with interference affecting these services has also been added to these requirements. Monitoring GPS/GNSS data is also important because these services provide a timestamp, which is essential for network synchronisation.

4.4 Status of drone monitoring in the Czech Republic

The CTU has its own unmanned and measurement equipment. It uses a subcontractor for fleet management, flight task administration and piloting. It employs its own experts for the evaluation of measurements and the preparation of measurement tasks.



4.4.1 Overview of available measurement equipment

The following is an overview of available measurement technology suitable for mapping and monitoring wireless and mobile networks. This applies not only to drones, but also to other mapping methods.

Aaronia

The SPECTRAN® V6 ECO³³ is a real-time spectrum analyser (RTSA) and monitoring receiver designed to capture even very short signals. Its scanning speed and recording rate/duration are 6 GHz in 2 ms (3 THz/s), making it one of the fastest USB spectrum analysers.

³² GNSS (Global Navigation Satellite Systems). A global navigation satellite system is a ranging system that uses specific signals transmitted from satellites to determine the position of a terminal. GPS is one version of GNSS; it is the US NAVSTAR GPS (Navigation Signal Timing and Ranging Global Positioning System) navigation system. Other GNSS systems include Beidou, GLONASS and the Galileo system.

³³ Source: <https://aaronia.com/>

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The **Spectran V6** is a range of spectrum analysers designed for frequency ranges from 9 kHz up to 6 GHz or 7.25 GHz.



The **SPECTRAN® V6 5G** is a real-time spectrum analyser (RTSA) specifically designed for monitoring 5G networks, including the detection of interference or performance degradation. A key advantage is the optimal price-performance ratio and the range of available additional features. The analyser scans 6 GHz in less than 10 ms (500 GHz/s), making it one of the fastest USB spectrum analysers. Three different versions are available, covering the full range of 5G bands.

Thanks to the modular design of the RTSA-Suite PRO software and its extensive flexibility, the analyser can be tailored to specific requirements, allowing for easy modifications and, of course, seamless future upgrades.

The **SPECTRAN® V6 5G 200XA-50** covers frequency ranges from 9 kHz to 7.25 GHz (FR1) and 24 GHz to 53 GHz (FR2).



Anritsu

Spectrum Master™ MS2760A³⁴

The portable design allows, among other things, measurements to be taken directly at the device under test:

- Frequency range: 9 kHz to 170 GHz.
- Measurements: channel power, adjacent channel power, occupied bandwidth.
- Spectrum and spectrogram display.
- -127 dBm DANL up to 110 GHz.
- Display of up to 6 waveforms, 3 waveform detectors and 12 markers.
- Dynamic range: >103 dB, typically at 70 GHz.
- RBW: 1 Hz to 3 MHz.
- Phase noise: -110 dBc/Hz @ 1 GHz, typical.



³⁴ source: <https://www.anritsu.com/>

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- 10 MHz external reference frequency input.
- External TTL trigger input.

Spectrum Master™ MS2762A

This SA model differs from the MS2760 in the following parameters:

- Frequency range: 6 GHz to 170 GHz.
- -142 dBm DANL, from 6 to 40 GHz.
- Dynamic range: > 108 dB at 70 GHz.



Deviser

The Ground to Air Integrated Testing System is a measurement drone designed primarily for interference analysis and detection. The entire solution is based on the integration of the E8900A High-Performance 5G NR Spectrum Analyser into a commercial drone directly by the manufacturer.



E8900A High-Performance 5G NR Spectrum Analyser

- Frequency range 9 kHz to 9 GHz.
- High-performance handheld spectrum analyser for the deployment and maintenance of 5G NR systems.
- High-speed spectrum analysis, measurement rate of 30 GHz/s @ 7.8 kHz RBW.
- Real-time analysis for bandwidths up to 110 MHz, with a signal capture time of less than 5 ms for 100% coverage.
- Testing and demodulation of 5G NR (FR1) and 4G FDD/TDD LTE signals.
- IQ data acquisition.
- Spectrogram, Spectrum Persistence Analysis, Gated Sweep and coverage mapping.
- Interference analysis and positioning using the Angle-of-Arrival algorithm.
- 10.1" touchscreen for easy navigation.



E8600N 5G NR Handheld Spectrum Analyser

- Frequency range 9 kHz to 6 GHz.
- Real-time analysis for 20 and 100 MHz bandwidths to detect hidden signals.
- Analysis of 5G NR (FR1), 4G FDD/TDD LTE, UMTS.
- Spectrogram, Spectrum Persistence Analysis, Gated Sweep.
- Interference analysis and positioning using the Angle-of-Arrival algorithm.



E816 Series 5G NR Scanning Receiver

4G/5G demodulation: The E816 can demodulate up to 32 frequency points simultaneously, with decoded Beam ID, Beam Index, RS-RSRP, RS-RSRQ and RS-SINR parameters for the relevant base station.

Spectrum analysis functions: The E816 supports measurement of up to 8 frequency bands with spectral trace, spectrogram and power measurement for spectrum verification and interference analysis.



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Table 5 – E816 analyser parameters.

REL	E816-A	E816-B	E816-D
Frequency range	350 MHz to 6000 MHz		
Demodulation	TDD-LTE, FDD-LTE, 5G NR		
Demodulation – sensitivity	LTE -136 dBm @ 15 kHz SCS	5G NR / -132 dBm @ 30 kHz SCS	
Measurement accuracy	± 1.5 dB		
Dimensions	262 x 160 x 80 mm	166 x 97 x 42 mm	292 x 210 x 82 mm
Weight	< 2 kg		

Source: www.deviserinstruments.com

Enhancell Ltd.³⁵

The Echo product range is a solution for measuring and analysing communication networks. All the tools listed below can be integrated into the cloud.

- Echo One is a solution for testing mobile networks in the form of a mobile phone app. In addition to measuring relevant network parameters (layers L1–L3), it also allows end-to-end user tests to be carried out.
- Echo Lite is a handheld tool for measuring mobile networks that does not require the mobile phone's operating system to be rooted. Echo Lite supports the Android and Harmony OS (from HiSilicon) operating systems on commonly available commercial phones. Like Echo One, the Echo Lite tool records key network indicators and communication network performance parameters. However, compared to Echo One, Echo Lite has more limited functionality.
- Echo FT is a solution for viewing key network performance parameters in real time.
- Echo Trek I and II are backpacks for drive and walk tests. Echo Trek I features slots for 6 phones, a tablet, a scanner, 4 batteries and a power supply. Echo Trek II features slots for 10 phones, 2 USB hubs, a miniature control computer, a battery and a charger.
- Echo Verify is a solution for verifying base station parameters (including the handover process between neighbouring sectors). Echo Verify supports all available 2G/3G/4G/5G (NSA/SA) technologies. The solution also enables voice call routing testing (Voice Call Test Routing), including emergency calls to the 112 (or 911) number.
- Echo Studio is a tool for data analysis, result visualisation and the creation of measurement reports. Individual Echo series measurement devices can be fully controlled remotely via the Studio application for testing purposes. The results obtained can be synchronised and shared via the Echo Cloud service.

Keysight Technologies, Inc.

Nemo Walker Air³⁶ is a system for indoor benchmarking.

Nemo Walker Air is a solution for performing indoor measurements and comparative tests across multiple technologies simultaneously. It is a lightweight system housed in a backpack, which is easy to carry and set up. The entire system can operate on its own battery for up to 10 hours.

Key features:

- Synchronisation of indoor comparative measurements and event scripts with up to seven test terminals (UE).
- The control unit performs measurements, controls and coordinates subordinate units connected via Bluetooth.
- Supported technologies: 5G NR, 5G NR NSA/SA, 5G Carrier Aggregation, LTE/LTE-A, legacy technologies from 2G to 4G, Wi-Fi and Wi-Fi 6.



³⁵ source: <https://enhancell.com/enhancell/>

³⁶ source: <https://www.keysight.com/>

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- Audio quality and video streaming quality tests (POLQA, PEVQ-S).
- Enables measurements to be performed using a 5G NR scanner via PCTEL Gflex™ / HBflex™ / IBflex™ and R&S@TSMa6 standalone mobile network scanners (see description of scanners below).

NOKIA Drone Networks

Nokia³⁷ is emerging as another major player in the market; the company manufactures complete infrastructure for mobile operators' networks. Since 2022, it has been working closely with Rohde & Schwarz on a 'drone-based network measurement solution'. The solution is based on the QualiPoc product, which is integrated directly into the NOKIA drone.



PCTEL

SeeGull IBflex® Scanning Receiver³⁸. The scanners currently enable parallel scanning of 4G/5G FR1 and 5G FR2; until now, scanners could only operate in one of the sub-6GHz or mmWave bands.

FR2 band parameters, modes and diagnostics:

- Option to measure FR2 in two antenna modes for faster dedicated FR2 measurements.
- Single-antenna mode for simultaneous measurement in the sub-6GHz and mmWave bands.
- In the 2-port high-speed FR2 configuration – 10 measurements/sec, DSS N/A.
- In the Simultaneous FR2 & 4G/5G FR1 configuration – 5 measurements/sec, DSS YES.

Feature	2 Port high speed FR2	Simultaneous FR2 & 4G/FR1
FR2 speed	10 meas/ sec	5 meas/sec
DSS	N/A	Yes

			
Gflex®	HBflex™	IBflex®	MXflex®

³⁷ source: <https://www.nokia.com/>

³⁸ source: <https://www.pctel.com/>

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Rohde & Schwarz GmbH & Co. KG

Rohde & Schwarz³⁹ offers solutions for testing mobile network infrastructure that address a variety of needs and enable the full potential of 5G networks to be realised. The solution portfolio covers all phases of the product lifecycle, from research and development of RF and digital designs, design validation and integration, through to 3GPP-defined base station conformance testing and production testing.

Solutions for 5G network testing

The complexity of 5G networks requires testing at all stages of the network lifecycle. 5G NR network measurements enable operators to deploy and operate networks more quickly and ensure their top-quality performance. Rohde & Schwarz offers a comprehensive portfolio for testing 5G mobile networks, with solutions for both passive and active testing:

The R&S@TSMx6 family of network scanners and the R&S@5G Site Testing Solution (STS) support the passive testing method. With this method, it is possible to gain an overview of all “always-on” DL signals in the area using Automatic Channel Detection (ACD), which includes decoding information on the transmission channel and RF parameters such as signal strength and quality. All base station signals (cells and beams) can also be analysed. No SIM cards are required for passive testing using network scanners.

Overview of key features:

- Signal overview – rapid identification of all signals on the air interface with Automatic Channel Detection (ACD) and high-speed 5G NR measurement.
- Signal information – analyses 5G base station signals (cells and beams) with high ser each location to prevent interference between cells.
- Reduction of unwanted interference – the ability to verify 5G TDD network synchronisation during a 5G drive test.



The QualiPoc Android software supports active testing. This requires a network connection. Network performance can be measured in terms of QoE or QoS, which includes data throughput and latency.

- QoE measurement of user-perceived network quality – measuring network performance in terms of QoS/QoE application quality.
- Interactivity test – use of standard test methods (ITU-T G.1051) to measure transmission delay with various traffic patterns.



Free Rider – a backpack designed for walk tests. This backpack can be equipped with both TSMx6 scanners and MT QualiPoc Android devices. In this case, it allows for the measurement of both QoS and QoE.



³⁹ Source: <https://www.rohde-schwarz.com/>

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FSH + K15, K16 options, etc. A spectrum analyser with extensions for spectrum monitoring. Rohde & Schwarz also

offers software for data analysis and quality monitoring:

- Smart Bench Marker – software primarily designed for drive testing in conjunction with the QualiPoc application and a data acquisition computer. Its counterpart is the SmartAnalytics software.
- SmartAnalytics – a software suite for data analysis.
- SmartMonitor – software for quality monitoring and drive test evaluation.

Analytical software – **SmartAnalytics**:

- provides a QoE insight into mobile network performance,
- provides an accurate assessment of the operator's own network quality, i.e. QoE from the end-user's perspective and the operator's competitive position in the market,
- analyses RAN data to improve end-users' QoE,
- highlights network performance issues and analyses their causes,
- cross-sectional analysis from the macro level down to network cells.



SmartMonitor is a web application that provides a real-time overview of the current network situation based on data from QualiPoc Android probes.

- supports QualiPoc Android probes, which can be installed on Samsung, LG, HTC and Sony smartphones,
- data sent from QualiPoc Android probes is visualised on the SmartMonitor application's dashboards, providing an immediate overview of service quality and network performance from the end-user's perspective,
- cost-effective real-time monitoring of service quality from the end-user's perspective,
- helps reduce operational costs in the field.

Tektronix, Inc.

Tektronix⁴⁰ has developed an RF spectrum monitoring solution based on the RSA series of spectrum analysers and Intel® NUC Mini PCs.

RSA306B USB Real-Time Spectrum Analyser

- The frequency range of 9 kHz to 6.2 GHz covers a wide range of analysis requirements.
- Measurement range: +20 dBm to -160 dBm.
- Ruggedness class according to Mil-Std 28800 2 – environment, shock and vibration, specifications for use in harsh conditions.
- Fast measurement – 2 per second across the entire 6.2 GHz range A 40 MHz sampling bandwidth enables wideband vector analysis of modern standards.
- Minimum signal duration of just 15 µsec for 100% capture probability.



RSA500A Series USB Portable Spectrum Analyser

- Frequency range 9 kHz to 3.0/7.5/13.6/18.0 GHz
- The 40 MHz acquisition bandwidth enables real-time analysis for capturing transient events and vector analysis



⁴⁰ source: <https://www.tek.com/>

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- High-speed sampling across the entire range (70 GHz/s)
- Standard GPS/GLONASS/Beidou receiver for mapping
- Optional tracking generator for gain/loss measurements of antennas and cables
- DataVu-PC software enables recording from multiple units
- Ruggedness class according to Mil-Std 28800 2 – environment, shock and vibration, specifications for use in harsh conditions
- Internal battery for extended field operation
- SignalVu-PC software offers real-time signal processing using DPX®
- Spectrum/Spectrogram, which minimises the time spent searching for transients and interference.

Signal Hound

An American manufacturer of measurement equipment⁴¹, which offers ultra-compact spectrum analysers.

The **BB60C** is a 6 GHz high-speed real-time spectrum analyser; the BB60D transmits 140 MB/s of digitised RF data to a computer in real time via a USB 3.0 interface, providing an instantaneous bandwidth of 27 MHz and a sweep rate of up to 24 GHz/s. Add a high-speed hard drive (sustained write speed of 250 MB/s) to your computer or laptop, and the BB60D doubles as an RF recorder, streaming up to 80 million IF samples per second or 40 million I/Q samples to the drive.

- RF frequency range from 9 kHz to 6 GHz.
- Up to 24 GHz/sec sweep speed.
- Wide dynamic range from -158 dBm to +10 dBm.
- RBW from 10 Hz to 10 MHz.
- Powered exclusively via USB.
- Software is included with the instrument.
- The SignalHound API (Application Programming Interface) is available for developing custom applications.
- Digitised IF data at 80 million samples per second.
- 27 MHz instantaneous bandwidth.
- Compatible with Windows 7/8/10 64-bit operating systems.
- Communication via USB 3.0 at a speed of 140 MB/sec.



The **BB60D** includes the same features as the popular BB60C model, but offers a 10 dB wider dynamic range and preselector filters from 130 MHz to 6 GHz.

- The BB60D 6 GHz high-speed real-time spectrum analyser transmits 140 MB/s of digitised RF data to a computer via a USB 3.0 interface in real time, providing an instantaneous bandwidth of 27 MHz and a sweep rate of up to 24 GHz/s. Add a high-speed hard drive (sustained write speed of 250 MB/s) to your computer or laptop, and the BB60D doubles as an RF recorder, streaming up to 80 million IF samples per second or 40 million I/Q samples to disk.
- Spectrum analysis can be performed with the BB60D using our proprietary application programming interface (API), which can process up to 1.2 million FFT spectra or 320 million FFT points per second, and send real-time spectrum data to the Spike graphical application or to your own software application.



⁴¹ source: <https://signalhound.com/>

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The **SP145** is a 14.5 GHz real-time spectrum analyser and monitoring receiver with a sampling rate of up to 200 GHz/s, a bandwidth of 40 MHz, a displayed average noise figure of -160 dBm, and an internal GPS for improved field measurements.

Spike is software for Signal Hound spectrum analysers, compatible with a wide range of Signal Hound spectrum analysers and tracking generators. Spike provides full control of the device, a configurable spectrogram display and user interface, and a range of analysis modes. Spike is the ideal application for powerful and affordable RF analysis.

EXFO Inc.⁴²

EXFO 5GPRO spectrum analyser

- FR1 band measurement (sub-6 GHz) 450 MHz – 6 GHz.
- FR2 band (mmWave) measurement: 24.25 GHz – 40 GHz.
- Real-time spectrum analysis (RTSA), bandwidth up to 100 MHz.
- Demodulation and beamforming analysis for 5G NR (New Radio).
- Modular test instrument.
- A complete and compact solution for validating 4G and 5G networks.
- Designed and built for the needs of technicians and practical measurements.

EXFO FTB 5GPRO test solution for 5G mobile networks

- Fully automated iORF software for RF interference and PIM detection.
- FR1 band (sub-6 GHz) measurements: 450 MHz – 6 GHz.
- FR2 band (mmWave) measurements: 24.25 GHz – 40 GHz.
- Real-time spectrum analysis (RTSA), bandwidth up to 100 MHz.
- Support for SyncE, 1588-PTP and Wander/TE for synchronisation and timing validation.
- GNSS/GPS module.
- Modular test instrument.
- Testing using BER and QoS (e.g. latency).
- Compact solution for validating 4G and 5G networks.

UE / MT manufacturers

UE / MT (User Equipment / Mobile Terminal) manufacturers are an integral part of the test chain, as their hardware is essential for tests such as QoE, walk tests, etc.

However, issues concerning the relationship between UE and test applications go beyond the scope of this study, and we therefore mention only a few selected aspects:

- The customisation of UE/MT applications and firmware is handled to a very high standard.
- A relatively small number of UE / MTs can be connected to monitoring applications – usually in the low tens.



⁴² source: <https://www.exfo.com/>

- For some tests, it is necessary to combine several different types and manufacturers of UEs, taking into account the processor used.
- The possibility or impossibility of calibrating UE/MT parameters – ‘calibration’ or verification of UE/MT parameters, e.g. as a function of temperature, is demanding in terms of measurement technology, as it requires a test bed, an antenna coupler and a shielded chamber.
- Dependence of UE/MT parameters on external influences – e.g. core performance.

4.4.2 Current use of drones by operators in the Czech Republic

For the purposes of this study, interviews were conducted with mobile operators in the Czech Republic (CETIN a.s./O2 Czech Republic a.s., T-Mobile Czech Republic a.s., Vodafone Czech Republic a.s.). Based on these, the following can be stated.

Drones for measuring mobile network parameters are used to a limited extent in the Czech Republic. Only one of the operators has its own drone, including suitable measurement equipment and its own trained personnel. The remaining two operators use the services of external suppliers. The current situation reflects, on the one hand, the high investment costs involved in acquiring a drone, suitable measuring equipment and qualified personnel, and on the other hand, the administrative hurdles associated with operating a drone.

A significant improvement to the situation could be achieved by amending the restrictions imposed by the Civil Aviation Authority on the use of drones. Drones used by mobile operators could fall into the same category as those operated by the Police of the Czech Republic (PČR) and the Fire and Rescue Service (HZS), where an exemption applies for flights over buildings and their surroundings. Similarly, it would be helpful to amend the current regulations governing the operation of drones in urban areas. The threat to air traffic posed by drones in these areas is minimal, as the maximum practical flight altitude exceeds the height of buildings by only a few metres.

Drones are most commonly used to identify so-called ‘white spots’, to compare data and coverage with competitors, or to verify compliance with development criteria. Additionally, operators also use them to a limited extent as an alternative to so-called ‘walk tests’, primarily to address specific purposes, such as customer complaints.

4.5 Partial conclusions

Drones for measuring mobile network operators’ parameters are used to a limited extent in the Czech Republic. Only one of the operators has its own drone, including suitable measurement equipment and its own trained staff. The remaining two operators use the services of external suppliers. The current situation reflects, on the one hand, the high investment costs involved in acquiring a drone, suitable measuring equipment and qualified personnel, and on the other hand, the administrative hurdles associated with operating a drone.

Current legislation lacks exemptions for selected state authorities and institutions (this does not apply to the Police of the Czech Republic and the Fire and Rescue Service). For the Czech Telecommunications Office, the existence of exemptions for conducting measurement flights would aid in the effective monitoring of the frequency spectrum. For example, it is inappropriate to seek the landowner’s consent to operate a drone where there is a source of RF interference on their land, an unauthorised transmitting station, or a station transmitting outside allocated bands. Practice shows that such monitoring is then pointless.

A drone equipped with measurement technology is a suitable and highly effective complement to drive tests or walk tests of mobile wireless networks. Various measuring instruments and different measurement methods are available for various parameters. An overview of the monitored parameters and measuring instruments is provided in detail in Chapter 5. Further work in this area should aim to obtain another set or much larger sets of measured data and expand the dataset. It is important to compare experiences in acquiring this data, evaluate the practical implementation and complexity of the tests, compare the data, and recommend a suitable method. We are only at the beginning of using drones for the purpose of mapping mobile operators’ networks.

In general, the operational requirements for a drone can be summarised as requirements for maximum flight time, maximum weather resistance, maximum payload capacity and minimum cost.

The requirements for measuring instruments are based on the measurement tasks and the payload capacity of the drone used. When selecting a specific instrument and UE, attention must be paid not only to its functions but also to its design and construction, as commonly available instruments and UEs are not primarily intended for use in drones. Most manufacturers also have the necessary accessories for measuring instruments in their portfolio, such as various types of antennas, RF measuring cables, etc. An exception are complete systems, e.g. from companies such as Nokia Drone Networks and Deviser, where the drone is supplied with an integrated measuring system.

However, when it comes to using drones to measure radio coverage parameters, drones are becoming an increasingly popular tool for various applications and commercial activities. Harmonised rules apply to the operation of drones in the EU, which are now enforced in all EU Member States.

5 Use of advanced simulation models and machine learning-based techniques

5.1 Theoretical background

5.1.1 Machine learning methods

Machine learning is an integral part of artificial intelligence (AI). A special subcategory of machine learning is deep learning (DL), which uses multi-layer neural networks to process big data, which is diverse, arrives in large volumes and at high speed. For solving the problems presented in this study, so-called narrow artificial intelligence (ANI) is relevant, which is capable of recognising patterns, learning from data, making decisions, etc. Machine learning utilises algorithms that learn autonomously from datasets and are capable of predicting outcomes and classifying information based on autonomous learning. Machine learning models also refine their predictions based on experience gained.

In the field of radio signal coverage modelling, machine learning has the potential to improve accuracy and efficiency. It offers new possibilities for simulating radio signal coverage and can also lead to significantly better results in actual communication and data transmission via radio channels. Here are some areas where machine learning is applied:

- Data analysis – Machine learning can analyse large amounts of data on signal sources, frequencies used, terrain configuration, obstacles and other factors. Based on these analyses, more sophisticated coverage models can be created. Existing data sources verified, for example, by measurement can be utilised to estimate coverage in other areas, other frequency bands or differently configured signal sources based on similarity.
- Interference prediction – Machine learning can better predict locations where interference occurs between signals, including signals from a single network and operator, but also between networks of different operators, or even signals from different types of services. This enables better radio planning and minimisation of interference, and can also be applied to coverage prediction (interference can limit the actual operation of services at the required quality).
- Adaptive power control and radio resource allocation – Machine learning algorithms can dynamically adjust transmitter power, allocate spectrum segments and time slots, steer beams, etc., based on current conditions. This helps to optimise coverage and the utilisation of radio resources, improve service quality and reduce energy consumption.
- Transmitter site optimisation – Machine learning algorithms can analyse data on signals, terrain and antenna locations. Based on this information, they can propose optimal transmitter sites for maximum coverage or minimise costs for the required coverage.

Examples of machine learning algorithms used for modelling radio signal coverage:

- Regression models:
 - Linear regression: Models the relationship between input and output variables. It can be used to predict signal levels based on various factors.
 - Polynomial regression: Extends linear regression to polynomial functions.
 - Support Vector Regression (SVR): Used to model non-linear relationships.
- Classification models:
 - K-Nearest Neighbours (K-NN): Classifies points based on their similarity to neighbouring points.

- Random Forest: A set of decision trees used to predict signal levels.
- Neural networks:
 - Feedforward networks: Can model complex relationships between inputs and outputs.
 - Recurrent Neural Networks (RNN): Enable the modelling of signal time dependence.
- Genetic algorithms:
 - Optimise model parameters based on evolutionary principles.
- Particle Swarm Optimisation (PSO):
 - Optimises model parameters based on the behaviour of a swarm of particles.

In practice, it is important to select an algorithm based on specific requirements and available data. Each of these algorithms has its own advantages and limitations. In specific commercially available applications, various modelling algorithms and combinations thereof are used.

5.1.2 Other advanced coverage modelling methods

The 'ray-tracing' method appears to be very promising for coverage modelling. It is a model that excels in extreme speed with sufficient accuracy, which can be improved through the use of ML/AI. It draws on experience with 3D graphics processing and precise 3D terrain models. The method has not yet been validated for 5G/6G networks, but its benefits can be expected, including the possibility of application in outdoor environments (particularly densely built-up areas). For Wi-Fi and RFID modelling, see article ⁴³. Brief description of the method:

- Accuracy: the method achieves accuracy comparable to other advanced 3D methods, such as MR-FDPF, with an average deviation of between 5 and 8 dB. This is acceptable for most indoor signal propagation prediction scenarios and ensures reliable results even in more complex environments.
- Speed: The method offers significantly faster simulation speeds than other 3D models, such as SRT or SBR methods, which can take hours. Our method can complete a simulation in tens of seconds to minutes, depending on the chosen heatmap resolution (e.g. 2 to 5 cm/pixel), which is a major advantage in time-sensitive applications.
- Optimisation for complex environments: The use of advanced ray tracing and global illumination techniques from the field of computer graphics enables the modelling of complex environments with a high degree of accuracy. This method accounts for the influence of various materials and obstacles, such as walls, windows or interior elements, allowing for more realistic simulations in challenging conditions.
- Suitability for indoor applications: The method is particularly well-suited for simulating wireless technologies, such as Wi-Fi or 5G, in environments with complex architecture, typically indoor spaces. Its flexibility and adaptability make it ideal for projects involving office spaces, homes or industrial buildings.
- Challenges and limitations: Although this method is faster than other 3D simulations, it remains more computationally intensive than simpler 2D models (e.g. the empirical COST 231 model). However, its main advantage is the ability to fine-tune the balance between simulation speed and detail, allowing the process to be optimised according to specific requirements for accuracy and time efficiency. Further refinements can be expected in the area of image processing, i.e. heatmaps using ML/AI.

5.2 Current status

Fifth-generation mobile networks represent a significant advance in telecommunications thanks to their ability to provide significantly higher speeds, lower latency and greater network capacity. These innovations open the door to a wide range of applications, such as autonomous transport, smart city systems, industrial automation and the massive connectivity of IoT devices. This development brings with it a need for more sophisticated simulation models. With their help, it is possible to fully exploit the potential of these networks and ensure their reliable operation. These models enable operators and developers to accurately predict network behaviour under various conditions,

⁴³ source: <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&number=10557547>

test new technologies and optimise the performance of 5G networks even before they are deployed in live operations. They provide a better understanding of the effects of variable factors such as network topology, user mobility, various types of interference, dynamic resource allocation, and the interaction between new technologies, leading to more efficient planning and improved service quality for end users.

5.2.1 Selected solutions available on the market

There is currently a large number of applications on the market from professional firms specialising in this field. In addition, there are also products originating, for example, from the scientific and academic sectors. These products are mostly of the 'freeware' type, with all the associated problems and benefits, and we will therefore not discuss them further.

Actix International Ltd. / Amdocs Ltd.

Actix has been part of Amdocs since 2013. Actix Analyzer is a multi-vendor desktop solution for the post-processing of data from drive tests and walk tests. Actix Analyzer includes tools for wireless network and device performance analysis, acceptance testing, benchmarking and optimisation.

Amdocs Drive Test Analysis, Suite by Actix⁴⁴ is an advanced software tool designed for the analysis and optimisation of mobile network performance, including 5G NR networks.

The application allows you to define KPIs (Key Performance Indicators) for QoS/QoE of services and events of interest. It enables the analysis of workflows to streamline the testing of technologies and services. The results and conclusions of defined procedures and processes can be shared with a wider team. It features tools for visualising results using report templates and filters.

Atoll3.5 – Forsk S.A.S.

Atoll features a modular architecture that allows customisation to the configurations, technologies and functional requirements of mobile operators.

Atoll modules:

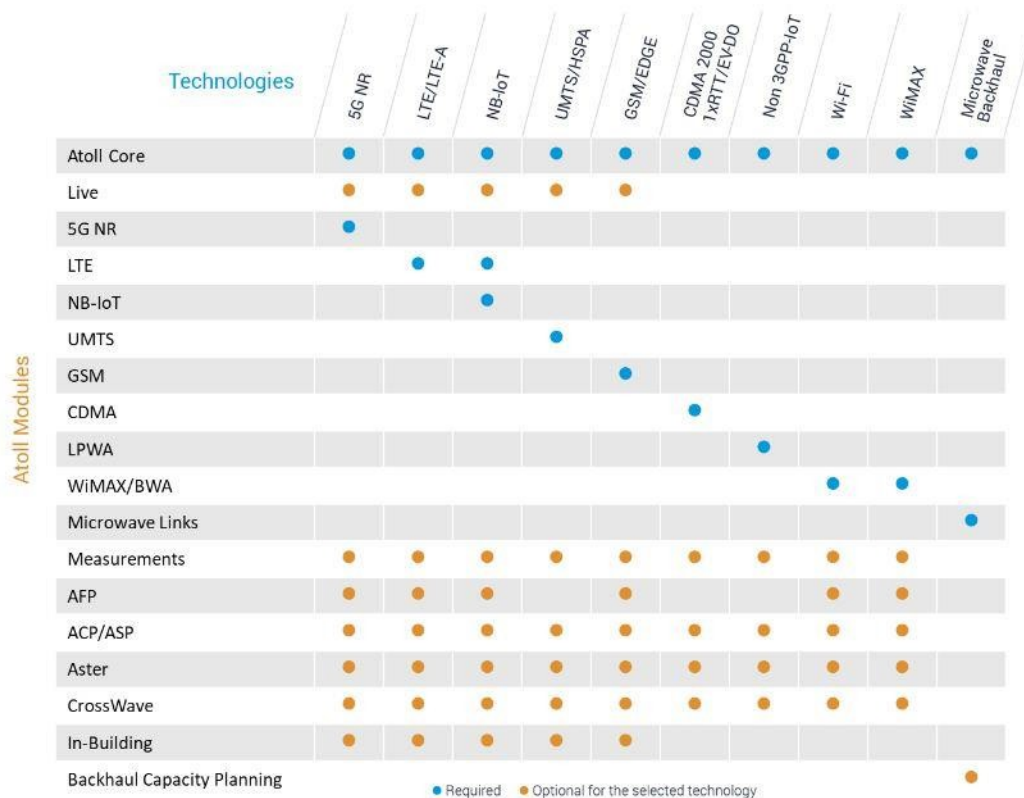
- **Atoll Core** – a module supporting the user interface, GIS functions, propagation modelling, data management services and interfaces.
- **Atoll Live** and **Atoll Automatic Cell Planning** – a module for combining mobile network operational data, such as met KPIs, UE/cell/MDT parameters, and data obtained from crowdsourcing, and for combining this primarily with data resulting from predictions of future conditions. As a result, the module further enhances the accuracy of the Atoll tool. Using the Live module, Atoll Automatic Cell Planning can utilise network operational data for site selection, optimisation and configuration processes.
- **Atoll In-Building** – a module for the design of indoor wireless networks.
- **Atoll Microwave** – is a comprehensive software suite (set of modules) for planning backbone and transmission networks. It is based on the Atoll Core platform and can be integrated with Atoll radio network planning configurations. Atoll Microwave includes advanced LOS modelling and features nLOS/NLOS capabilities for small cell backhaul.
- **Aster** and **Aster mmWave Propagation Model** – are modules for advanced signal propagation modelling, including multipath propagation and calculations for frequency bands below and above the 6 GHz band.
- **Crosswave Propagation Model** – is a universal propagation model developed by Orange Labs. It supports modelling for all wireless technologies and all types of environments, from rural areas to densely populated urban areas.

The table below⁴⁵ shows the modules suitable for individual technologies. For planning projects involving multiple technologies, several modules can be combined within a single Atoll configuration.

⁴⁴ source: www.actix.com, www.amdocs.com

⁴⁵ source: <https://www.forsk.com/>

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Infovista Technologies, Inc. – TEMS⁴⁶

TEMS – is a product from Infovista Technologies, Inc. for testing mobile networks by operators and infrastructure manufacturers. The product combines orchestration, analytical tools and a multi-mode network testing system. The following is available:

- **TEMS Investigation** – used to perform drive tests for verification, optimisation and troubleshooting across all mobile technologies.
- **TEMS Pocket** – used to perform walk tests indoors and testing in hard-to-reach locations using drones.
- **TEMS Paragon** – used to optimise mobile network operations and conduct benchmarking campaigns.
- **TEMS Director** – used to control, manage and monitor TEMS measurement probes and analyse data in real time.
- **TEMS Sense** – used for proactive end-to-end monitoring of wireless network services with active testing.
- **TEMS Discovery** – used to process network testing data and generate analyses and statistics for optimisation.

The TEMS product enables the streamlining of activities across all areas related to mobile network operations, i.e. planning, network deployment, operations, administration and management.

iBwave Solutions Inc.⁴⁷

- **iBwave Design** is a software tool for designing wireless networks in both indoor and outdoor environments, including complex wireless networks, Wi-Fi networks, DAS (Distributed Antenna Systems), small cells and 5G networks. In addition to signal propagation modelling and coverage prediction, the tool's functionality also enables interference analysis and allows the integration of data from real-world field measurements, for

⁴⁶ source: <https://www.infovista.com/>

⁴⁷ source: <https://www.ibwave.com/>

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refine simulations. It enables the optimisation of antenna placement, power settings and the determination of other key parameters to ensure optimal network performance.

- **iBwave Unity Integration** is a tool for managing, synchronising and sharing datasets, created components and models, and entire projects across the team.
- **iBwave Mobile Integration** is a tool integrated into iBwave Design that streamlines the wireless network design process, from the site survey phase through to the final delivery of the design. A preliminary design for the area of interest can be created based on real-world data, with finalisation carried out by taking into account additional information from surrounding areas or higher levels of the existing network, using the iBwave Design application.
- **iBwave Viewer** is a free, simplified version of the iBwave Design viewer, designed for viewing completed designs, 3D prediction designs and running custom output reports.

The product offers flexible licensing of individual components, providing access to advanced features that speed up and improve the quality of the final design, whilst reducing the costs associated with network construction and operation. This applies even to local networks in challenging environments, such as large buildings, stadiums or underground spaces.

HCM Agreement – Harmonised Calculation Method⁴⁸

The HCM Agreement is the official designation of the agreement between the regulatory authorities of Austria, Belgium, the Czech Republic, Germany, France, Hungary, the Netherlands, Croatia, Italy, Liechtenstein, Lithuania, Luxembourg, Poland, Romania, the Slovak Republic, Slovenia and Switzerland, on the coordination of frequencies in the band between 29.7 MHz and 43.5 GHz for the fixed service and the land mobile service. This agreement forms the basis for the HCM model for calculating cross-border interference, which has a significant impact on the usable spectrum in border areas. Example: Spectrum allocation in a location where the borders of 2, 3 or 4 countries meet: 2 countries = 50%, 3 countries = 33.3%, 4 countries = 25%.

Huawei Technologies Co., Ltd.⁴⁹

- **Huawei – Omstar** is an integrated software platform for the management and optimisation of mobile networks. The tool combines several key modules that support operators in ensuring high-quality service and efficient network management, including diagnostics, testing and performance analysis.
- **Huawei Genex Probe & Assistant** are tools used for testing and optimising mobile networks. Huawei Genex Probe is a powerful tool for measuring mobile network parameters and performance (signal strength, data throughput, latency, handover performance, etc.). Genex Probe is typically used in conjunction with Huawei Genex Assistant software, which enables users to analyse test data and generate evaluation reports.
- **Probe** is software for testing the radio interface. Using Probe, network performance can be evaluated, network optimisation carried out and faults rectified. Test data collected from the radio interface can be saved in standardised formats for use by other software components or for post-processing.
- **Huawei FMA – Fault Management Assistant** is a module for collecting and managing network faults, enabling rapid identification and diagnosis of problems, automatic monitoring, and the generation of reports on network faults.
- **Vnet** is a tool designed for the visualisation and simulation of virtual network environments. Using Vnet, it is possible to visualise network topology, simulate changes and analyse the impact of new technologies, such as the roll-out of 5G, or new types of network architectures. Vnet enables better capacity planning and efficient management of network resources, leading to an improvement in overall network performance.

Together, these tools provide a comprehensive platform for the optimisation and management of mobile networks, enabling operators to plan, monitor and improve the quality of their services more effectively.

⁴⁸ Source: <https://www.hcm-agreement.eu/>

⁴⁹ Source: <https://carrier.huawei.com/>

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Keysight Technologies, Inc.⁵⁰

Nemo Analyze Drive Test Post-Processing Solution – Nemo Analyze is a desktop solution for analysing data from Nemo products. Nemo Analyze is used to perform post-processing analysis, troubleshooting and the creation of statistical reports based on data obtained from Nemo tools.

- Fast and efficient post-processing and analysis of data from drive tests and drone tests.
- Provides a complete automated data processing workflow with other Nemo tools, from the collection of raw measurement data to automatically generated results in workbook format.
- Data visualisation with fully customisable, time-synchronised multi-page workbooks and a comprehensive set of data views and visualisations, including maps, networks, line charts, bar charts, pie charts, area networks, colour networks and tables.
- 3D visualisation of 5G NR test data and sectors.
- Fully user-customisable settings for KPIs and reports.
- Data visualisation in web maps, Google Maps and OpenStreetMap.
- A wide range of reporting options, from instant reports to MS Excel-compatible reports.
- Comprehensive off-the-shelf CDR-based reports available for voice and data, supporting technologies from GSM to VoLTE, LTE 8CC and 5G NR.
- Best-in-class, up-to-date support for data from Nemo measurement tools.

RadioLab – CRC Data spol. s r.o.⁵¹

CRC Data is a purely Czech company supplying software, technologies and services in the field of computing, networks and the internet, and providing its own software solutions in a range of areas (radiocommunications, information systems, technological systems, language support and more).

The company focuses on the development, supply and management of software solutions, dominated by radio-communication computing systems. Their systems are used, for example, by the Czech Telecommunications Office (ČTÚ), Telefónica O2 Czech Republic, a.s., T-Mobile Czech Republic a.s., the Civil Aviation Authority (ÚCL), and others.

This comprises a suite of applications and tools for the computational support of tasks involving the analysis of radio signal propagation, the evaluation of key criteria for radio communication services, and the design and optimisation of radio networks. Solutions range from basic tasks such as detailed analysis of terrain profiles, including the display of beam paths on maps, or the calculation and display of radio visibility, to large-scale tasks such as the evaluation of coverage quality criteria for digital television or cellular networks.

RadioLab 4

A computational system for the analysis and visualisation of radio signal propagation over the Earth's surface, including terrain profile analysis, calculation of signal propagation losses, calculation of radio visibility and radar visibility, and calculations of the spatial distribution of electromagnetic field intensity.

- Propagation models – RadioLab 4 includes a range of propagation models based on ITU recommendations as well as models developed by TESTCOM or CRC Data. In addition to these models included in the basic installation, ITU P.1812, ITU P.526 and, soon, ITU P.2001 propagation models are available.
- RadioLab Applications – Offers a wide range of functionality, from complex computational tasks, through the management of various types of data objects, to presentation tools.

⁵⁰ source: <https://www.keysight.com/>

⁵¹ Source: <https://www.crcdata.cz/>

Rohde & Schwarz GmbH & Co. KG⁵² SmartAnalytics –

analytical software:

- provides a QoE insight into mobile network performance.
- provides an accurate assessment of the quality of the operator's own network, i.e. QoE from the end-user's perspective and its competitive position in the market.
- analyses RAN data to improve end-users' QoE.
- highlights network performance issues and analyses their causes.
- Cross-sectional analysis from the macro level down to individual network cells.

SmartMonitor is a web application that provides a real-time overview of the current network situation based on data from QualiPoc Android probes.

- Supports QualiPoc Android probes, which can be installed on Samsung, LG, HTC and Sony smartphones
- Data sent from QualiPoc Android probes is visualised on the SmartMonitor application's dashboards, providing an immediate overview of service quality and network performance from the end-user's perspective
- Cost-effective real-time monitoring of service quality from the end-user's perspective
- Helps reduce operational costs in the field

NESTOR is analytical software for mobile networks. The application manages a network of mobile network scanners and analyses, evaluates and visualises the measured results. NESTOR enables real-time analysis during data collection and the logging of measured data, followed by in-depth analysis. Its application-oriented user interface enables intuitive operation even for complex tasks carried out by public authorities. This information allows authorities to gain an overview of available networks and their coverage. The systems can determine cell locations, detect incorrectly configured base stations and even assist during forensic investigations.

ROMES is a universal software platform for network optimisation. In combination with other test and measurement equipment, such as RF communication scanners and test mobile phones, it provides solutions for all basic tasks related to coverage measurement, interference detection, power measurement and quality analysis in mobile networks. In addition to measuring and displaying test parameters, data is processed immediately and statistical data is calculated in real time. It is designed for networks ranging from 2G to the latest 5G technologies. Another advantage of the software is its ability to visualise measurement results using maps and graphs, enabling easy identification of problem areas such as zones with interference, weak signals or congestion. ROMES also supports the analysis of data service quality, including voice and data transmissions.

SIRADEL⁵³

Volcano ML is a new version of the Volcano propagation model based on machine learning technology.

The Volcano ML model has sufficient performance and the capability to operate across all relevant frequency bands. It enables a significant reduction in the number of propagation models required to cover cities and ensures a very high degree of confidence in the accuracy of the modelling results.

For many years, SIRADEL has been collecting measurement results in numerous countries and environments, across all frequency bands, and uses these results to fine-tune propagation models so that they meet telecommunications operators' coverage accuracy targets. The Volcano ML model provides an extensive knowledge base on how radio signals propagate under various real-world conditions.

⁵² source: <https://www.rohde-schwarz.com/>

⁵³ source: siradel.com, infovista.com

5.2.2 Tools used by operators in the Czech Republic

For the purposes of this study, interviews were conducted with mobile operators in the Czech Republic (CETIN a.s./O2 Czech Republic a.s., T-Mobile Czech Republic a.s., Vodafone Czech Republic a.s.). Based on these, the following can be stated:

- All operators use models and applications for planning, construction, simulation and analysis, primarily from Forsk – Atoll, Aster and Siradel – Vulcano.
- There are discrepancies between the results obtained from simulations and the actual measured values, which are explained primarily by the limited resolution and accuracy of the terrain model and, of course, the variability of the physical parameters of the environment.
- Operators see the main cause of the discrepancies in the terrain models used and, furthermore, for example, in simplified HCM models that do not reflect today's computational capabilities.
- Current legislation requires strict compliance with authorisation and licensing criteria and does not take into account, for example, the physical and climatic conditions prevailing during the measurement and verification of criteria.

From the perspective of both operators and the CTO, an appropriate solution could be to amend the current legislation and create a publicly available 'reference' terrain model developed in collaboration with the Czech Office for Surveying, Mapping and Cadastre (ČÚZK).

5.2.3 Tools used in the CTU's activities

The Czech Telecommunications Office currently uses the RadioLab system for coverage modelling. This system is also used by operators Telefónica O2 Czech Republic, a.s., T-Mobile Czech Republic a.s., the Civil Aviation Authority (UCL) and other entities.

The Czech Telecommunications Office carries out all its measurements in outdoor areas. Data obtained from simulations and from field network measurements are visualised on the VPortal at <https://Vportal.ctu.cz>. The VPortal is used for validating, storing, visualising and sharing data. It is developed and maintained in accordance with the Ministry of the Interior of the Czech Republic's guidelines for the design of public administration websites.

The CTU currently uses the following tools for measuring and verifying network parameters:



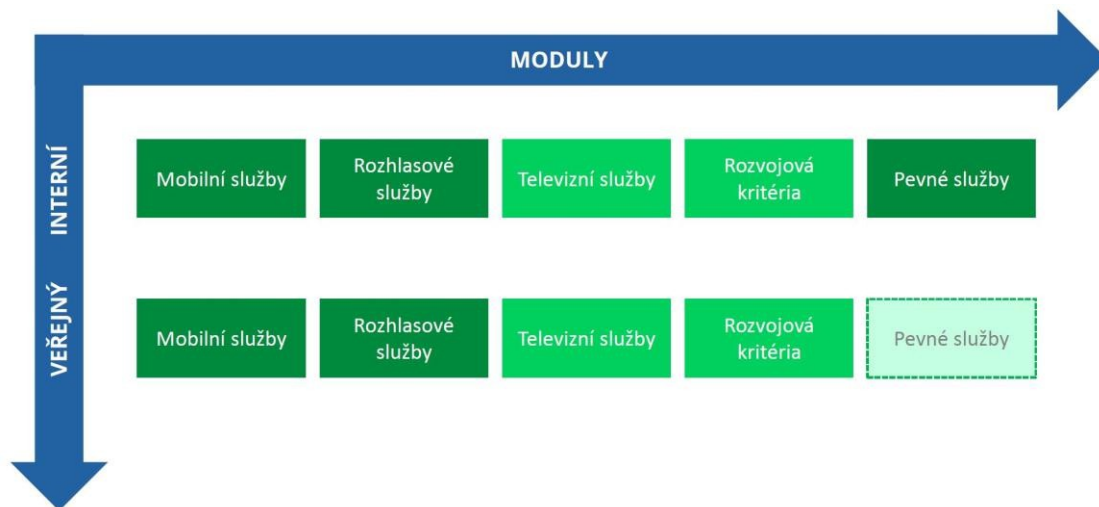
(source: ČTÚ, K. Holec)

The portal primarily contains the following information:

- Coverage calculation results.
- Data obtained from measurements.
- Data analysis overlaid on a map.
- An overview of compliance with development criteria.
- Public complaints and other information.

The portal is divided into an internal and a public section. Both of these sections are further divided into modules.

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(source: ČTÚ, K. Holec)

Data can be displayed over map backgrounds or exported in a data format. The base map allows the display of layers such as the base and aerial layers, a layer containing address points, a layer enabling the display of elevation profiles, etc.

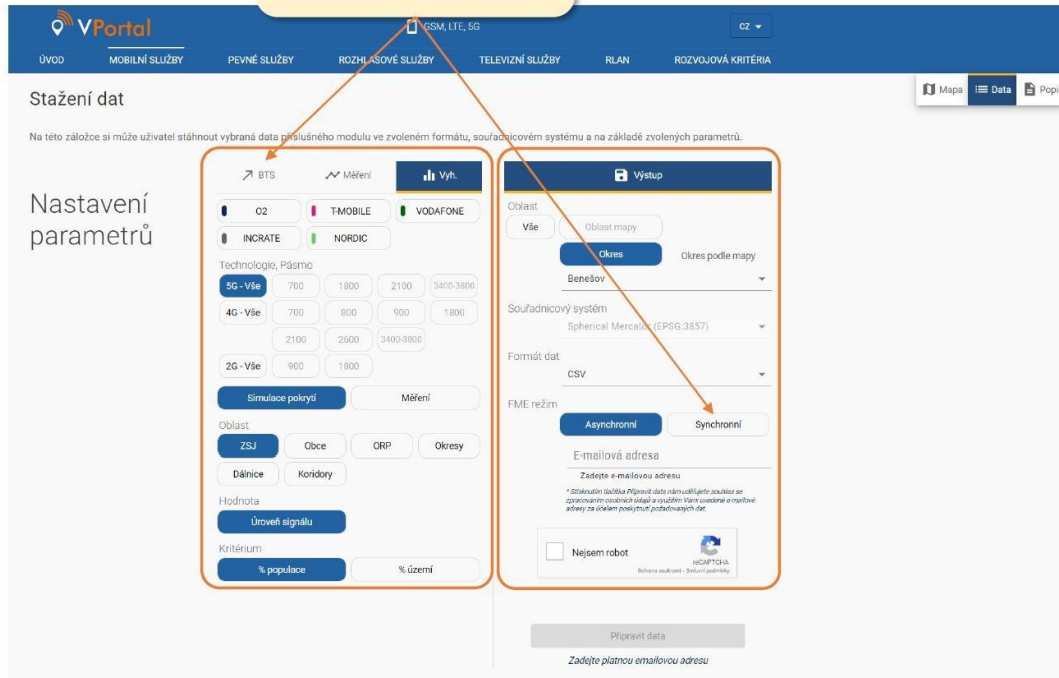
The following parameters can be selected for mobile services:

- Display.
- BTS (Base Transceiver Station).
- Measurement.
- Evaluation.
- Operator.
- Technology, Band.
- Area.
- Value.
- Criterion.
- Coordinate system.
- Data format.

Once the selection and display parameters have been set, the FME server sends a link to download the result to the email address provided.

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Existují rozdíly mezi interní a veřejnou verzí stahování dat z VPortálu.



(source: ČTÚ, K. Holec)

The VPortal is being developed as an open system with a view to further expansion in the future. In the short term, there are plans to expand and supplement selected modules, and in the long term, the development of further new modules is anticipated:



(source: ČTÚ, Ing. K. Holec)

5.3 Identified issues and opportunities

5.3.1 Difference between the simulation models used by operators and the ČTÚ

The CTO and operators use very similar and often identical simulation models.

From the CTU's perspective, differences arise in the simulations, and particularly in relation to the measured values of the simulation models. These differences are caused by:

- Different initial accuracy settings.
- Terrain morphology.
- The categorisation of buildings in built-up areas.
- The determination of population indicators in the given areas.

Furthermore, it is necessary to take into account the fact that measurements of mobile operators' signal coverage of the population are carried out in outdoor areas.

Assessing indoor coverage is problematic, as it depends on many factors. Mobile operators are unable to significantly influence many of these factors:

- The construction materials used in buildings.
- The geometric layout of buildings.
- Applicable laws and standards – these primarily concern health and safety standards relating to permissible levels of exposure to electromagnetic radiation for various types of occupied spaces.
- Technical standards and licensing conditions set by the national regulator – the Czech Telecommunications Office (ČTÚ).

5.4 Partial conclusions

Simulation models play a key role in the development and optimisation of 5G mobile networks and are an indispensable tool. Today, mobile network modelling has reached a high level of sophistication. There are companies on the market that have been dealing with this issue for a long time. These advanced applications not only enable the planning of network deployment and predicted signal coverage, but can also be used to assess the status of existing mobile networks and perform advanced analyses and required predictions. Recently, artificial intelligence has been utilised to process data from network testing, generating analyses and statistics that can be used for optimisation.

The choice of simulation tool depends on the specific requirements and the type of simulations needed for a given project.

Practice shows that there are differences between simulation results and measured values in real-world terrain and operation. These differences exist both between individual mobile network operators and between operators and, of course, in relation to the Czech Telecommunications Office (ČTÚ). These differences stem from the fact that each entity uses different initial conditions describing the given territory and different simulation applications.

From the perspective of both operators and the CTO, a suitable solution could be to amend the current legislation and create a publicly available 'reference' terrain model developed in collaboration with the Czech Office for Surveying, Mapping and Cadastre (ČÚZK).

Given the rapid pace of development in mobile technologies, it appears that standardisation and legislative processes are lagging behind in some respects and require greater attention.

6 The use of more advanced technologies for measuring and monitoring coverage

6.1 Introduction to the issue, identification of opportunities and shortcomings of current solutions

Based on an initial analysis, it was concluded that the measurement technology currently used to measure radio communication service coverage at the physical layer is sufficiently advanced and accurate. This primarily concerns spectrum analysers. The current measuring instruments used by the Czech Telecommunications Office (ČTÚ) can handle frequencies up to 90 GHz. Higher bands are not yet relevant for practical use and should only be considered in the longer term (after 2030 and beyond).

The situation is more complex when it comes to verifying services at higher communication layers. This does not strictly involve measurement, but rather verifying communication availability and data transmission performance. Measurement applications, much like the services on offer, change relatively quickly, and it is not entirely straightforward to select a solution that is stable and promising in the long term. Following discussions with staff at the Czech Telecommunications Office (ČTÚ), the scope of the assignment was refined to focus on research into measurement applications for mobile terminals (mobile phones), with an emphasis on innovation in tools for measuring voice services. Measurement in this area is used primarily to address user complaints regarding the poor quality of the service provided. In the case of the core voice service, this concerns its availability, problems with call interference, and dropouts/poor handover. The CTO's equipment in this area is becoming obsolete, and modern terminals (mobile phones) and modern measurement applications are not available. A clear trend is the gradual shift of voice services from circuit-switched GSM technology to packet-based VoLTE and VoNR (Voice over LTE, Voice over New Radio) communication.

The advantage of testing using mobile terminals is that it most closely reflects the user experience, including the use of the specific hardware and operating system (which can sometimes be a disadvantage, e.g. insufficient processor computing power).

A general problem with this segment of testing is that the mobile terminal market is evolving very rapidly, is extremely broad, and it is not possible to keep fully pace with the speed of market development; furthermore, it is neither economically nor logistically feasible to dynamically update the portfolio of test terminals. It is only possible to focus on the typical and most widespread models on the market and to carry out updates not every year, but, for example, every three years.

In line with this problem, even manufacturers of test applications for mobile terminals are unable to respond dynamically to changes, and it is sometimes they who hinder the deployment of a new terminal because they have not yet completed or properly tested the software support for it.

6.2 Testing of voice services

Voice signal transmission remains one of the key services provided by LTE/5G mobile networks. The specific characteristics of packet-switched networks have necessitated the development and implementation of technologies known as VoLTE and VoNR. Modern networks transmit the voice signal with higher quality and lower latency compared to traditional mobile networks. Future developments in voice transmission in mobile networks are likely to include further improvements in call quality, reduced latency and integration with new technologies such as artificial intelligence and augmented reality. However, with the growing number of devices connected to 5G/6G networks, it is expected that the volume of data transmitted for voice calls will remain relatively stable, whilst the volume of data for other services will continue to grow.

6.2.1 Basic classification and evaluation of voice services

There are two main types of voice services available on mobile networks:

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- VoLTE / VoNR voice services defined and contractually guaranteed at the operator level, which have strict QoS support and do not form part of the public internet.
- OTT voice services are generally provided over the internet and will continue to be provided via mobile networks on a best-effort basis alongside general traffic based on network neutrality (e.g. Viber, WhatsApp, Skype and others).

As with other services offered, it is necessary to monitor and measure the quality parameters of voice services to ensure that the end user is satisfied with the service. The basic methodology for testing voice connections in LTE networks is set out in ITU-T G.1028. 5G mobile networks then build upon this methodology.

The basic KPI performance parameters for voice signal transmission in LTE networks are defined in G.1028. The key parameters are:

- CBR (Call Blocking Rate) – the percentage of calls that fail to connect.
- CDR (Call Drop Rate) – the percentage of dropped calls out of all successfully established calls.
- Occurrence of one-way calls (asymmetrically) – this condition can be verified by measuring MOS.
- MOS (Mean Opinion Score) Call quality in the parameter – LQO (Listening Quality Objective) – listening quality measured objectively, with the aim of extending this to conversation quality (MOS-CQO, MOS-Conversation Quality Objective) compared to existing systems.
- Call setup time (for analysis, it is useful to break this down into sub-phases: initiation, start of ringing, actual ringing, answer, channel availability); certain events can be detected from the 5G modem, others from the audio channel.

6.2.2 Methodologies for evaluating call signal quality

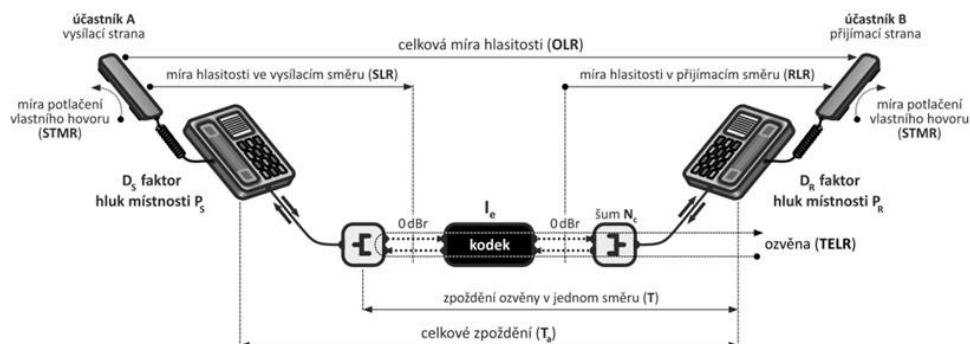
For historical reasons, there are a number of methodologies for evaluating voice signal transmission parameters, which have gradually emerged in response to evolving requirements.

Subjective evaluation. The principle involves the statistical evaluation of speech sample quality by a sufficiently large, randomly selected group of individuals based on a completed questionnaire. The questionnaire is set out in ITU-T Recommendation P.82. The economic costs of this methodology are increased by the need to ensure defined test conditions in accordance with ITU-T P.800. However, the result of this methodology is a true average rating, referred to as MOS-LQS (Mean Opinion Score – Listening Quality Subjective).

Objective evaluation. The principle involves the statistical evaluation of speech sample quality through digital signal processing and mathematical models that simulate the human auditory system. This methodology is not as time-consuming or costly. Its disadvantage is its dependence on the accuracy of the mathematical model. The result of this methodology is the MOS-LQO value.

Estimation method. This method does not work with speech samples, but uses the so-called E-model. The E-model is a tool that describes the complete chain for the transmission of the speech signal and its parameters. The E-model was developed by an expert group at ETSI and is described in ITU-T Recommendation G.107 (G.107.1 Wideband E-model; G.107.2 Fullband E-model). For each individual factor that influences call quality, the model defines a coefficient with a specific range of values. The significance of the coefficients is illustrated in the following figure, which shows a reference connection between two subscribers, including the acoustic interfaces (shown here for fixed telephony, but generally applicable to mobile and hybrid telephony, including VoIP).

Figure 5 – Transmission chain diagram for the narrowband E-model.



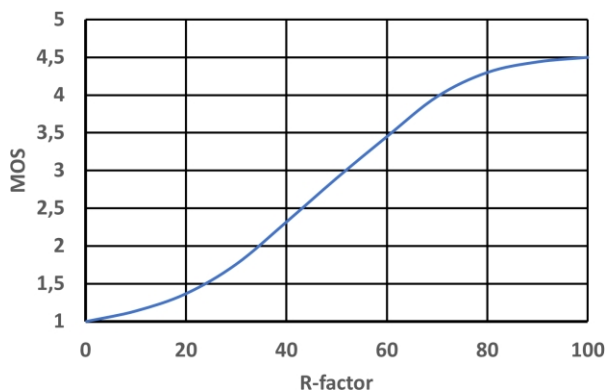
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The resulting R-factor (Rating) is defined as the simple sum of the individual coefficients and takes values ranging from 0 to 100 (however, an acceptable value is only within the range of 50 to 100). It takes into account the effects of noise, volume, quantisation distortion, coding method, echo and delay. The R-factor is determined for the entire transmission chain between the acoustic interfaces of the telephone network; that is, it takes into account not only the telephone channel itself but also the terminal equipment. The higher the R-factor value, the higher the quality of the telephone service. The resulting R-factor value can be converted to the MOS scale. The result is then simply the Estimated Quality Value (MOS-LQE, MOS – Listening Quality Estimated).

Table 6 – Assignment of R-factor values to quality categories.

R-factor range	Speech transmission quality
$90 \leq R < 100$	Best
$80 \leq R < 90$	High
$70 \leq R < 80$	Medium
$60 \leq R < 70$	Low
$50 \leq R < 60$	Poor

Figure 6 – Conversion of the R-factor parameter to the MOS scale.



6.2.3 Algorithms for evaluating call signal quality

Both non-intrusive and intrusive measurements are used to assess speech signal quality.

Non-intrusive measurement – computational algorithms do not have a reference speech sample available for evaluation. For this reason, it is difficult to detect certain specific types of sample distortion during transmission. The basic methodology is INMD (In-Service Non-Intrusive Measurement Device, ITU-T P.561), which is designed for in-service measurement in both circuit-switched and packet-switched networks. The INMD methodology lists the necessary evaluation parameters and the principles for their measurement. The method for combining the measured parameters into a single resulting quality parameter, the CCI (Call Clarity Index, © Copyright British Telecommunications plc.), is prescribed by ITU-T Recommendation G.562.

The ITU-T P.563 standard (3SQM, Single Sided Speech Quality Measure) describes a methodology for non-intrusive, objective measurement of voice signal transmission quality. The received sample is first appropriately processed; a model of the receiving telephone is applied; time intervals containing speech are identified, etc. The subsequent analysis of the pre-processed speech sample can be divided into three independent parts:

- Analysis of the vocal tract and voice unnaturalness:
 - Gender recognition (male voices and female voices).
 - Synthetic voice.
- Noise analysis:
 - Background noise level.
 - Noise in segments.
- Interruptions, attenuation and time clipping (transmission dropouts).

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The result of each part is evaluated (assigned a main distortion class) and the MOS-LQO parameter value is calculated from the partial results as an overall assessment. A drawback of this method is its limited accuracy, particularly for less common languages such as Czech.

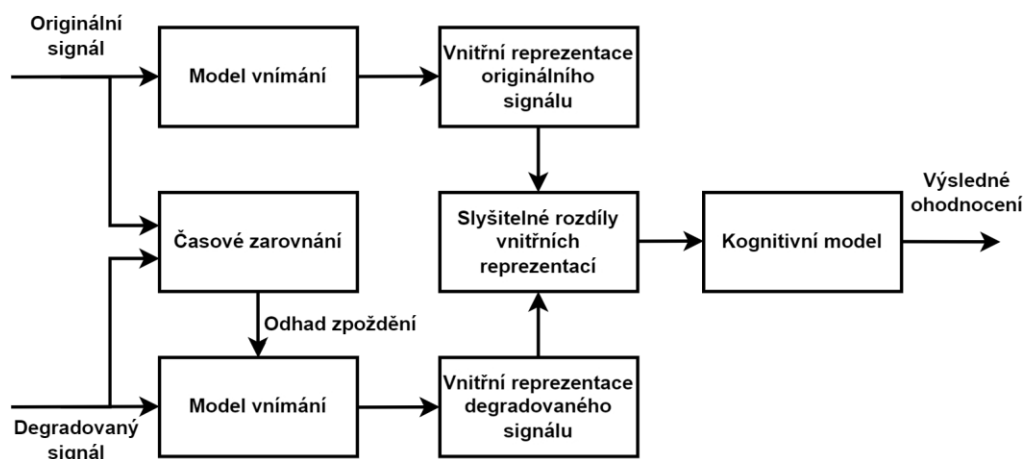
Intrusive measurement – computational algorithms operate by comparing a reference speech sample with a degraded (transmitted) speech sample.

For historical reasons, there are a number of objective methodologies for evaluating speech samples that utilise intrusive measurement. These methodologies were designed not only for the telecommunications sector (narrowband codecs and signals), but primarily for the television and radio broadcasting sector (broadband codecs and signals). The individual methodologies are similar in principle, which involves comparing the original sample with the degraded one. They differ significantly in the implementation of the model of human perception (cognitive model) and in the method of mutual amplitude and time correlation (alignment) of speech samples. The resulting quality score consists of a single number representing the acoustic distortion of the tested signal.

PSQM (Perceptual Speech Quality Measure, ITU-T P.861) is the fundamental methodology for assessing the quality of speech signal transmission, optimised for narrowband telephone speech signals. The PSQM methodology first maps the signals (original and degraded speech samples) into a psychoacoustic representation (auditory conversion) so that they correspond to the internal representations of speech signals (as represented within the human brain). The quality of the encoded speech is determined based on the resolution of these internal representations by a cognitive model.

The PESQ (Perceptual Estimation of Speech Quality) methodology is standardised as ITU-T P.862. It is essentially PSQM with delay compensation and improved detection of silence in the call, which is particularly important for VoIP. The result is the MOS-LQO parameter. A drawback of PESQ is that it is not suitable for real-time applications. It is both time-consuming and computationally intensive; it injects samples for transmission evaluation into the live network, thereby burdening it with artificial traffic.

Figure 7 – Schematic block diagram of the PESQ evaluation methodology.



The POLQA methodology (Perceptual Objective Listening Quality Analysis, ITU-T P.863) is based on the PESQ methodology and addresses its shortcomings, typically the time alignment of individual samples and compatibility with new codecs. Unlike PESQ, POLQA supports wideband codecs for speech signals (up to 24 kHz). During evaluation, POLQA examines the original speech sample and its defects (reverberation, noise, etc.), taking these into account in the overall assessment.

ViSQOL⁵⁴ (Virtual Speech Quality Objective Listener) is an objective methodology for evaluating the perceived quality of sound and speech. It compares a reference sample with a sample degraded by transmission through a communication network. The output is a prediction of speech quality expressed by the MOS-LQO parameter. The first phase involves pre-processing the samples being compared, during which they are power-aligned and resampled to the required sampling frequency (48 kHz for audio mode, 16 kHz for speech mode), and spectrograms are generated. The second phase is alignment, in which the generated spectrograms are first segmented and

⁵⁴ Hines, A.; Skoglund, J.; Kokaram, A.; et al. ViSQOL: The Virtual Speech Quality Objective Listener. Acoustic Echo Noise Control (IWAENC), IEEE Intl. Workshop on, Jan 2012: pp. 1–4.

the similarity between individual segments of the reference sample and the test sample. In the third phase, the MOS-LQO score and the time distortion measure are calculated based on the similarity measure. Compared to other standard metrics, such as PESQ and POLQA, ViSQOL often achieves comparable or better results, particularly when addressing issues such as time distortion or playback delay. ViSQOL is constantly being updated and expanded to support new technologies and audio processing methods, such as deep neural networks and generative models.

6.2.4 Further developments in voice call quality testing

Testing voice signal transmission using the aforementioned intrusive methodologies, which are also suitable for automated measurements, involves comparing the original and transmitted samples and using a psychoacoustic model of human perception to estimate the results of subjective tests. With the methodologies currently in use, a high degree of agreement with subjective tests is achieved. Essentially, these methods assess what is known as Listening Quality. However, this quality does not account for the effects of signal delay during transmission, speaker and listener echoes, artefacts from concurrent speech, switching of the comfort noise generator, etc., i.e. factors affecting the conversation between two end-users.

The influence of these parameters on a conversation is so significant that, to assess overall conversation quality (CQ), it is necessary to use more comprehensive methodologies, where listening quality is merely one of several parameters. Other parameters under consideration include technical parameters such as transmission delay, echo level, etc. More comprehensive methodologies include the E-model or the Management Conversational Quality Predictor (ETSI TR 103 121).

The E-model (according to ITU-T G.107) was designed for the purposes of communication network planning, including the interconnection of networks from different providers and the use of various end terminals. The results provided by the E-model are more pessimistic compared to listening tests. Based on this experience, an advanced MCQP (Management Conversational Quality Predictor) model was developed and standardised for the objective evaluation of voice signal transmission quality, which takes into account more evaluation parameters than the E-model. For this reason, the implementation of this model into measurement tools is likely in the future.

6.3 Testing of video multimedia services

In the context of historical developments, there are generally a number of international recommendations for the measurement and evaluation of parameters in the field of video signal distribution. With the advent of modern communication networks, a relatively simple situation has become many times more complex. Originally, data stream distribution was solely unidirectional (from the information source to the consumer) and signal transmission was possible only via terrestrial means or cable television networks. Today, different transmission technologies are used; the format of the transmitted information has changed, and the way the service is used by the end-user has also changed, as the end-user can now participate in content creation. For these reasons, criteria that take into account additional time-dependent factors (variation in delay, response time on the part of the information source, etc.) are added to the usual objective quality parameters of the data stream (error rate, propagation time, etc.). The resulting evaluation is then significantly influenced by subjective criteria assessing the transmitted content.

6.3.1 Evaluation of OTT multimedia services

OTT (Over-The-Top) services can be regarded as a substitute for traditional telecommunications services. Their proliferation has coincided with the development of high-speed internet connections. For the end user, OTT services offer similar benefits to traditional telecommunications services (text messaging, transmission of multimedia signals, etc.). However, the advantages of OTT services lie in the dynamism of their development, as they are not subject to the usual standardisation processes. For this reason, they can respond quickly to new user requirements and satisfy them.

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From the perspective of BEREC BOR (16) 35⁽⁵⁵⁾, OTT services are divided into:

- OTT-0 – an OTT service that is of the nature of an ECS (Electronic Communications Service)⁵⁶,
- OTT-1 – an OTT service that is not an ECS but potentially competes with ECS,
- OTT-2 – other OTT services.

Three basic criteria for identifying an ECS service follow from the definition of an ECS service. An ECS service:

- is usually provided for remuneration,
- consists wholly or mainly of the transmission of signals,
- does not include services providing content or exercising editorial control over content.

ECS and OTT services offer similar benefits to the end user. However, OTT services usually have an encrypted data stream, the server providing the OTT service is not accessible to the network operator, and OTT services not subject to standardisation may change their parameters.

It follows from the above that it is very difficult to diagnose a non-standardised service that changes its parameters or nature depending on various requirements. The evaluation of OTT multimedia service parameters is based on verified ECS service methodologies, whilst also respecting the recommendations of industry associations such as the DASH Industry Forum⁵⁷ or the Streaming Video Technology Alliance⁵⁸.

The methodologies for measuring quality parameters in video data streams are, in principle, the same as those used for measuring voice services. Depending on whether stream or service parameters are verified in In-Service/Out-of-Service mode, objectively/subjectively, intrusively/non-intrusively, and depending on the availability of undamaged source information, one can speak of measurement with full or partial reference, or measurement without reference.

Data streams of multimedia services generally utilise UDP/TCP protocol structures over IP, and therefore it would be possible to evaluate them using standard QoS metrics at the L3/L4 layers. However, given the nature of the transmitted information and how it is perceived by the end user, evaluation at L3/L4 is insufficient, and assessment must be carried out at the application layer of the network model (L7). For the evaluation of video information itself, methods such as Peak Signal-to-Noise Ratio (PSNR), Video Quality Metric (VQM) or Structural Similarity (SSIM)⁵⁹ can be used.

The principles outlined above can be applied to traditional video telephony or traditional IPTV services. OTT multimedia services typically use the TCP communication protocol for data transmission, which is capable of ensuring error-free data transmission within certain limits. Furthermore, at the cost of increased transmission delay, advanced algorithms for detecting and correcting errors in the transmitted data stream can also be utilised. The aforementioned methods for evaluating image information in OTT multimedia services thus lose their informative value, as the end user may be consuming content entirely different from that transmitted over the communication network.

Due to the considerable complexity of subjective QoE evaluation (requiring a sufficient number of evaluators, training, and questionnaires), there is an effort to replace subjective QoE evaluation with objective evaluation. That is, to use a mathematical model capable of predicting the end-user's resulting perceived evaluation – QoE – based on selected key quality indicators (KQI) for QoS evaluation. Such analytical models predicting QoE evaluation are therefore called predictive QoE models.

⁵⁵ Source: <https://www.berec.europa.eu/en/document-categories/berec/reports/berec-report-on-ott-services>

⁵⁶ Directive 2002/21/EC of the European Parliament and of the Council: <https://eur-lex.europa.eu/legal-content/cs/TXT/?uri=CELEX%3A32002L0021>

⁵⁷ source: dashif.org

⁵⁸ Source: www.svta.org

⁵⁹ DE ANGELIS, Francesco. A lightweight QoE evaluation model for OTT media services. Online. EBU Technology & Innovation. 2019, p. 15. ISSN 1609-1469. Available from: <https://tech.ebu.ch/publications/a-lightweight-qoe-evaluation-model-for-ott-media-services>. [accessed 16 September 2024].

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We can evaluate the parameters of multimedia streams for the purpose⁶⁰ :

- monitoring, where we objectively assess the quality of the data stream of the application of interest in real time (e.g. according to ITU-T P.1202).
- planning, where, prior to the launch of the multimedia service in question, we verify compliance with the required parameters, i.e. the parameters of the transmitted data stream and the data network are verified (ITU-T G.1071).
- precise laboratory testing, where the aim is to evaluate service parameters under non-operational conditions of the communication network, for example in the presence of undistorted reference information, or when verifying the parameters of a network element (ITU-T J.341).

Objective evaluation using predictive QoE models can be divided into:

- The multimedia layer model works with real multimedia signals (audio/video). It reflects the influence of the parameters of the codec and transmission channel used. Depending on the availability of a reference sample for evaluation purposes, this model is further divided into categories:
 - Full Reference – a complete reference sample is available for determining evaluation parameters, which is compared with a degraded sample (transmitted via a communication network). FR models are typically used for precise evaluation in laboratory tests (in accordance with ITU-T J.247).
 - Reduced Reference – only certain characteristics from the reference information are available for evaluation (e.g. information on motion vectors, edges, textures, etc.). For the purposes of evaluation at the receiving end, these characteristics can be transmitted within the stream under examination itself, such as metadata (ITU-T J.246).
 - No Reference – evaluation models do not have a reference sample available; using algorithms, they search the received content for undesirable conditions, which in the case of videos may include so-called pixelation, freezing of parts of the image, blurring, etc. These methods are generally used for real-time video quality assessment in multimedia applications (ITU-T P.1201).
- The packet layer model uses only information from the headers of data packets to predict the QoE rating, without taking into account the actual transmitted content (payload). Such models are primarily intended for monitoring multimedia streams via network probes. (ITU-T P.1201).
- The bit-stream layer model is a combination of the packet and multimedia layer models, as the assessment takes into account not only the information in the bit-stream but also the information from the packet header. (ITU-T P.1202, ITU-T P.1203).

For subjective evaluation, ITU-T Recommendation P.910 can be used, which includes the Absolute Category Rating (ACR), Absolute Category Rating with Hidden Reference (ACR-HR), Degradation Category Rating (DCR), and Pair Comparison (PC) algorithms.

Hybrid methods combine objective and subjective evaluation methods. Hybrid methods typically use a subjective evaluation method at the start of the evaluation process. The aim is to obtain an assessment of the quality of the reference samples (video sequences) from the evaluators. The reference samples are subsequently degraded appropriately depending on the QoS factors of the transmission environment, and predictive QoE evaluation models are applied for assessment, taking into account the initial subjective test.

The PEVQ-S methodology was developed by OPTICOM GmbH (author: POLQA). The methodology is designed for the evaluation of QoE in video transmissions, including OTT services, in both fixed and mobile networks. The methodology is based on PEVQ® (Perceptual Evaluation of Video Quality) in accordance with the ITU-T J.247 standard. During evaluation, a reference sample is compared with a degraded sample, and the evaluation output is transformed into a MOS scale.

Rohde & Schwarz SwissQual AG uses a methodology based on ITU-T J.343.1, which is a hybrid, reference-free methodology for evaluating QoE in IPTV/CaTV networks, combining a bit-stream model and a multimedia layer model. As no reference sample is used for evaluation, it is also possible to evaluate multimedia streams such as live TV broadcasts, including encrypted data streams. The implementation of the methodology by Rohde & Schwarz SwissQual AG also enables the testing of OTT multimedia streams.

⁶⁰ PAL, Debajyoti and TRIYASON, Tuul. A Survey of Standardised Approaches towards the Quality of Experience Evaluation for Video Services: An ITU Perspective. Online. International Journal of Digital Multimedia Broadcasting. 2018, vol. 2018, pp. 1–25. ISSN 1687-7578. Available from: <https://doi.org/10.1155/2018/1391724>. [accessed 16 September 2024].

6.3.2 Partial conclusions

There is no universal methodology for testing OTT voice or video applications and the information they transmit. There are methodologies for assessing the transmission quality of video or audio/video information alone in standardised transmission technologies, e.g. CaTV, IPTV and video calls using RTP/RSTP/SIP protocols, etc. When determining QoE for services of interest, the aim is to replace more accurate but costly and time-consuming subjective assessments with objective ones. Objective assessment methodologies focus on finding mathematical models that will faithfully replicate the end-user's perceptual behaviour in relation to the parameters of an undegraded service and transmission conditions.

The evaluation of OTT services is usually carried out in accordance with the proprietary methodology of the company offering such services. The services provided by these companies are comprehensive, including the monitoring of parameters and the provision of results in real time, with recommendations for follow-up processes.

6.4 Systems for measuring and monitoring radio network services

Verification of voice signal transmission parameters, or multimedia transmission parameters in modern mobile networks, utilises two principles.

The first principle involves measuring basic mobile network QoS parameters, such as transmission delay, delay variation, transmission error rate, etc. The E-model (ITU-T G. 107) computational model is applied to the measured parameters, with evaluation using the MOS parameter. A major drawback of this approach is that it is not possible to take into account the complex nature of voice communication and the dynamic behaviour of the mobile network. The resulting QoE evaluation is an estimate based on the measured parameters of the mobile data network.

The second principle utilises specialised end terminals or commonly available mobile terminals (mobile phones) equipped with special software that emulates real voice communication. A specialised terminal sends known data samples representing a voice signal to the remote test terminal. The latter is located in an environment that, by its nature, precludes any negative influence on the test. This intrusive testing is as reliable as possible. A disadvantage of using standard mobile phones is the possibility of the test being influenced by the mobile phone's parameters and the need to modify specialised software.

Generally, a mobile terminal testing system consists of the following components:

- A mobile terminal (a set of typical models from different generations and manufacturers, equipped with various SIM cards for testing different operators and different types of services).
- An application running on the mobile terminal.
- A control unit coordinating the local execution of tests on the set of terminals (typically via a USB interface).
- A server against which the tests are run (a dedicated data source or selected internet servers).
- A central cloud-based application for data collection, test coordination, evaluation, visualisation and statistics.

It makes sense to perform tests within a single network (between terminals on a single operator's network), for tandem connections between networks of different operators (combined mobile or fixed terminals), and also against a reference point (test server) in a fixed VoIP network.

6.4.1 Current solution for testing voice services

At present, the Czech Telecommunications Office does not have a specific methodology for evaluating the quality parameters of voice services in mobile networks. Quality criteria for voice services are not included in tender procedures for the allocation of radio frequencies. The Czech Telecommunications Office does not have sufficient suitable hardware available for measurement and evaluation, nor is it of a standard that meets modern requirements.

The current situation stems from the historical context of the roll-out of GSM mobile networks, when the primary purpose of the network was to transmit voice signals. To ensure the quality parameters of voice services, it was sufficient to measure the parameters of the radio interface. If these parameters were within the relevant limits, the voice service was available at the required level.

For voice service parameters, the Network Plan for Transmission Parameters of Public Communications Networks (General Measure No. SP/2/01.2022-1 and No. SP/2/05.2011-7⁶¹) is currently in force, which specifies the quality of voice communication, including mobile networks.

Mobile communications network operators in the Czech Republic use the services of subcontractors to test voice communications. Analyses focus primarily on compliance with the specified KPIs, i.e. in particular the ability to establish and maintain a call.

6.4.2 Future approaches to testing voice services and their combination with other services

Current and future voice signal transmission via mobile operators' networks is based on the VoLTE or VoNR principle.

The POLQA methodology is used worldwide to assess quality, in fixed, mobile and IP networks alike. The third version, POLQA v3, has been available since 2018. The POLQA algorithm is the result of development by OPTICOM, SwissQual and TNO. It is protected by copyright and patents. In accordance with the relevant licence from the aforementioned companies, it is available as software for various platforms. The licence is currently used by more than 100 entities (manufacturers and operators) worldwide.

Products utilising POLQA are offered by leading manufacturers, typically:

Enhancell Ltd.

Enhancell Ltd. is a Finnish company that has developed a family of tools for comprehensive analysis of wireless networks under the umbrella brand Enhancell Echo. The individual components enable the collection of relevant data, its processing, and the visualisation of the results obtained. The Enhancell Echo family of tools enables, among other things, the evaluation of call connection parameters.

The Enhancell Echo suite of tools includes the following products:

- Echo One and Echo Lite – these are standalone software tools for measuring mobile network parameters, which can be installed on mobile phones running Android and Harmony OS. Chipsets from Qualcomm and HiSilicon are supported, and now also Exynos. The Echo Lite product has limited functionality in terms of acquiring radio interface parameters (displaying information about the cell, band, etc.) and does not require root access to the Android OS to run.
- Echo Scanbox/Scanbox Pro/ScanMaster is a family of standalone measurement probes for monitoring LTE/5G NR mobile network parameters.
- Echo Plus is a software tool for tablets that enables the configuration and management of measurement probes in real time. It allows for the parallel running of indoor/outdoor tests, logging of activity and measured results from individual probes. It also enables the visualisation of results and synchronisation with the cloud. The probe can be the Echo One/Lite software tool, an EADS TETRA device, or third-party network scanners (e.g. PCTel IB/HB flex® devices are supported).
- Echo Studio – is a software tool for personal computers/laptops running Windows/Linux/Apple OS. It offers similar functionality to the Echo Plus product, including the management and control of measurement probes, indoor/outdoor testing, data collection and visualisation of results, and synchronisation with the cloud. Furthermore, Echo Studio can be used to decode and analyse captured signals, perform post-processing and visualise results stored in the cloud and obtained by other tools in the Echo family, and generate reports.
- Echo Analyzer – is a software tool optimised for the post-processing of large volumes of data with subsequent visualisation.

⁶¹ source: <https://ctu.gov.cz/opatreni-obecne-povahy-c-sp2052011-7-kterym-se-vydava-sitovy-plan-prenosovych-parametru-verejnych>

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- Echo Cloud – is an online service for all Echo tools, enabling remote monitoring and management, automatic synchronisation of configurations and results, the creation and distribution of tests, automation of activities, map data management, and licensing.

To enhance user-friendliness, the company offers the Echo Connect dongle, which, when connected to a (certified) mobile phone running Android, functions as Echo One, but without the need to root the OS. Pre-configured solutions for walk/drive tests are available to end customers.

Solution functionality in terms of voice signal transmission evaluation:

- Outdoor and indoor tests (iBWave solution).
- Support for LTE/LTE-A / 5G NSA / 5G SA / 5G NR.
- Support for commonly available mobile devices with a compatible chipset (Qualcomm/HiSilicon/Exynos), support for EADS TETRA, third-party scanners.
- Flexible licensing policy (licence transfer, floating licences, short-term licences, etc.)
- Remote management functionality, scripting, test parameterisation, parameter synchronisation, visualisation via graphs and mapping, processing of large volumes of data.
- Support for tests to evaluate voice transmission quality between mobile terminals or between a mobile terminal and a fixed network.
- Support for evaluation using the ViSQOL methodology.
- Evaluation using the POLQA v3 methodology with real-time calculation of the MOS parameter for both narrowband and wideband codecs.

Figure 8 – Example of POLQA test settings.

The image shows a screenshot of a software interface titled "VOICE CALL". It contains several input fields and dropdown menus for configuring a test. The fields are: "Name" with the value "Test"; "Mode" with a dropdown menu showing "Call"; "Number" with the value "722922553" and a small black square icon to its right; "Duration (seconds)" with the value "15"; "MOS Algorithm" with a dropdown menu showing "POLQA NB (Narrow Band)"; and "Reference sample" with the value "Czech_SWB_f2s1_m1s4_6s.wav".

Rohde & Schwarz GmbH & Co. KG

Rohde & Schwarz (which includes SwissQual, one of the developers of standardised speech quality testing methods) offers a comprehensive solution for monitoring and analysing wireless networks – Rohde & Schwarz Mobile Network Testing (MNT). The MNT portfolio includes specialised hardware devices and software products for data collection, tools for planning and operating measurements, and software for analysing the results obtained. MNT also offers measurement of call quality parameters in mobile networks. To measure relevant parameters in voice signal transmission, a measurement system comprising three software components can be used.

- R&S@QualiPoc is software for implementing a measurement probe for mobile networks. The best known is QualiPoc Android, which is a measurement probe in a standard mobile phone (the standalone QualiPoc Android Probe). The QualiPoc software, in conjunction with the appropriate hardware, offers functionality for measuring parameters from the lowest communication layers (RF) right up to QoS/QoE evaluation in OTT applications (audio and video streaming, WhatsApp communication, etc.). Major chipsets from Qualcomm, Samsung Exynos and HiSilicon are supported. A range of models from various manufacturers (Samsung, Xiaomi, OnePlus, Sony, etc.) are certified for installation.
- SmartAnalytics is an analytics software that provides insights into the quality of experience (QoE) of mobile network users. The software tool enables the storage, processing and visualisation of measured data on map overlays (indoor/outdoor). It features the necessary post-processing for optimal utilisation of available data. Based on the data obtained, it is also able to recommend next steps for optimising the tested network. It uses data collected by the SmartMonitor and SmartBenchmarker components for its analyses.
- SmartMonitor is a server-based monitoring application with a web interface for real-time monitoring of mobile network service quality. It controls remote measurement probes (typically R&S@QualiPoc), aggregates results, and performs their analysis and visualisation.

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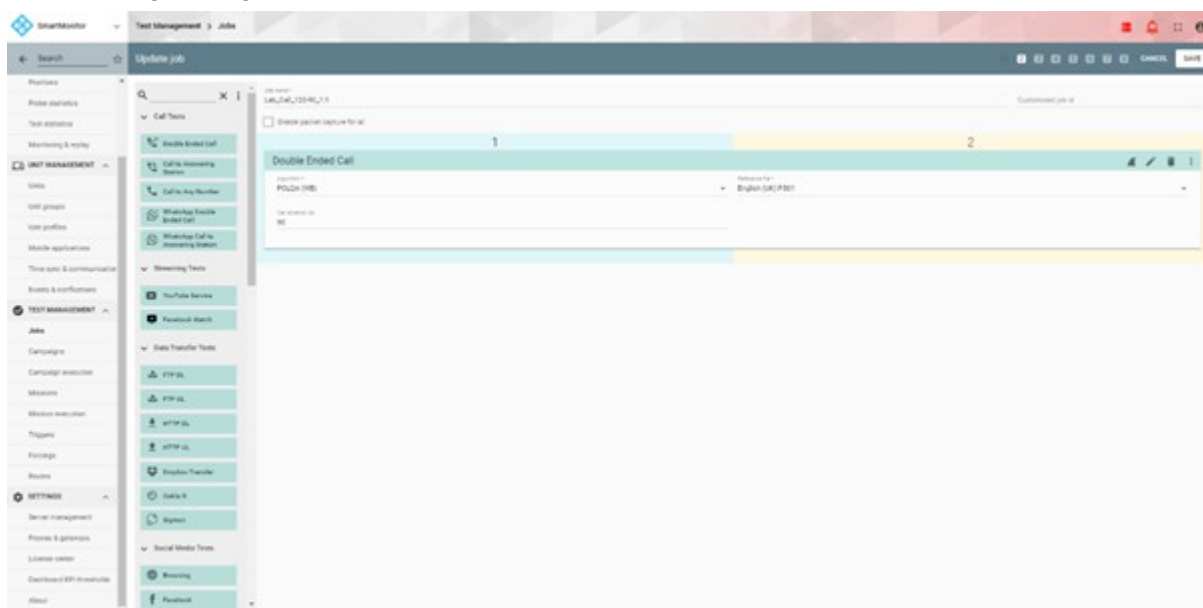
- The SmartBenchmarker component is designed for measurement-related activities. It enables easy configuration, execution and monitoring of test campaigns (scenarios). SmartBenchmarker supports various hardware modules (R&S@TSME6, R&S@TSMExxDC, R&S@Benchmarker 3, ...) and can be used for both drive tests (VBR roof box) and walk tests (R&S@Freerider 4). Tests can also be performed directly on mobile phones using the native Qualipoc Android software. SmartBenchmarker can be remotely monitored and configured using SmartMonitor.

The PESQ, POLQA and SQuad08 methodologies can be used to evaluate voice signal transmission quality, with outputs in the form of the MOS parameter, between two mobile phones or between a mobile phone and a fixed-network terminal. Multimedia data streams can also be evaluated using the ITU-T J.343.1 algorithm, which is designed for objective, non-intrusive testing of even encrypted streams (YouTube, etc.).

Solution functionality from the perspective of voice signal transmission evaluation:

- Outdoor and indoor tests (iBWave solution).
- Support for relevant mobile network technologies up to LTE-A / 5G / 5G NR.
- Support for commonly available mobile devices with compatible chipsets from manufacturers (Qualcomm / HiSilicon / Exynos),
- Variable (floating) licensing
- Features analysers for L3 communication protocols with message decoding functionality (SIP, TCP/IP, etc.).
- Remote management, scripting, test parameterisation, parameter synchronisation, visualisation via graphs and mapping, and processing of large volumes of data.
- Support for tests to evaluate voice transmission quality between mobile terminals or between a mobile terminal and a fixed network.
- Support for the evaluation of multimedia transmissions using the ITU-T J.343.1 methodology.
- Evaluation using the PESQ, POLQA and SQuad08 methodologies, with real-time calculation of the MOS parameter for both narrowband and wideband codecs.

Figure 9 – Screen showing the settings for the 'Double Ended Call' task.



Keysight Technologies, Inc.

Keysight offers the comprehensive Nemo Wireless Network Solution (NWNS) for the monitoring and analysis of wireless networks. The solution features relevant hardware components for parameter measurement, appropriate software for data storage and processing, including software tools for the analysis and visualisation of results. Selected components of the solution are:

- Nemo Handy – a software application that can be installed on a mobile phone running the Android operating system. When used in conjunction with the hardware, the application enables outdoor and indoor, manual and automated measurements of radio interface parameters (including LTE-A / 5G NSA / 5G SA / 5G NR), including QoS / QoE assessment. Standard phones from reputable manufacturers (Samsung, Xiaomi, Sony) with chipsets (Samsung Exynos, Qualcomm and MediaTek) are supported.

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Voice transmission quality can be monitored in real time using the POLQA v2 and v3 methodologies, as well as ViSQOL with MOS scoring. It enables testing of multimedia data streams from OTT applications (YouTube, Facebook, WhatsApp, etc.) using the PEVQ-S methodology from OPTICOM GmbH. Third-party PCTEL Gflex

®/IBflex®/HBflex® and R&S® TSMA6 can be used to measure RFI parameters. Unsupported mobile phones can be retrofitted with an external diagnostic module (Nemo Diagnostic Module, via USB) to bypass issues such as rooting. The Nemo Handy component is available in various products with differing functionalities (Handy Basic, Handy Pro, Handy Field Test, etc.).

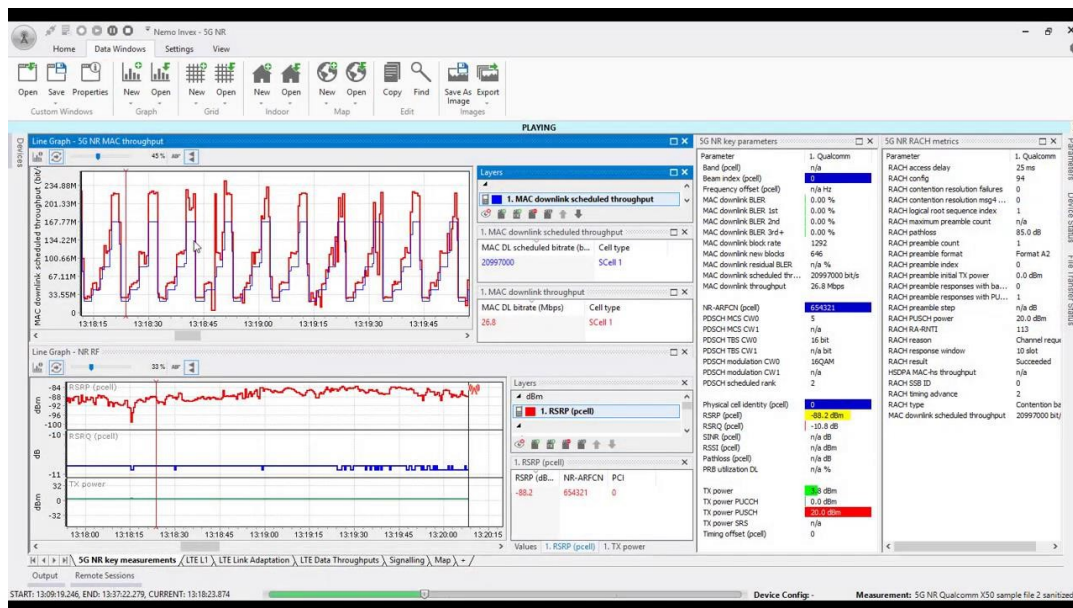
- Nemo Industry Probe/ Nemo Active Probe – are hardware components of the NWNS solution that enable diagnostic applications to run in industrial environments or, more generally, in environments requiring a high number of automated or continuous measurements for monitoring the status of a communication network.
- Nemo Walker Air – is an umbrella tool that utilises the Nemo Handy component for walk tests both outside and inside buildings.
- Nemo Outdoor 5G – is a software tool that diagnoses communication network parameters, RFI parameters and higher-layer parameters, including QoS/QoE, in drive tests.
- Nemo Cloud – is an online service connecting Nemo components. The system enables real-time remote access to individual components, allowing their control, the automated launch of measurement tasks, the automated processing of measured results and their sharing, playback, and storage in a centralised repository.
- Nemo Global License Server – is a tool for centralised licence management, including dynamic allocation as required.
- Nemo Analyze, Nemo WindCatcher – are additional software components that, in conjunction with Nemo Cloud, enable the post-processing and visualisation of measured data.

Solution functionality from the perspective of voice signal transmission evaluation:

- Outdoor and indoor tests (iBWave/Google Maps solution).
- Support for LTE / LTE-A / 5G NSA / 5G SA / 5G NR.
- Support for commonly available mobile devices with compatible chipsets (Qualcomm/MediaTek/Exynos), third-party PCTEL and R&S® scanners, and the external NDM diagnostic module.
- The solution offers remote management, measurement automation and result processing, result storage and sharing, visualisation in the form of graphs and mapping, and processing of large volumes of data.
- Remote management functionality, scripting, test parameterisation, parameter synchronisation, visualisation via graphs and mapping, and processing of large volumes of data.
- Flexible licensing policy (licence transfer, floating licences, short-term licences, etc.)
- Evaluation of OTT application multimedia streams using the PEVQ-S methodology.
- Support for evaluation using the ViSQOL methodology.
- Evaluation using the POLQA v2, v3 methodology with real-time MOS rating.

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Figure 10 – Nemo Outdoor product interface⁶².



6.5 Partial summary

The test solutions and applications are designed to verify various services. This can be done either sequentially or, in some cases, simultaneously. In addition to voice services, these include data services, where the availability of video and audio streaming, file transfer and web services is verified. As part of test management, tests are scheduled into sequences according to the given objective and then carried out, typically at a stationary point, whilst walking or driving.

A common feature of the individual solutions is:

- Intuitive and easy configuration of an extensive portfolio of tests, including the processing of results and their visualisation in the form of reports.
- The ability to combine tests into a custom scenario.
- The ability to measure at a stationary location as well as the option for walk/drive tests.
- Parallel use of multiple measurement terminals.
- A range of certified measurement terminals and the option to install measurement software at the customer's premises or use external measurement modules.
- Capability to process large volumes of data and perform detailed analysis via a cloud service. Visualisation tools (typically map-based).

Voice transmission quality testing is based on the same methodologies (POLQA) across different suppliers. The provision of results via the MOS scale is also consistent. The manufacturer may also offer additional evaluation methodologies, e.g. VISQOL.

R&S and Keysight Technologies offer a wider range of applications than the Enhancell system, thanks to greater flexibility in settings and the number of parameters in the test configuration.

⁶² Image source: 5G NR field measurements with Nemo Outdoor and Qualcomm X50 modem, Keysight Technologies, Inc., <https://www.youtube.com/watch?v=LTPRKLVRJY4>.

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The sophistication and complexity of solutions for monitoring communication network parameters differ only minimally among renowned multinational manufacturers. The tools offered by manufacturers for data acquisition (proprietary scanners or third-party scanners), as well as tools for data processing and visualisation, do not differ significantly in terms of their functionality.

7 Simultaneous and correlated verification of radio parameters and quality of service parameters

7.1 Introduction to the topic

7.1.1 Data communication parameters and their relationship to radio interface parameters

In general, it can be stated that the methodologies currently used to evaluate mobile network parameters focus independently either on RFI parameters (determining signal coverage) or on data transmission parameters (achieved transmission speed). The fundamental requirement is to verify whether a given operator's communication network meets the development criteria arising from frequency plans or other documents and regulations.

A specific area of measurement is the verification of quality parameters from the end-user's perspective (QoS / QoE), typically the verification of user experience in the event of complaints and within the framework of consumer protection. A more detailed analysis is provided in Chapter 2.1. Communication network parameter measurement methodologies serve not only to verify their correct functionality but also to evaluate the communication network for a range of other purposes. Currently, for example, to meet subsidy criteria when building networks or parts thereof, etc.

Identifying the relationships between physical layer parameters and parameters at higher communication layers would help to refine evaluation processes and facilitate the interpretation of results. It is clear that in fixed communication networks, where the parameters of the transmission environment do not change or change very slowly, such a relationship between the parameters of individual layers can be found and described more easily through analytical relationships.

However, modern mobile networks are significantly more complex (different frequency bands, control, etc.) due to the demands placed on them (mobility) and the nature of the transmission environment used (time-varying parameters, interference, etc.). Determining the interrelationships between RFI parameters and higher layers is therefore expected to be based more on estimates or recommended ranges for the parameters of interest, as outlined in Section 2.1.7.

7.1.2 Procedure for data processing and analysis

The aim of this section of the study is to answer the question of whether there are correlations between parameters measured in different ways (using different types of analysers) and at different points (layers) of the communication chain, and whether these correlations can be used to simplify processes, refine evaluations, infer relationships, etc.

The following text outlines the basic data processing procedure and provides examples of data sample processing and their interpretation.

The determination of the interrelationship (correlations) between RFI parameters and parameters at higher communication layers is based on data obtained from measurements carried out in accordance with the currently valid CTU methodology for checking criteria in Tender Procedures for the Use of Frequency Bands in Mobile Networks.

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Types of locations selected for analysis:

- Measurements whilst on the move:
 - Continuous population coverage measurements,
 - Linear infrastructure – motorways,
 - Linear infrastructure – railway corridor.
- Stationary measurements – area of interest (specific location).

Mobile network operators: Provider_A/B/C.

Mobile network technology:

- LTE (4G),
- 5G.

For comparison, the results of measurements taken by ČTU staff using the TSMA spectrum analyser and the F-Tester data communication parameter tester (transmission parameters at higher communication layers alongside a record of RFI parameters provided by the radio modem) are utilised. The following steps were primarily applied during data processing:

- Filtering of data for the relevant areas of interest according to:
 - Mobile network technology,
 - Frequency band, etc.
 - Mobile network cells (PCI),
 - Locations (GPS),
 - Status of the measuring device's data connection to the mobile network (excluding situations where the network connection is lost).
- Time alignment – determining the offset between parameters obtained from different devices.
- Level alignment – determining the difference between the measurement paths of different devices and taking into account antenna and signal configuration (1 antenna vs. 4x4 MIMO).
- Statistical data processing.
- Comparison of trends.

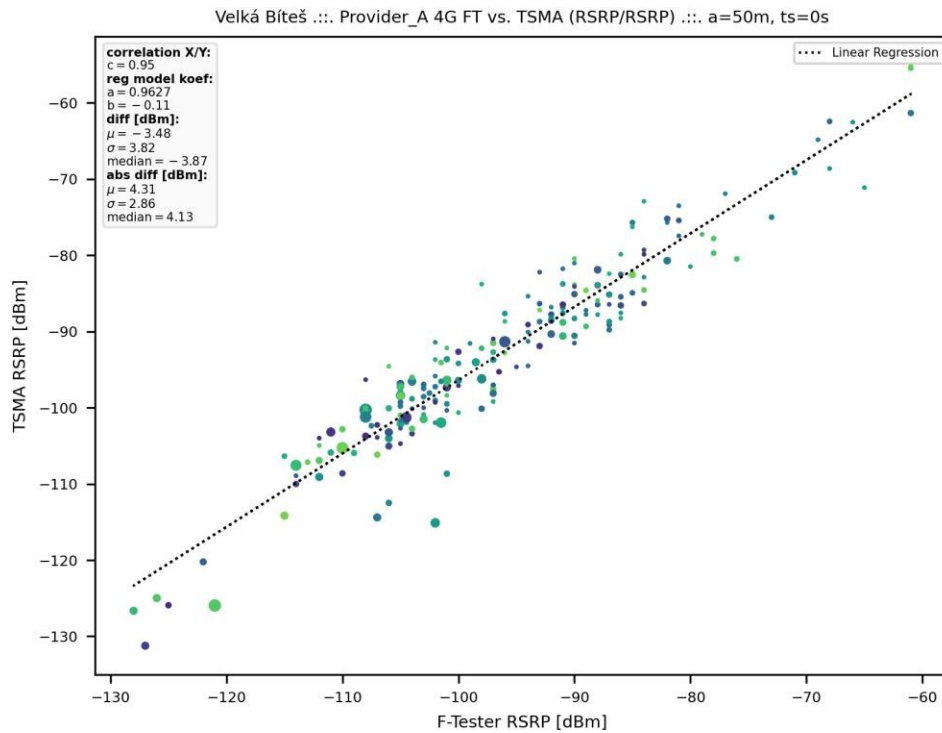
7.2 Analysis results and data processing

7.2.1 Correlation between RFI parameters obtained by different methods

The first step was to verify the consistency of the measured results from both analysers under consideration. The graph below compares the measured RSRP results from the TSMA analyser and the F-Tester platform. The measurements are referenced to the same geographical location, with the results processed in a 50 m grid. The measurement location is the town of Velká Bíteš, using 4G technology.

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Figure 11 – Comparison of the measured RSRP parameter from the TSMA analyser and the F-Tester for the Velká Bíteš location.



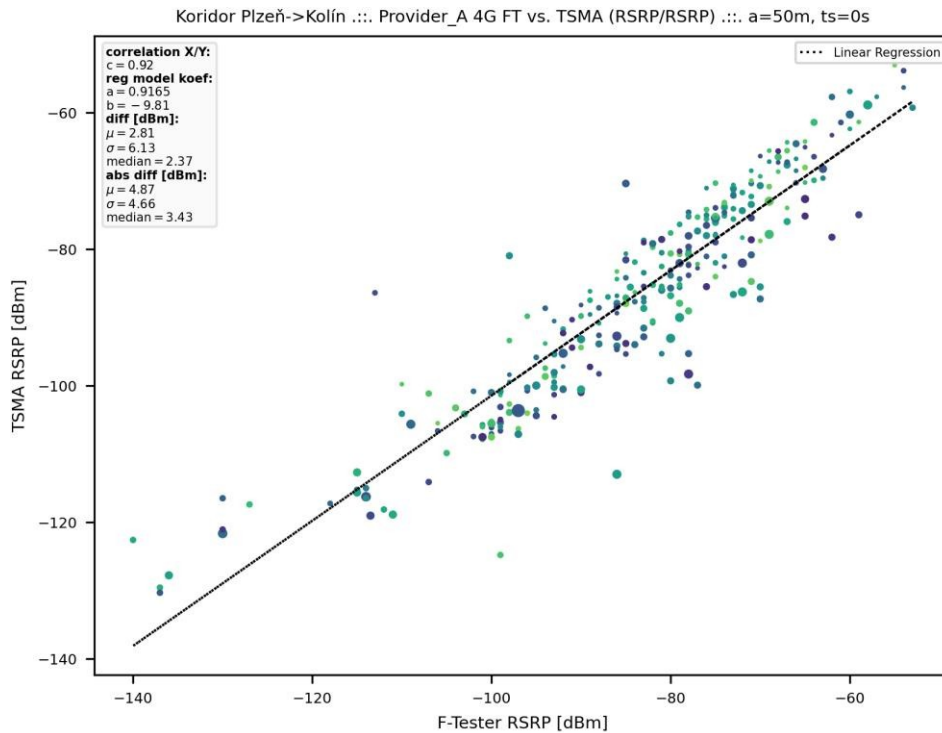
The number of RSRP measurements taken in each square is reflected by the size of the point. The parameter ts indicates any time correction between the individual measurements of both analysers. The correlation between the results of the TSMA and F-Tester analysers is expressed by Pearson's correlation coefficient c. The more the relationship between the results of interest is directly proportional (as one increases, so does the other), the closer the coefficient approaches 1. For uncorrelated results, the coefficient is 0. If the compared results are inversely proportional, the coefficient approaches -1.

When processing the measured data, a linear regression calculation is also performed using the Scikit-learn model to verify statistical dependencies. The calculation determines the curve parameters and statistical parameters for the measured TSMA and FT values relative to this curve – the median, mean and standard deviation.

Using the same filtering parameters as for the Velká Bíteš site, the following graph shows the results of a comparison of the linear structure of the Plzeň-Kolín corridor.

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Figure 12 – Comparison of the measured RSRP parameter from the TSMA analyser and the F-Tester for the Plzeň-Kolín railway corridor.



A sub-section of the analysis examined the relationship between the RSSI parameter (used in terminals to indicate the signal level across the entire band) and the RSRP parameter (which indicates the reference signal and is used in the Czech Telecommunications Office's (ČTÚ) conditions for defining signal coverage). The value of the difference reflects the extent to which transmission conditions on the radio interface vary and how dynamically the automatic transmit power control system operates within the context of OFDM modulation and the time slots allocated by the base station to terminals.

The theoretical assumptions are based on the ratio of the total bandwidth used (corresponding to RSSI) to the bandwidth of a single OFDM subchannel (corresponding to the reference subchannel in which the RSRP level is measured). The ratio expressed in dB corresponds to the difference between the two parameters according to the relationship:

$$\text{RSRP} = \text{RSSI} - 10 \cdot \log(S) = \text{RSSI} - 10 \cdot \log(12 \cdot N) = \text{RSSI} - 10 \cdot \log(B \cdot 12 / 0.2) \quad [\text{dBm}; \text{dBm}, -; \text{dBm}, \text{MHz}]$$

where S is the number of subchannels used by OFDM modulation and N is the number of PRBs (Physical Resource Blocks). One PRB corresponds to a bandwidth of 200 kHz and corresponds to 12 OFDM subchannels. B is the bandwidth used for the given band (data transmission). Theoretically, therefore, the differences between RSSI and RSRP are 28 dB for the 10 MHz band and 31 dB for the 20 MHz band (under stable, unchanging transmission conditions).

7.2.2 The relationship between RFI parameters and data transmission parameters

The following graphs show the processing of measured results for achieved data throughput at L4 as a function of RSRP for the F-Tester platform. To demonstrate the possibility of correlating the dependence of RFI parameters with parameters of higher communication layers, standardised locations were analysed, including a populated area – the town of Velká Bíteš – and linear structures – the Plzeň–Kolín railway corridor and the D4 motorway. All measurements were conducted using 4G technology in the downlink direction.

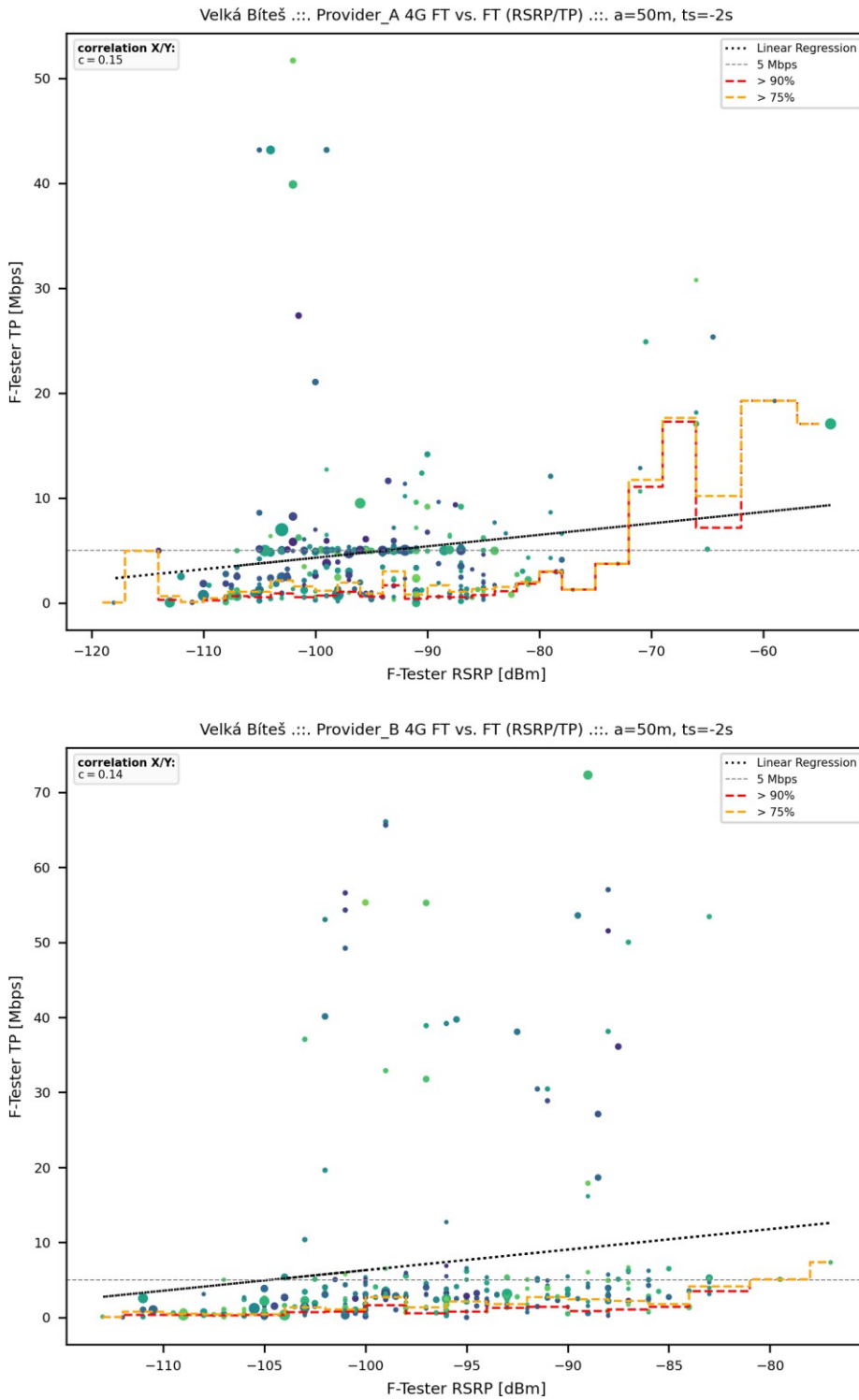
The graphs highlight the complexity of the interdependence of data communication parameters in mobile networks. In addition to radio interface parameters, data transmission is also influenced by base station parameters and settings, mobile network core settings, and Internet connectivity parameters. In the Velká Bíteš urban area, the transmission speeds achieved in the sample measurement (TP parameter) are relatively low. However, without further measurements, it is impossible to determine the cause of this situation. It is possible, for example, that this is the result of the policy set on the base stations and a consequence of the immediate network load, as the measurement results for Providers A and B are of a similar nature. The results for Provider C, however, are different.

The graphs show a transmission speed limit of 5 Mbit/s. For linear infrastructure such as the D4 motorway, the transmission speed limits are increased to 10 Mbit/s. The graphs also show the 25th percentile (orange curve), which indicates

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the fact that 75% of measurements lie above the curve. When meeting the conditions of the Radio Frequency Tender, the orange curve should therefore lie above the line representing the transmission speed limit. The red curve demonstrates stricter conditions, where the minimum transmission speed would need to be met in more than 90% of measurements.

Figure 13 – Dependence of data link throughput on the RSRP parameter for the Velká Bíteš location.



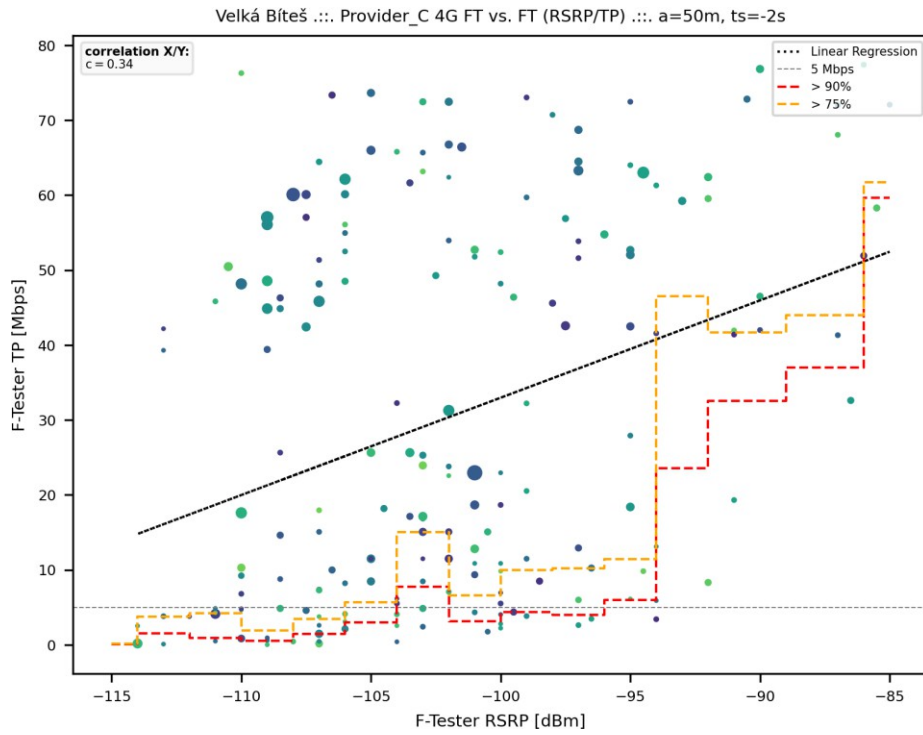
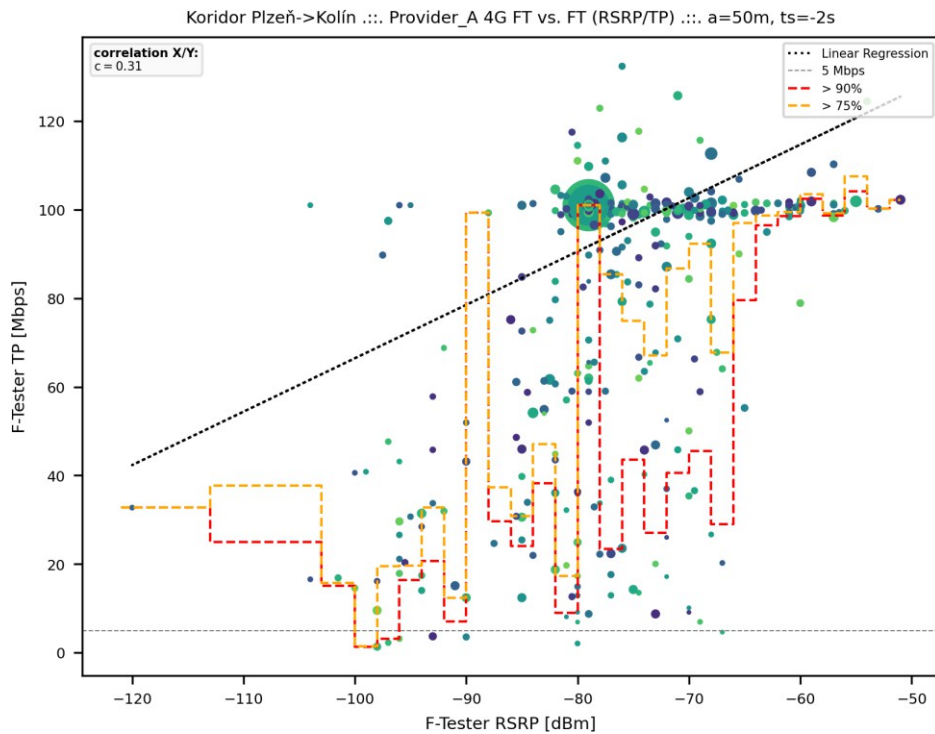
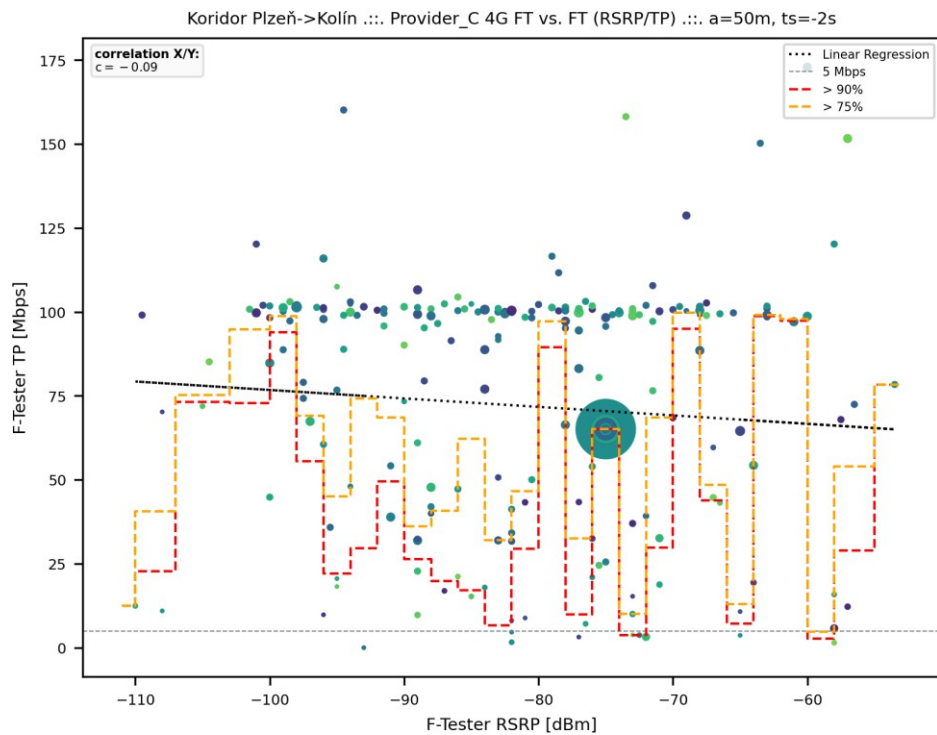
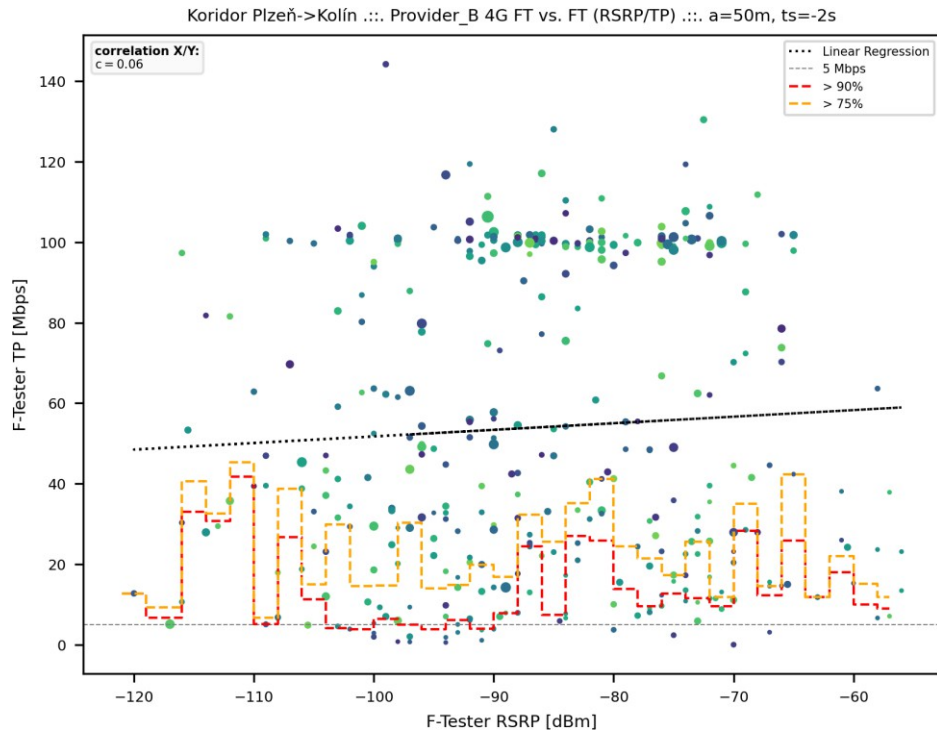


Figure 14 – Dependence of data link throughput on the RSRP parameter for the Plzeň–Kolín railway corridor.

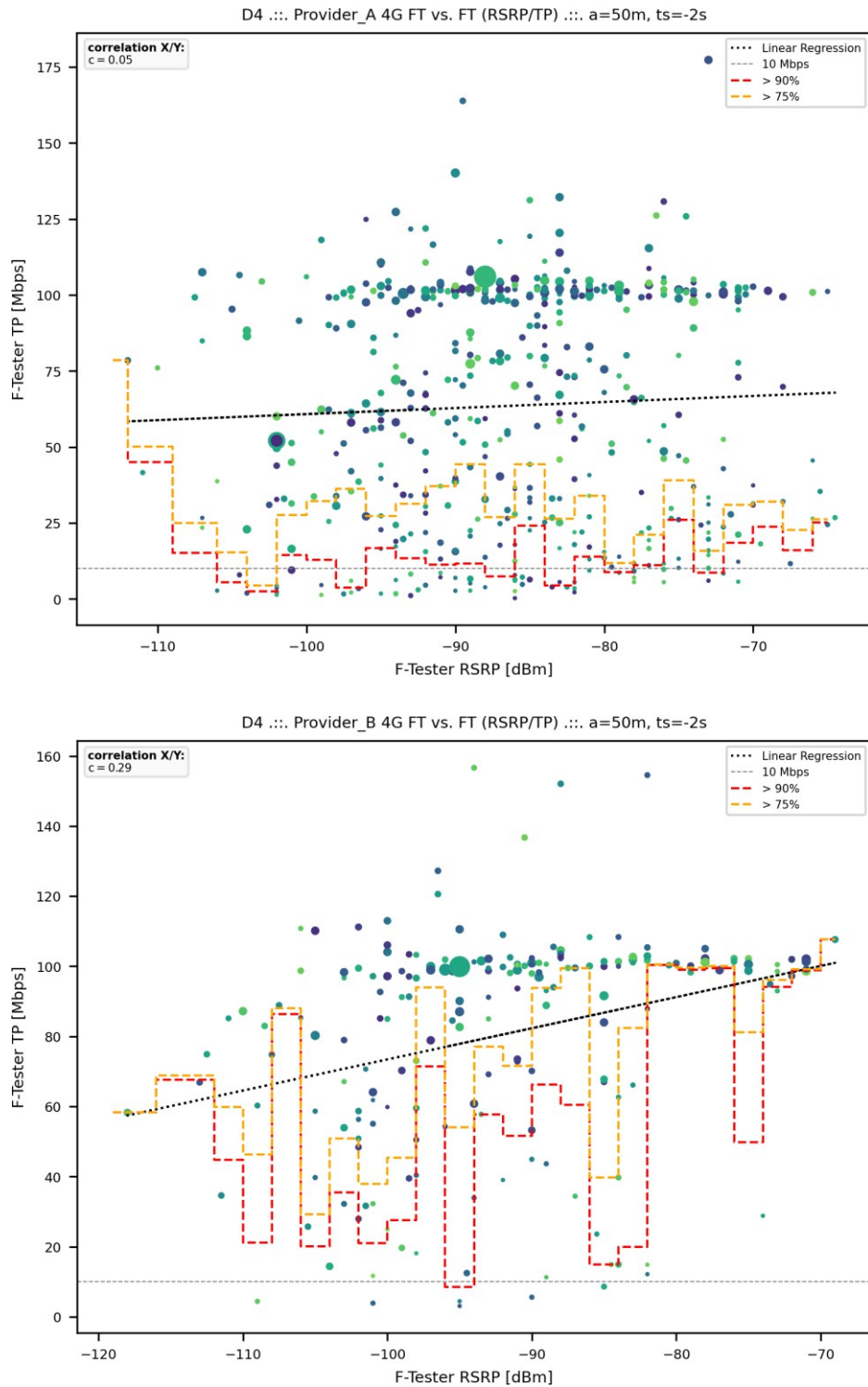


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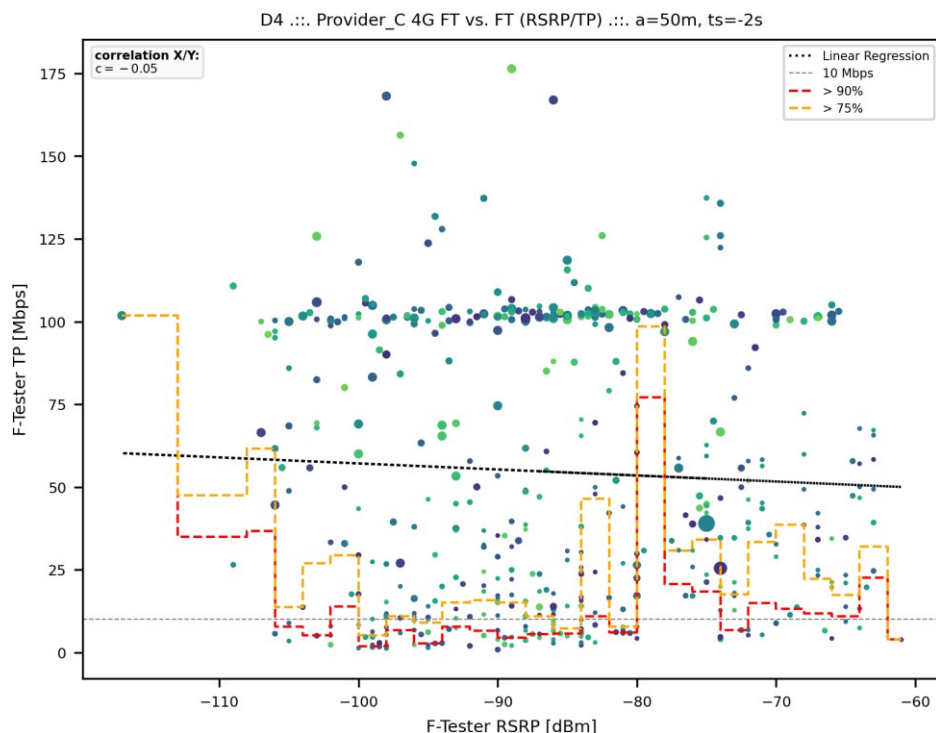


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Figure 15 – Dependence of data link throughput on the RSRP parameter for the D4 motorway.



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From the graphs shown, it is possible to roughly determine the RSRP value at which 75% of end-users achieved a data transfer rate of 5 Mbit/s or 10 Mbit/s. The table below lists the measured values, together with a conversion to reference conditions (corresponding to the results of the TSMA analyser measurements), including the RSRP threshold value specified in the tender conditions for individual types of locations.

Table 7 – Comparison of measured RSRP values with the achievement of TP = 5 Mbit/s (or 10 Mbit/s for the D4 motorway) and RSRP values according to the development criteria for ensuring coverage.

Location	Operator	Measured FT RSRP [dBm] for TP = 5 Mbit/s	RSRP value [dBm] according to criteria	Converted RSRP for TSMA	Note
Velká Bíteš	A	-73	-100 to -109	-69.5	
	B	-75	-100 to -109	-73.5	
	C	-106	-100 to -109	-103.6	
Pilsen–Kolín corridor	A	-98	-109 to -114	-100.8	
	B	-114	-109 to -114	-117.4	
	C	-110	-109 to -114		Correction cannot be performed based on the measurement data.
D4 motorway	A	-102	-118	-102.6	
	B	-118	-118	-120.8	
	C	-98	-118	-99.01	

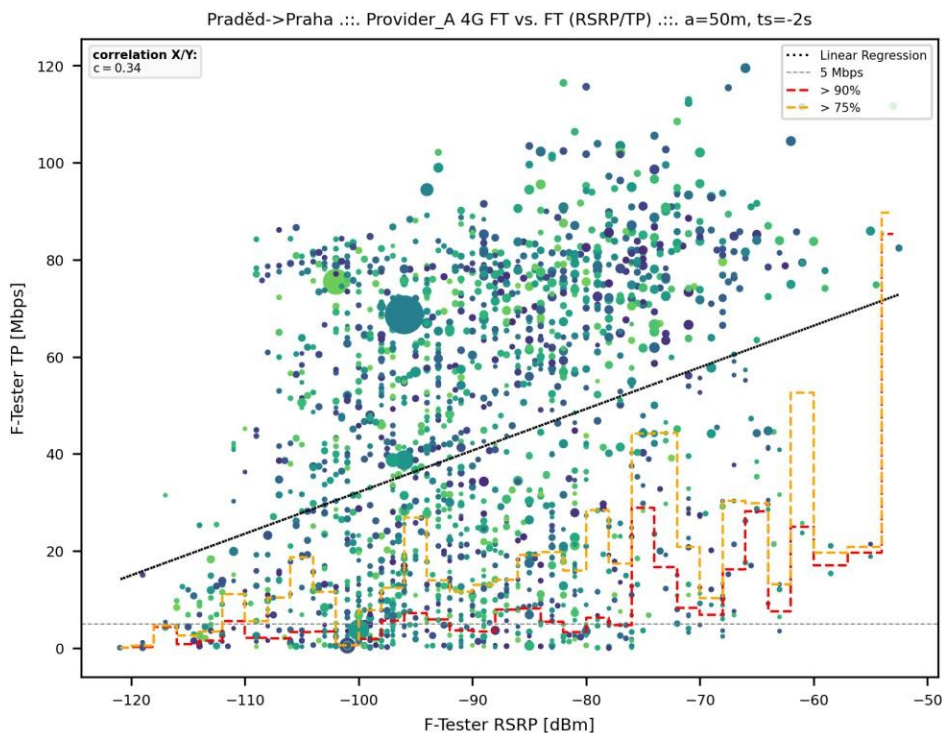
The measurements and graphs show that:

- When verifying transmission speeds on the railway corridor and motorway, a limit is evident in the maximum transmission speed of the test data stream (100 Mbit/s UDP stream).
- As the RSRP value decreases, the data link transmission rate should decrease. The graphs indicate that, across a wide range of values, the transmission technology is capable of providing adequate means to achieve the required transmission rate of approximately 100 Mbit/s. This rate corresponds to the set value for the analyser's test data stream (constant UDP stream). At the RSRP limit value, the data link breaks down rapidly.

- As the RSRP value increases, data transmission should become more reliable – achieving the transmission rate of the test data stream. The graph does not confirm this assumption. The most likely explanation appears to be that the sharing of network capacity among a larger number of users and their mutual influence are having a more significant effect.
- A significant exceeding of the test data stream's transmission rate then indicates the use of data stream buffering in network elements (storing data in a buffer and releasing it when network resources become available).

7.2.2.1 The relationship between RFI parameters and TCP throughput

The configuration of the test data flow plays a crucial role in testing higher communication layers. When using TCP-controlled data flows at a different processing location, the following dependence of throughput on RSRP can be derived from the measured results.



Following analysis, the data was aligned to a standard square grid with a side length of 50 m, aggregated, and a time shift was applied due to the different time points at which the values were obtained (RSRP vs. TP).

The results show that the test data stream was able to detect the actual throughput of the mobile network. As the RSRP parameter increases, the throughput value also gradually rises towards the mobile network's limit – approximately 80 Mbit/s. Even with increasing RSRP, this throughput value is not significantly exceeded, which may be caused, for example, by base station policy or congestion on the data link between the base station and the network core. The graph shows that even at high RSRP values, very low throughput values (units or low tens of Mbit/s) are often achieved. This may indicate a heavy load on the radio access network by users, or signal interference at cell boundaries.

The graph shows that for values of approximately RSRP = -100 dBm, the requirement for a sustained data rate of 5 Mbit/s is met in 75% of measurements.

It is important to bear in mind that the transmission rate is made up of individual data streams within the available (and network-allocated) frequency bands. The recorded RFI parameter values relate to a single specific band, typically the primary band, in which the connection to the network is established and signalling messages are exchanged. Generally, parameters may vary across different bands, and this can cause significant deviations from expected trends (data may flow more through a different band than the one for which we have RFI data and which has better values). For bands that are not too far apart, a similar trend can be assumed (a decrease in level as the distance from the base station increases). For a more comprehensive analysis, it would be necessary to record RFI parameters for all active bands and perform averaging, or alternatively include weighting based on the bandwidth of the given band within the carrier aggregation.

On the data already analysed and aligned, a test correction can be performed by excluding data with a high transmission delay value (RTT parameter). After disregarding such data—i.e., data typically transmitted over a network with

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low BDP, any correlation between the parameters of interest in the azimuth will break down. No new or different dependency appeared in the azimuth. Further measurements would be required for a more detailed analysis. At present, one can only speculate, for example, that the data network still has excessive 'data buffering' and therefore, under load, there is an increase in RTT without any significant restriction on the part of the network.

When searching for correlations between RFI parameters and parameters of higher communication layers, one of the key factors will be the correct configuration of the test data stream. The test data stream must not overload the data capacity available at the base station of interest. Measurements should be repeated in a defined manner to eliminate anomalies caused by the characteristics of the transmission environment or unusual behaviour by end-users.

Measurements combining TCP flows with a concurrent UDP flow in the background could resolve the issue of network congestion and the associated problem of buffers filling up and subsequently emptying at the cell and network core interfaces.

7.3 Preliminary conclusions and recommendations for further action

As the analysis of the data sample has shown, drive tests generate data with a wide dynamic range and variations along the measurement trajectory. In this case, data averaging plays a significant role, which is currently performed on a reference grid of squares.

From the graphs showing the dependence of throughput on the reference signal level, it is possible to roughly determine the RSRP value at which 75% of end-users achieved a data transfer rate of 5 Mbit/s. In the analysis carried out, the values converted to reference conditions (corresponding to the measurement results of the TSMA analyser) are compared with the currently valid limit values for the RSRP parameter, as specified in the tender conditions for individual types of locations. No reason was identified for any change to these limits. For more definitive conclusions, it would be necessary to process and analyse a significantly larger dataset across a large number of locations.

For a more accurate determination of limits, it is recommended not to use high-speed UDP load tests (typically 100 Mbit/s downlink) for mobile measurements (due to data buffering issues at cell handover points and in network fringe areas), but only for stationary measurements in well-covered areas. Conversely, we recommend measurements at the very limit speed (UDP flow of 5 Mbit/s downstream, or even lower in network edge areas), as the results can easily indicate the RFI parameters at which the speed was not met. To determine the available network capacity, concurrent TCP streams can be used, which, due to their own regulatory mechanism, do not lead to network congestion.

It is important to bear in mind that the transmission speed is composed of individual data streams in the available (and network-allocated) frequency bands. The recorded RFI parameter values relate to a single specific band, typically the primary band, in which the connection to the network is established and signalling messages are exchanged. Generally, parameters may vary across different bands, and this can cause significant deviations from expected trends (data may flow more through a different band than the one for which we have RFI data and which has better values). For bands that are not too far apart, a similar trend can be assumed (a decrease in level as the distance from the base station increases). For a more comprehensive analysis, it would be necessary to record RFI parameters for all active bands and perform averaging, or possibly include weighting based on the bandwidth of the given band within the carrier aggregation.

8 Summary, conclusions and recommendation

S

Coverage verification is an important activity within the Czech Telecommunications Office's spectrum management, when assessing operators' compliance with development criteria for allocated frequency bands, but also from the perspective of consumer protection and verifying compliance with contracts for the provision of electronic communications network services.

The assessment and verification of coverage of the territory by radiocommunication services in the Czech Republic is carried out using commonly employed methods and techniques, in particular by measuring signal levels at various locations using portable measuring equipment, measurements using vehicles equipped with specialised measuring equipment, evaluation using software tools and mathematical models in the form of coverage level predictions, and real-time monitoring of network status and performance.

Based on the terms of reference and technological developments in this field, the study focuses on selected methods of determining and verifying coverage, with partial conclusions as analysed in detail in separate chapters and briefly summarised in this overview. During the preparation of the study, the main focus was on mobile service coverage, particularly 5G services.

Satellites for monitoring the radio spectrum, primarily of mobile networks in the terrestrial segment in real time, are proving to be practically unusable. Only if the radiation patterns of terrestrial transmitters allow the signal to propagate into space is it possible, after passing through the Earth's atmosphere, to identify with a certain degree of probability the geographical location of the signal source, in addition to the spectrum of the propagated signal itself. In this way, it is also possible to monitor the emission of radio smog from terrestrial transmitters of radio communication services into outer space.

In connection with the growing focus on the use of space, demands are also being placed on the development of space telecommunications. This will also lead to the need to develop and implement appropriate technical methods for monitoring the radio spectrum. This issue will undoubtedly require a separate study that comprehensively addresses the topic of radio spectrum management in space telecommunications, taking into account the outcomes and findings of the WRC-27 and WRC-31 radio communication conferences, as well as the development of satellite technologies and the promotion of their applications in science, research, industry and services.

The use of drones – this is a suitable and highly effective complement to drive tests or walk tests in mobile wireless networks. Various measuring instruments and different measurement methods are available for various parameters. Generally, the operational requirements for a drone can be summarised as requirements for maximum flight time, maximum weather resistance, maximum payload capacity and minimum cost. The requirements for measuring instruments are based on the measurement tasks and the payload capacity of the drone used. In addition, we must also focus on the design and construction, as standard instruments are not primarily intended for use in drones. Most manufacturers have suitable instruments and the necessary accessories in their portfolio, such as various types of antennas, RF measurement cables, etc. An exception are complete systems, e.g. from companies such as Nokia Drone Networks and Deviser, where the drone is supplied with an integrated measurement system.

Current legislation lacks exemptions for selected state authorities and institutions. A specific example is the Czech Telecommunications Office (ČTÚ), which is responsible for monitoring the frequency spectrum. It should have exemptions for carrying out measurement flights. For example, it is inappropriate to seek consent for drone operation from a landowner who has a source of RF interference on their land, an unauthorised transmitting station, or a station transmitting outside allocated bands. Practice shows that such inspections are then pointless.

Practice shows that there are differences between simulation results and measured values in real-world terrain and operational conditions. These differences exist between individual operators, between operators and, of course, in relation to the Czech Telecommunications Office (ČTÚ). These differences stem from the fact that each entity uses different initial conditions describing the given territory and different simulation applications. It would be beneficial to standardise the initial conditions or, alternatively, to analyse in detail the circumstances under which these differences arise.

The part of the study focusing on **the use of more advanced technologies** was, following discussions with the client, directed towards testing voice communication, where there is a current need to upgrade measurement equipment. Voice transmission quality testing is based on the same methodologies (particularly POLQA) across different suppliers. The reporting of results using the MOS scale is also consistent. Solutions for monitoring communication network parameters differ only minimally among reputable multinational manufacturers. Nor do the tools for data acquisition, processing and visualisation differ significantly in terms of their functionality.

Testing solutions and applications are usually designed to verify various types of services, either sequentially or some of them simultaneously. In addition to voice services, these include data services, where the quality of video and audio streaming, file transfer and web service availability are verified.

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There is no specific methodology available for testing OTT voice or video applications. Methodologies exist for evaluating the quality of transmission of video or audio/video information in standardised transmission technologies, e.g. CaTV, IPTV and video calls using RTP / RSTP / SIP protocols. The evaluation of OTT services is usually carried out in accordance with the proprietary methodology of the company offering such services.

As the analysis of a selected data sample has shown, **simultaneous and correlated verification of radio parameters and quality of service parameters** is possible, but requires the processing of large amounts of data from various locations to draw meaningful conclusions. Drive tests generate data with a wide dynamic range and variations along the measurement trajectory. In this case, data averaging plays a significant role, which is currently performed on a grid of reference cells.

From the dependence of throughput on the reference signal level, it is possible to broadly determine the RSRP values at which a significant percentage of end-users achieved the required data transmission rate. These can be compared with the currently applicable RSRP limit values specified in the tender conditions. No reason has been identified for any change to these limits. In such cases, it would be desirable to generate a UDP flow at the required minimum speed to prevent network congestion, or to fill the remaining capacity with a TCP flow.

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8.1 Summary

Table 8 – Summary of the characteristics of the analysed solutions

	Benefits	Special conditions	Feasibility	Limitations	Countries where implemented	Approximate costs	Other important facts
Spectral monitoring using satellites (real-time results)	Cannot be used for the ground segment, but is relevant to the space sector.	Due to the extreme conditions of space missions.	Feasible in cooperation with other countries and the ESA.	Satellites can only locate significant terrestrial transmitters (or sources of interference) to a limited extent.	More suited to experiments and monitoring space debris.	Very high costs, which can be reduced by sharing with other entities and projects. The costs of small satellites are an order of magnitude lower.	Does not appear to be an immediate need given the small size of the Czech Republic; more relevant for the wider European region.
Use of drones for measurement (carrying out measurements in hard-to-reach or dangerous areas)	A technology that is now well established. A safe, fast and relatively inexpensive solution.	In most cases, conducting measurements requires a special permit in accordance with current legislation.	Testing is already underway at the Czech Telecommunications Office; expansion to other tasks is desirable.	Geographical zones, densely populated areas, Climatic influences.	EU	Includes the costs of the drone, measurement equipment and flight crew. Costs can be reduced by using subcontractors.	Only one mobile operator uses its own equipment and staff; the others use subcontractors.
Use of advanced simulation models and machine learning-based techniques	Increased accuracy of modelling and data interpretation.	Unification of simulation model inputs is required. Extensive datasets are required for model training.	Reducing inaccuracies in current models is contingent upon legislative support and the introduction of a terrain reference model with the assistance of the Czech Office for Surveying, Mapping and Cadastre (ČÚZK).	Dynamic changes in transmission environment parameters.	EU	Software licence fees, computing costs.	
Use of more advanced technologies (voice transmission quality measurement)	Voice services remain essential in electronic communications networks, and monitoring their quality is desirable.	Specific algorithms for the objective evaluation of quality on sets of voice samples.	Standard functionality of testing systems from renowned manufacturers, adapted for walk and drive tests.	Most solutions use standard mobile terminals; results may be influenced by them, and it is not realistic to rapidly replace them with new models.	Used in virtually all developed countries and by most operators for continuous quality monitoring.	From several hundred thousand to several million CZK, depending on equipment and configuration.	For voice services, it will be desirable to supplement call quality assessment with conversation quality evaluation.
Simultaneous and correlated verification of radio parameters and service quality parameters (QoS or QoE)	Signal strength does not always guarantee service with the specified parameters; comprehensive monitoring and evaluation can refine coverage limits.	It is necessary to continuously monitor and evaluate large amounts of data; conditions in the mobile network, particularly whilst on the move, change very dynamically.	Feasibility is good, as it involves processing existing and continuously acquired data, supplemented by additional perspectives and analysis.	Limitations are determined by the number of measurement vehicles and their crews, as well as the speed of transit, which may result in insufficient data for evaluation within a given area.	Separate measurement of radio parameters and QoS parameters is usually used.	Costs associated with developing additional software modules for processing large volumes of data. Adjustments to methodologies for measuring data transmission speeds.	During throughput tests, it is advisable to combine UDP and TCP flows to prevent network congestion.

8.2 Recommendations arising from the study

Measuring the coverage of a geographical area by radio signals, and the ongoing monitoring and evaluation of service parameters, are essential tasks associated with ensuring the operation of wireless electronic communications networks and the efficient use of the spectrum. Consequently, this also relates to consumer protection.

We recommend continuously monitoring developments in the field of methods and techniques for determining and verifying coverage by radio communication services, in particular international standards, measurement methods, evaluation techniques and simulations. In particular, focus should be placed on the following:

- In light of the growing importance of fixed LTE and fixed 5G, analyse measurement and testing requirements in this area, including in the context of VHCN networks and conditions.
- In connection with the growing development of private 5G networks, particularly in industry, analyse measurement and testing requirements in this area, including in the context of the expected use of the 26 GHz band.
- When using drones, strive to expand their usability, including by introducing exemptions in current legislation for conducting measurement flights.
- Initiate a more detailed analysis of simulation and measurement tools and their results among operators and the CTO with the aim of harmonising baseline conditions, methodologies and criteria.
- Analyse in greater detail and on an ongoing basis the relationships between radio parameters and quality of service parameters, leading to the validation and, where necessary, modification of coverage limits. For these purposes, optimise the methodology for measuring data transmission parameters.
- In connection with the growing focus on the use of space, address the issue of radio spectrum management in space telecommunications, taking into account the outcomes and study results of the WRC-27 and WRC-31 radio communication conferences, as well as the development of satellite technologies and support for their applications in science, research, industry and services.