RIGA TECHNICAL UNIVERSITY

Alīna Stafecka

DEVELOPMENT OF THE SOLUTION FOR PROVISION OF MOBILE INTERNET SERVICE QUALITY MEASUREMENTS

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY

Faculty of Electronics and Telecommunications
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 15 September 2023 at 11.00 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Āzenes Street, Room 201.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Alīna Stafecka ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an introduction, 4 chapters, conclusions, 25 figures, 29 tables, 7 appendices; the total number of pages is 177, including appendices. The Bibliography contains 127 titles.

ANNOTATION

In the light of the annual increase in the range of services provided via the Internet, as well as the increasing amount of online content, the quality of Internet access service, especially in the case of the mobile network, where the number of end-users already significantly exceeds the number of landline end-users, is becoming increasingly important when assessing the possibility of receiving the service or accessing content. Consequently, a regulatory framework is provided, within the framework of which the responsible authorities must ensure an open and transparent assessment of the Internet access service.

In the Doctoral Thesis, a study has been carried out, within the framework of which the process of monitoring and evaluating the quality of Internet access service has been examined and evaluated, in regard to the choice of the type of measurements depending on the requirements of the regulatory framework and the objectives of performing measurements, factors affecting the measurement and other technical and regulatory aspects. In addition to the norms specified in the regulation, the Doctoral Thesis proposes and practically evaluates the additional criteria for placement of the measurement equipment, which are based on the assessment of signal parameters.

As a result of the research, guidelines for the performance of measurements of the quality of the Internet access service have been developed, which provide a specific set of activities and conditions, determining the time of the measurements, the location of measurement equipment, values of reference parameters, and other conditions in order to ensure openness and transparency of the measurement process, as well as comparability and objectivity of measurement results.

CONTENTS

ABBREVIATIONS

A

AS – autonomous system

B

BEREC – Body of European Regulators for Electronic Communications

BOR – BEREC report

C

CEPT –European Conference of Postal and Telecommunications Administrations

CISCO – Commercial & Industrial Security Corporation

CQI – channel quality indicator

D

dB – decibel

dBm – decibel–milliwatts

E

ECC –Electronic Communication Committee

EG – ETSI guide

ETSI – European Telecommunications Standards Institute

EU– European Union

G

GB – gigabyte

GSMA – Global System for Mobile Communications Association

I

IP – Internet Protocol

IPv4 – Internet Protocol Version 4

IPv6 – Internet Protocol Version 6

ITU – International Telecommunication Union

ITU-T – ITU Telecommunication Standardization Sector

IXP – Internet exchange point

L

LTE – long-term evolution

M

MCC – mobile country code

MNC – mobile network code
Mbps – megabit per second
ms – milliseconds

N
NR – new radio
NRA– National Regulatory Authority
NTP – network termination point

O
OECD – Organisation for Economic Co-operation and Development

Q
QoS – quality of service

P
PUC – Public Utilities Commission of Latvia

R
RIPE NCC – regional Internet registries
RSRP – reference signal received power
RSRQ – reference signal received quality
RSSI – received signal strength indication

S
SINR – signal-to-interference-plus-noise ratio

T
TS – technical specification

GENERAL DESCRIPTION OF THE DOCTORAL THESIS

Relevance of the topic

Every year an increasing number of public services, including services provided by the state, are integrated into the Internet environment, and online services are gradually replacing the provision of services in person. European regulations and supported projects require the member states of the European Union to develop electronic service systems that will be available to all citizens of the country, which citizens should be able to use in order to receive actual information, complete documents, as well as medical consultations and other services [1], [2]. In addition, with the development of technological capabilities of terminal equipment and online content platforms that allow the creation of large volumes of content and the deployment of this content to online platforms, the demand for high-performance electronic communication networks is only increasing. Along with the integration of a large part of services to the Internet environment, the social value of the Internet as a service also increases and is determined by the limited opportunities of end users to integrate and operate in modern society without access to the opportunities provided by the Internet service.

Compared to fixed electronic communication network technologies, mobile electronic communication network technologies offer much wider functionality, which includes ensuring the mobility of users around the world. With the development of technologies of the mobile network the quality of the electronic communication services provided by these networks also increases, resulting in a significant increase in the observed proportion of mobile connections and equipment compared to fixed connections [3], [4]. At the end of 2020, the number of mobile connections in the Republic of Latvia already seven times exceeded the number of fixed connections [3]. According to the OECD data, one resident of the Republic of Latvia already consumes more than 30*GB* of data per month using only mobile electronic communication network [3].

However, along with the increase in demand the load on the network also increases and as a result a deterioration in the quality of the provided Internet access service can be observed, which is especially manifested in the mobile electronic communication network, considering its technological characteristics, which are affected by increase in the number of mobile connections and growth of traffic [5].

Taking into account the above, provision of electronic communication coverage of mobile electronic communication networks is one of the priority directions and goals of the European Union, although it does not exclude the need to stimulate the development of fixed electronic communication networks, considering that fixed electronic communication networks are used not only to provide electronic communication services to end users, but also to provide capacity for mobile network up to the base station [1].

The regulation of the European Union requires national regulatory authorities to introduce a strict monitoring mechanism for the provided Internet access service, for the purpose of which regulatory acts, guidelines and other binding documents have been developed that determine the requirements for the Internet service measurement tool used for regulatory measurements, measurable QoS parameters, data collection and display criteria and for activities promoting the development of networks [6], [7], [8], [9], [10].

However, neither international nor European Union standards, recommendations, and other documents provide detailed criteria and conditions for performing practical measurements, therefore, there is no unified approach to the arrangement of measurement process. As a result, the openness and transparency of the measurement process is not ensured, which prevents Internet service providers and end-users from performing service measurements that would be equivalent to regulatory measurements and that could be used as a legal confirmation of the quality of the service provided or received.

In order to ensure comparable results of the performed measurements, which can then be summarized in accordance with the regulatory requirements of the European Union and based on which conclusions can be drawn about the quality of the Internet access service provided by electronic communications merchants in the measurement locations and within the country, it is not enough to develop a standard measurement methodology, which is foreseen by European and national regulation, but it is necessary to define the requirements and conditions of the measurement process and to strictly monitor them [10], [11].

At the same time, electronic communications merchants also demand a detailed methodology for the Internet access service evaluation, which would include an open and transparent measurement procedure, which would clearly define the measurement conditions and the equipment used for measurement, thus allowing to check and compare the results of measurements performed by the regulatory authority and to ensure equal measurement process for merchants and end users [12].

Aim and objectives

Taking into account that there are no unified guidelines for measurement process of mobile Internet access service quality, which would be applicable regardless of the technology used in the electronic communication network and would ensure that reasonable and comparable quality measurement results can be obtained, **the aim of the Doctoral Thesis** is to perform the research on aspects and parameters necessary for ensuring measurement process of mobile Internet access service, developing guidelines for the measurement performance, which are based on standards, recommendations, mathematical calculations, and practical results and ensure the openness and transparency of the measurement process.

To achieve the aim, the following **key objectives** were put forward:

1. To evaluate different types of Internet access service measurements, determining the advantages and disadvantages of each type of measurements, defining the conditions for carrying out measurements specific to each type of measurements and the factors affecting the measurement results.
2. To determine the optimal location of the Internet access service measurement server in the public Internet network of the Republic of Latvia, which would allow to meet the requirements of the European Union regulation and ensure comparable measurement results at the national level.

3. To develop a measurement automation algorithm, which would be setting criteria for measuring and reading Internet access service and signal parameters, as well as collecting the obtained results in a database.
4. To study the dependence of values of electronic communication service quality and of signal parameters on the place and time of measurement.
5. To determine appropriate distribution of Internet access service measurements between different types of municipalities, based on the mathematical processing of practically obtained results.
6. To assess the influence of the location of measurement equipment on the Internet access service measurement results and to determine the criteria for the placement of measurement equipment for different types of measurements.
7. To compare the efficiency of unattended probe measurements and drive-test measurements in populated areas, based on the mathematical calculations of the practical results and time consumption.
8. To evaluate the connection and correlation between the quality parameters of the mobile Internet access service and the values of the signal parameters.
9. To develop guidelines for mobile Internet access service measurement process meant for the person performing the measurement, which may be made public in order to ensure the openness and transparency of the activities of the national regulatory authority.

Research methodology

Literature analysis, practical measurements, mathematical calculations, statistical data analysis, and creation of mathematical processing algorithms have been performed in order to achieve the goal and to fulfil the tasks set in the Doctoral Thesis. For measurements of *QoS*, signal parameters and data collection, a program script was written in *python* programming language and tools for measuring Internet access service quality and signal parameters developed by various companies and institutions were used. The processing of measurement results was carried out using mathematical and statistical analysis methods. Mathematical processing algorithms were expressed in the form of formulas for defining the parameters necessary for the measurement process. The program code developed using *python* programming language and *Microsoft Excel* software were used for data analysis. A *Command Prompt* interface was used to monitor the flow of measurement traffic.

Research results and scientific novelty

Practical value and contributions:

1. A measurement automation and data collection algorithm has been developed in the form of a program script, which can be used both for further research and for providing Internet access service monitoring measurements for the needs of PUC.
2. The practical Internet access service measurement performance models and their parameters have been evaluated and proposed and therefore considered when setting

requirements for the Internet service quality measurement system, which could be used to fulfil the functions of PUC.

3. Based on the results of the conducted research and observations, universal guidelines for performing Internet access service measurements have been developed. After the development of the Internet service quality assessment system these guidelines can be used to determine the requirements regarding the order and execution of the Internet access service quality measurement and included in the legal acts of PUC.
4. It is proposed to revise the developed internet access measurement principles on a European scale, thus ensuring the implementation of unified measurement principles at the European level.

Key conclusions of the Doctoral Thesis:

1. By conducting an analysis of autonomous system interconnections and autonomous systems owned by electronic communications merchants, it was found that in the Republic of Latvia it is possible to choose one location of the Internet service quality measurement server, which would ensure the shortest path to the measurement server and national content resources when making measurements from any electronic communication network of the Republic of Latvia, thus ensuring compliance with all regulatory requirements, as well as allowing to obtain comparable and objective measurement results.
2. If terminal equipment intended for end users is used to perform measurements, the replacement of terminal equipment with a newer one must be done at least once every three years, thus ensuring that the mobile Internet access service provided by electronic communications merchants is evaluated taking into account all the latest technologies and all radio frequency spectrum assigned to the merchants.
3. Drive test measurements is the only type of measurement that is able to meet the requirements set by the European Union to ensure the availability, inspection and assessment of Internet service on highways, and it is more efficient than unattended probe measurements in terms of both resources and time, thus drive test measurement support is an important criterion for choosing a measurement tool.
4. Signal parameter measurements are recommended to be used indoors, in a vehicle, or outdoors to determine the location for measurement equipment placement, by choosing a place for measurements where the signal parameter values are better or ensuring measurements in certain ranges of signal parameter values, thus ensuring that the measurements have been made under the same conditions and measurement results are comparable in further analysis. At the same time, for the purposes of publication of the measurement results, it is recommended to sort the data obtained during the measurements according to the signal conditions.
5. If it is not possible to evaluate the signal parameters as part of the regulatory measurements, then the measuring equipment must be placed in the vehicle on the front panel of the vehicle at the height of the windows, and in the interior – as close as possible to the window.

6. For the calculation of the number of planned and actual measurements, the calculation Formula (3.1) defined in international standards must be used, adjusting its parameters according to the criteria of the degree of reliability and relative measurement accuracy set by the institution, which are defined in relation to the purpose of processing the measurement result. However, during the course of measurements, taking into account the availability of resources, it is necessary to revise the number of measurements, taking into account that the number of planned measurements depends on the results of control measurements, but in the case of practical measurements, with different values of the measurement results, a larger number of measurements may be necessary to achieve the level of reliability of the actual measurements.
7. Drive test and unattended probe measurements, which are not scheduled to be performed outside of standard working hours, must be performed on weekdays between 9:00 a.m. and 3:00 p.m., thus ensuring that the measurement results are within 4 % error of measurements result of the measurements which are made 24/7.
8. There is a direct correlation between QoS and signal parameters in the LTE mobile network, which is manifested in the strong correlation coefficient values between the values of download, upload speeds, and the values of RSRP, RSSI and RSRQ parameters. For other QoS parameters the correlation coefficient is different. Therefore, it can be concluded that based on the signal parameter values it is possible to predict the signal parameter values in the coverage area of the mobile cell, however, specific QoS parameter values are predictable only in a specific operator network.
9. For the purpose of collecting regulatory measurement data it is not recommended, without a valid reason, e.g. in case of the end user complain, to place measurement equipment in places where the values of the signal parameters for RSRP are lower than –100 dBm, for RSSI lower than –75 dBm, for RSRQ lower than –20 dB, and for SINR lower than 0, because in that case a significant deterioration of QoS parameters is observed, which significantly affects the compilation and comparability of measurement results.
10. A measurement automation algorithm has been developed in the form of a program script, which ensures continuous mobile Internet access service measurements, as well as compilation of the obtained results in a database, which ensures the economy of employees and time resources, eliminating the possibility of human errors in the measurement process.
11. Guidelines for mobile Internet access service measurement process have been developed. These guidelines are based on standards, recommendations, practical and mathematically obtained research results and can be used to ensure regulatory measurements.

In addition, during the development of work and information analysis, it was ascertained that the reference point of signal parameters according to international standards is defined as the antenna plug of the terminal equipment receiver, thus the network termination point (NTP) in the case of a mobile electronic communication network should also be defined as the terminal equipment and the receiver antenna connection. Such definition would be a more accurate NTP location definition compared to the one currently defined in the BEREC guidelines, and subsequently also in the Latvian regulatory acts, where mobile NTP is characterized as a point in the air between the transmitter and the receiver.

Practical application of the Doctoral Thesis results

The results obtained during the development of the Doctoral Thesis and reflected in the study will be used in the development of regulatory acts of the Public Utilities Commission of Latvia, in the provision of regulatory measurements, and in the selection of the Internet access service evaluation system.

Theses to be defended in the Doctoral Thesis

1. In the Republic of Latvia, it is possible to choose one Internet service quality measurement server location in the network so that it meets all regulatory requirements and ensures comparable and objective measurement results.
2. The signal parameters must be used to determine the measurement place and for further data analysis, thus ensuring the comparability and validity of the results and predictability of future operations necessary for the mobile network development.
3. In order to determine and plan the time, volume, and geographical location of measurements on a national scale, it is necessary to perform statistical forecast calculations in accordance with international standards for each reporting period, taking into account the available resources and conditions specific to the types of measurements.
4. There is a strong correlation between the signal and QoS parameters in LTE mobile electronic communication networks.

Approbation of the Doctoral Thesis results

The main results of the Doctoral Thesis have been presented at 8 international scientific conferences, as well as included in 1 publication in scientific journal, 7 publications in conference proceedings, and 1 publication submitted and presented at an international scientific conference, which took place in July 2023 and will be published shortly.

Reports at international scientific conferences

1. **Stafecka, A.**, Lizunovs, A., Olins, A., Rjumsins, M. and Bobrovs, V., "The Evaluation of the Internet Access Service QoS Measurement Equipment Placement Conditions Based on Signal Parameters Values". 2023 Photonics & Electromagnetics Research Symposium (PIERS), Praque, Czech Republic, 3–6, July 2023.
2. **Stafecka, A**., Bobrovs, V. "Evaluation and determination of the internet access service quality parameter measurement equipment placement conditions". 63rd International Scientific Conference of Riga Technical University, 14.10.2022.

3. **Stafecka, A**., Lizunovs, A., Ivanovs, G., Bobrovs, V. "Dependence between Signal Parameter Values and Perceived Internet Access Service QoS in Mobile Networks". Progress in Electromagnetics Research Symposium, November 2021, pp. 1419–1427.
4. **Stafecka, A.**, Lizunovs, A., Bobrovs, V., Gavars, P., Zarins, Z. "Quality of Service and Signal Evaluation Parameter Comparison between Different Mobile Network Operator in Urban Area". Progress in Electromagnetics Research Symposium, June 2019, pp. 3887–3894, 9017680.
5. Lizunovs, A**., Stafecka, A.**, Bobrovs, V. "Internet Access Service QoS and Signal Parameter Measurements in Urban Environment". Proceedings of the 23rd International Conference Electronics 2019, ELECTRONICS 2019, 8765584.
6. **Stafecka, A.**, Lizunovs, A., Bobrovs, V. "Mobile LTE network signal and Quality of Service parameter evaluation from end-user premises". Proceedings – 2018. Advances in Wireless and Optical Communications, RTUWO 2018, 2018, pp. 209–212, 8587890.
7. Lipenbergs, E., Smirnova, I., **Stafecka, A.**, Ivanovs, G., Gavars, P. "Quality of service parameter measurements data analysis in the scope of net neutrality". Progress in Electromagnetics Research Symposium, November 2017, pp. 1230–1234.
8. **Stafecka, A.**, Lipenbergs, E., Bobrovs, V., Sharashidze, T. "Quality of service methodology for the development of internet broadband infrastructure of mobile access networks". Proceedings of the 21st International Conference on Electronics, 2017, 7995229.
9. Lipenbergs, E., **Stafecka, A.**, Ivanovs, G., Smirnova, I. "Quality of service measurements and service mapping for the mobile internet access". Progress in Electromagnetics Research Symposium, 2017, pp. 2526–2532.

Publications in scientific journals

1. Ancans, G., **Stafecka, A**., Bobrovs, V., Ancans, A., Caiko, J. "Analysis of Characteristics and Requirements for 5G Mobile Communication Systems". Latvian Journal of Physics and Technical Sciences, 2017, 54(4), pp. 69–78.

Publications in conference proceedings

1. **Stafecka, A.**, Lizunovs, A., Ivanovs, G., Bobrovs, V. "Dependence between Signal Parameter Values and Perceived Internet Access Service QoS in Mobile Networks". Progress in Electromagnetics Research Symposium, 2021, November 2021, pp. 1419–1427.
2. **Stafecka, A.**, Lizunovs, A., Bobrovs, V., Gavars, P., Zarins, Z. "Quality of Service and Signal Evaluation Parameter Comparison between Different Mobile Network Operator in Urban Area". Progress in Electromagnetics Research Symposium, 2019, June 2019, pp. 3887–3894, 9017680.
3. Lizunovs, A., **Stafecka, A.**, Bobrovs, V. "Internet Access Service QoS and Signal Parameter Measurements in Urban Environment". Proceedings of the 23rd International Conference Electronics 2019, ELECTRONICS 2019, 2019, 8765584.

4. **Stafecka, A.**, Lizunovs, A., Bobrovs, V. "Mobile LTE network signal and Quality of Service parameter evaluation from end-user premises". Proceedings – 2018. Advances in Wireless and Optical Communications, RTUWO 2018, pp. 209–212, 8587890.
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Scope and structure of the Doctoral Thesis

The Doctoral Thesis is 155 pages long. The Thesis consists of an introduction, four chapters, a list of references and seven appendixes.

In **Chapter 1**, the principles and parameters of Internet access service quality assessment are examined, and on its basis, various types of regulatory measurements and measurement tools are evaluated based on global, European, and national regulatory guidelines. In this chapter the interconnections of the autonomous systems of the Republic of Latvia are also evaluated, thus determining the autonomous system in which the Internet service measurement server should be located, so that the measurements comply with the European Union regulation and the results of the measurements performed in the networks of different operators are objective and comparable. Factors affecting the measurements, including the impact of the choice of terminal equipment intended for regulatory Internet service quality measurements on the measurement results, are also examined and evaluated. In the scope of regulation, the need for additional signal parameter measurements is analysed in the context of ensuring the performance of other functions of the national regulatory authority, which include the monitoring of the development of the electronic communications market and services.

In C**hapter 2**, the influence of the placement of measurement equipment on the measurement results is analysed, in the framework of which the mathematical processing of the results was performed, conclusions were put forward, and proposals were made regarding the conditions that should be set in relation to the selection of the geographical locations for the measurements and the placement of the equipment in the premises or in the vehicle. These proposals can be used for practical measurements, ensuring comparability of all performed measurements. The alternative use of different types of measurements is also evaluated, including the comparison of indoor and outdoor measurements, as well as of unattended probe measurements performed in a stationed vehicle and drive test measurements. Advantages and disadvantages of different types of measurements are also evaluated in the chapter.

Chapter 3 defines the criteria for determining the amount of Internet service measurements and the principles of choosing the measurement time depending on the type of measurement, which is necessary to ensure that the measurements are carried out according to the degree of reliability determined by international standards and the summary of the measurement results allows to assess the quality of the service actually available to end users. Considering the defined method of calculating the number of measurements, the location models of measurement sites in the territory of the country and individual municipalities are analysed and proposed. Certain factors affecting the measurements, including the human factor, which should be taken into account when performing quality measurements and during the processing and analysis of the obtained data, are defined.

In **Chapter 4**, the dependencies between the radio frequency spectrum, signal parameter values and QoS parameter values are analysed and determined using mathematical and statistical methods, where data is based on practically obtained measurement results. The chapter determines the correlation between the QoS parameters and signal parameters, as well as analyses the measurement results of the measurements made in different measurement location.

The Doctoral Thesis concludes with a **summary**, where the results of the Thesis research are defined and justified. Based on the results obtained during the research, the procedures and conditions for performing Internet access measurements in the form of universal guidelines are described.

The **appendices** include the script for the Internet access service measurement automation and data collection program developed during the research, displays and summaries of research results, lists of scientific conferences and publications, as well as CEPT certificate of participation in the development of CEPT documents.

OUTLINE OF THE DOCTORAL THESIS CHAPTERS

Chapter 1

In Chapter 1 of the Thesis, the principles and parameters of Internet access service quality assessment are examined, and on its basis various types of regulatory measurements and measurement tools, which are used in the countries of the EU and elsewhere in the world, are evaluated. Taking into account the considered types of measurements, the chapter defines and evaluates the factors influencing the measurements, including the impact of the choice of terminal equipment [13]–[16] used for performing regulatory Internet service quality measurements on the measurement results (Table 1).

Table 1

Measurement Results for Measurements that Were Made Using Three Different End Devices

Parameter	RSRP, dBm			RSSI, dBm			RSRQ, dB		
Smartphone	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
Samsung Galaxy A6 (2016)	–94.34	–94.00	0.65	–77.98	–78.00	1.24	–13.04	–13.00	1.19
Samsung Galaxy A70 (2019)	–87.14	–87.00	1.22	–55.89	–55.00	1.63	–12.38	–13.00	0.93
Samsung Galaxy S22 Ultra (2022)	–88.00	–83.00	7.95	–89.00	–89.00	0.00	–11.09	–11.00	1.49
Parameter	CQI			Download speed, Mbps			Upload speed, Mbps		
Smartphone	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
Samsung Galaxy A6 (2016)	7.33	8.00	1.25	9.16	7.47	4.91	8.15	7.55	1.79
Samsung Galaxy A70 (2019)	-	-	-	43.48	43.40	2.85	15.53	15.96	1.93
Samsung Galaxy S22 Ultra (2022)	8.35	9.00	2.90	68.20	73.05	16.82	15.35	15.47	0.93
Parameter	Latency, ms			Jitter, ms			Packet loss ratio, %		
Smartphone	Average	Median	Standard deviation	Average	Median	Standard deviation	Average		
Samsung Galaxy A6 (2016)	106.80	107.00	2.57	11.60	11.50	1.71	0.00		
Samsung Galaxy A70 (2019)	34.00	34.00	3.50	9.90	6.50	6.59	0.00		
Samsung Galaxy S22 Ultra (2022)	123.90	123.50	7.16	17.50	15.50	5.38	0.00		

Therefore, it can be concluded that in order to ensure comprehensive and up-to-date measurements of the Internet QoS, the terminal equipment used for measurements must be updated at least once every three years, choosing the equipment of the most popular manufacturer on the market, which supports all the radio frequency spectrum ranges allocated for commercial use to the mobile network electronic communications merchants [17], newest network technologies and technological solutions [13]–[15].

The BEREC Guidelines on Very High Capacity Networks state that in order to evaluate network performance, the measurement server should be located in the nearest interconnected electronic communications network, i.e. in an autonomous system [8], whereas the BEREC

Guidelines on Net Neutrality Regulatory Assessment Methodology and the Guidelines on Net Neutrality Measurement Tool Specification state that measurements should be performed until the national Internet exchange point (IXP) [6] [7]. In order to ensure that the measurement results are reasonable, comparable, and appropriate for the measurement purpose, it is necessary to ensure that a correct measurement server is selected, because different measurement results can be observed depending on the selected measurement server and these results may differ several times, which can be concluded taking into account the results of the practical measurements presented in the chapter.

Taking into account the above, the chapter analyses the structure of the national Internet network of the Republic of Latvia, i.e. the public IP network, the parts of the network supported by the service providers and interconnections of these networks (Figs. 1 and 2) [18]–[20]. As a result, specific autonomous systems appropriate for placement of Internet QoS measurement server are defined, thus ensuring equal and comparable measurements of the Internet QoS, regardless of the place of measurement in the national Internet network.

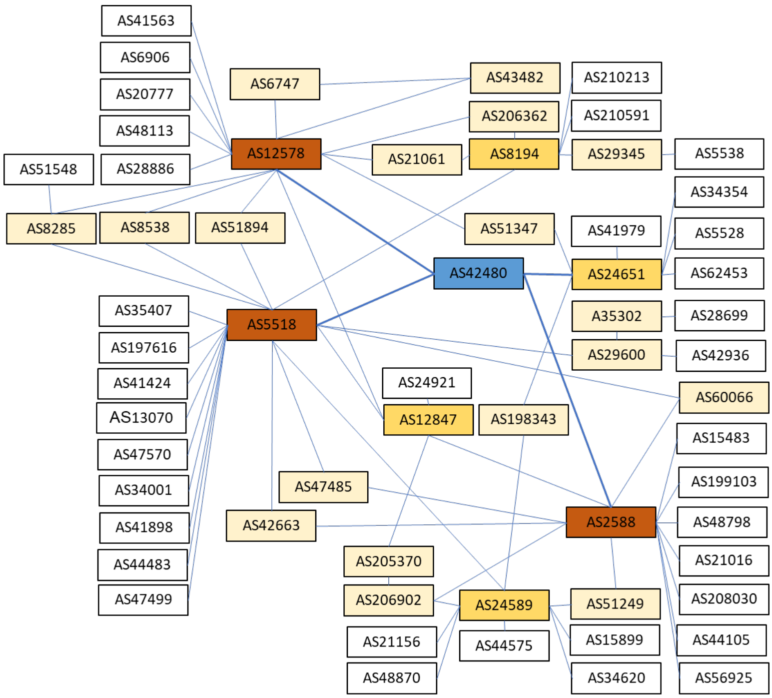

Fig. 1. Topology of autonomous systems of Internet access service providers of the Republic of Latvia for IPv4 traffic.

At the same time, analysing the interconnections of the national Internet networks of the Republic of Latvia and the ownership of autonomous systems [18]–[20], it was concluded that IPv6 support is currently not provided in all electronic communication operators networks, thus choosing the location of the measurement server in the network and taking into account development plans, it is necessary not only to justify the selection of the measurement server location based on the number of interconnections, but also to ensure that the electronic communication network in which the measurement server is located also supports the IPv6 addressing and routing scheme.

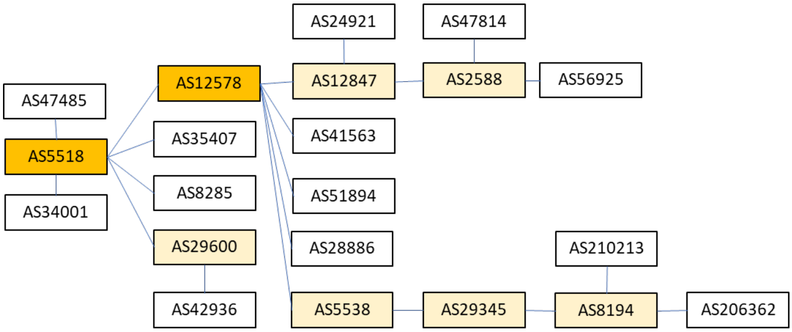

Fig. 2. Topology of autonomous systems of Internet access service providers of the Republic of Latvia for IPv6 traffic.

It can be concluded that if it is necessary to choose an autonomous system in which to place a measurement server, or in which the existing measurement server should be located, one should choose such an autonomous system that supports both IPv4 and IPv6 traffic routing and has the largest number of national interconnections, thus ensuring both measurements up to national IXP and as close as possible to the autonomous system of the operator to be measured. Taking into account the results of the research, it can be concluded that in the Republic of Latvia it is possible to meet the requirements of regulatory acts by providing only one measurement server, therefore, it is recommended to place the measurement server in an autonomous system AS5518 or AS12578.

Evaluating the limitations and requirements of practical measurements of Internet QoS, the chapter examines the binding regulatory framework of the EU [6]–[11] and the Republic of Latvia [21]–[26], in relation to the mobile electronic communication networks and the monitoring requirements of the radio frequency spectrum necessary for their provision. It can be concluded that although the regulation provides for the monitoring of service quality, network, and radio frequency spectrum as separate unrelated functions, by slightly expanding the functionality of the Internet QoS monitoring tool and process, for example, by reading MCC and MNC, it is possible to ensure the simultaneous performance of several regulatory functions.

Chapter 2

In Chapter 2 of the Doctoral Thesis, the influence of the location of measurement equipment on the measurement results is analysed, within the framework of which the mathematical processing of the measurement results was carried out, conclusions were drawn and proposals were made regarding the conditions that should be set in relation to the selection of the geographical locations of the measurements and the placement of the equipment in the premises or in the vehicle. The results can be used for carrying out practical measurements, ensuring the comparability of all performed measurements and the results.

Different types of measurements were analysed and defined in Chapter 1, their performance conditions, as well as defined advantages and disadvantages, the Internet QoS and signal measurements were carried out within the research, and the results of these measurements were evaluated in Chapter 2.

Within the scope of the chapter, the criteria for indoor measurement equipment placement were examined and it was concluded that when placing Internet QoS measurement equipment indoors, it is possible to determine the specific measurement location based on signal parameter values, however, when choosing an indoor measurement location, it is important to analyse not only the values of signal parameters, but also the range of base stations, cells, and frequencies with which the connection is made in the specific location. Therefore, if the coverage of several mobile cells is detected within the same premises, additional test QoS measurements should be performed. If making of test measurements is not possible, taking into account the results of the study, it is recommended to place the measuring equipment as close as possible to the window.

Within the scope of research an evaluation of the placement of measurement devices in the vehicle was also carried out, so that the results could be used both for unattended probe measurements while in the vehicle and for providing drive test measurements. The evaluation was based on the results of practical measurements, in the framework of which signal and QoS parameters were measured in three possible locations of measuring equipment in the car (Fig. 3).

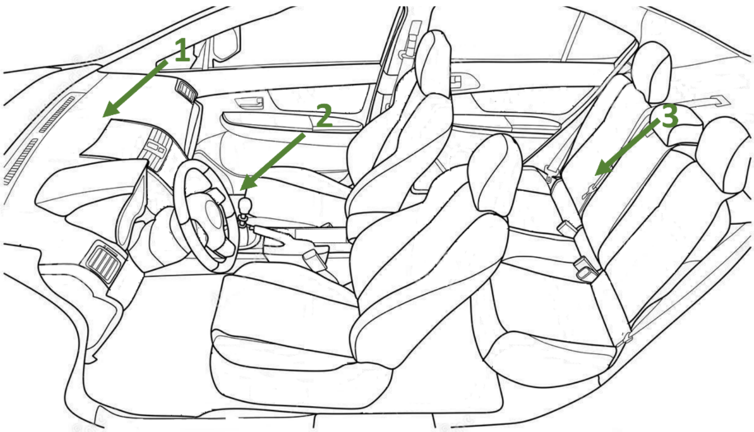

Fig. 3. Measurement locations in the car. The points where the measurements were taken are indicated on the schematic drawing of the car interior: 1 – on the front panel of the car; 2 – on the floor of the front passenger seat of the car; 3 – on the rear passenger seat, at the height of the windows.

Taking into account the variety of car sizes and equipment level, which can affect the measurement results, experimental measurements were carried out in two different cars (Tables 2 and 3) in order to determine possible differences between the selection of measurement locations and to define the criteria for the placement of measurement equipment.

Table 2

Results of Practical Measurements Made in Vehicle 2003 Renault Clio

Parameter	RSRP, dBm			RSSI, dBm			RSRQ, dB		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
1	–94.10	–94.00	1.27	–94.53	–95.00	1.14	–9.47	–10.00	1.07
2	–99.67	–100.00	2.11	–100.07	–101.00	2.15	–9.90	–10.00	1.12
3	–94.43	–94.00	1.07	–94.67	–95.00	1.18	–9.70	–10.00	1.09
Parameter	CQI			Download speed, Mbps			Upload speed, Mbps		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
1	7.83	7.00	1.64	40.73	44.09	19.06	15.38	16.51	2.23
2	7.60	7.00	1.25	29.53	26.58	12.34	10.01	9.55	1.51
3	8.97	8.50	1.88	35.45	39.84	22.93	6.80	7.80	2.24
Parameter	Latency, ms			Jitter, ms			Packet loss ratio, %		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average		
1	129.20	128.00	6.80	15.30	16.00	2.16	0.00		
2	133.30	134.00	5.76	15.20	13.00	6.09	0.00		
3	132.10	132.50	7.84	16.90	14.50	7.67	0.00		

Table 3

Results of Practical Measurements Made in Vehicle 2017 Skoda Kodiaq.

Parameter	RSRP, dBm			RSSI, dBm			RSRQ, dB		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
1	–86.37	–87.00	3.39	–86.87	–87.00	2.87	–8.97	–9.00	1.71
2	–84.37	–81.00	6.78	–85.27	–83.00	7.06	–10.90	–10.50	1.75
3	–94.93	–95.00	1.17	–95.60	–95.00	1.07	–9.13	–10.00	1.31
Parameter	CQI			Download speed, Mbps			Upload speed, Mbps		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
1	10.87	10.50	2.37	23.87	19.70	10.04	14.12	15.29	3.17
2	11.73	12.00	2.39	23.69	23.72	7.95	7.84	8.65	4.24
3	9.30	9.00	1.90	28.06	27.45	9.39	11.76	10.58	3.26
Parameter	Latency, ms			Jitter, ms			Packet loss ratio, %		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average		
1	136.10	138.00	4.15	15.20	14.00	2.82	0.00		
2	140.80	140.50	4.94	19.10	17.50	5.34	0.00		
3	140.50	140.50	4.40	15.00	15.50	3.33	0.00		

Taking into account the results of the measurements, it can be concluded that in order to determine the best placement of the measuring equipment, specifically the location of the signal receiver and transmitter, in the vehicle, it is necessary to perform control measurements in a specific vehicle, on the basis of which the placement of the measuring equipment can be carried out. RSRP or RSSI, and RSRQ, which indicate the strength of the received signal and allow to evaluate the impact and quality of the signal, can be put forward as determining parameters for the assessment of equipment placement. If it is not possible to carry out control measurements based on general trends of measurement results observed during the study, it is concluded that it is preferable to place the measurement equipment on the front panel of the vehicle or at the front panel or window level above the front passenger seat.

Considering the above mentioned and results of other practical measurements, it was also concluded that to determine the exact location of the measurement equipment, it is necessary to use measurements of signal parameters, determining a specific measurement location according to the strength and quality of the signal received in the room, outdoor space or in the vehicle. Considering the possible functional limitations of measurement tools, recommendations for the placement of internet QoS measurement equipment indoors and in the vehicle are put forward in the Thesis.

The chapter also evaluates the process of conducting drive test measurements. A formula is defined for the calculation of the number of measurements, according to which it is possible to calculate the approximate number of measurements along a certain road section for drive test measurement performance at a specific speed:

$$ms = \frac{d_{cp}}{v_{cp} \times t_m}, \qquad (1)$$

where

ms – number of measurements in a road section;

d_{cp} – the length of the road section where measurements are performed, km;

v_{cp} – travel speed along the road section, km/h;

t_m – the time required for one measurement, h.

It is concluded that drive test is the only type of measurement that can accurately describe the quality of the Internet service available to the end user on a certain road section, allowing to evaluate both signal and QoS parameter changes within the road section, as well as to draw conclusions about the values of QoS parameters and the effect of the signal on them [27], [28]. However, it should be noted that when making measurements in the mobile networks of several operators, it may not be possible to ensure that geographical points of the measurements in different operators' networks are exactly the same, following the observation that one measurement may take different time depending on the mobile network and its coverage. Therefore, it may not be possible to compare the measurement results of multiple mobile network operators at the same geographical point.

Based on the functional characteristics of different measurement types and the results of practical measurements, the chapter evaluates the possibilities of mutual interchangeability of measurement types, which would enable the economy of resources for the institution performing the measurements. Types of measurements replacement of which is not possible and which are able to ensure compliance with the requirements of the regulatory framework on Internet QoS monitoring, as well as types of measurements and conditions replacement of which is possible and does not affect the objectivity of the measurement results are determined in the chapter [29], [30].

The efficiency of unattended probe measurements and drive test measurements is also compared, within the framework of which practical measurements of QoS and signal parameters of the mobile Internet access network in a city and a village (Fig. 4), whose territorial dimensions are approximately close, were made.

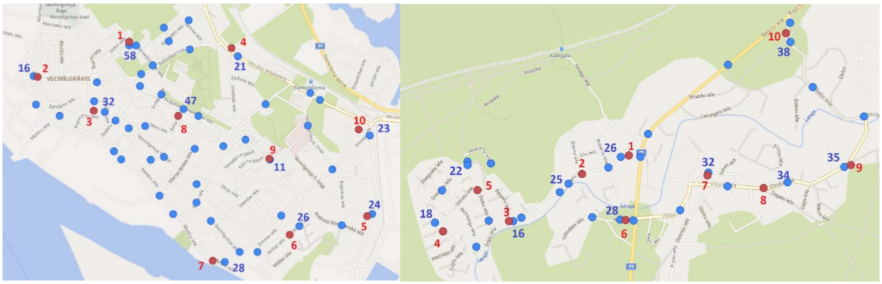

Fig. 4. Geographical placement of the measurements in the city and in the village.

As a result, the data obtained in the measurements were analysed, taking into account the deviation of the results obtained in geographically closer places and the statistical values of the results obtained in the entire populated place (Table 4).

Table 4

Comparison of Static and Drive Test Measurement Results Carried out in a City

Para-meter	Download speed, Mbps			Upload speed, Mbps			Latency, ms			Jitter, ms		
Place	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation
All static	66.65	54.05	49.83	13.33	5.11	17.36	89.28	30.00	189.89	41.02	10.00	84.43
All drive test	59.79	48.67	38.17	15.58	11.37	11.97	88.98	29.00	200.09	44.29	8.00	110.96
Para-meter	Packet loss ratio %	RSRP, dBm			RSSI, dBm			RSRQ, dB				
Place	Average	Average	Median	Standard deviation	Average	Median	Standard deviation	Average	Median	Standard deviation		
All static	0.37	–98.20	–101.00	9.73	–65.71	–67.00	7.97	–12.05	–12.00	2.32		
All drive test	0.42	–91.26	–92.00	9.95	–60.00	–59.00	7.28	–12.31	–12.00	2.46		

Evaluating the results of the practical experiments, it can be concluded that the average value of the parameters obtained in the measurements, which is mostly used when evaluating and determining the value of the available QoS parameters in one populated place, in the case of measurements in static places and in the case of a drive test, varies depending on the measurement place and the parameter from 0 % to 65 %. It can be explained by the fact that in the case of drive test measurements, measurements are made in several places, thus covering not only a few geographical points in the area, but a much larger number of geographical points in the same area.

Also, from the results, it can be stated that the measurements made using the drive test and as unattended probe measurements in the closest geographical points are relatively close, taking into account the displacements of the measurement points. Therefore, it follows that the drive test measurements are more suitable for evaluating the overall QoS provided within one municipality because the number of geographically located measurement points is greater, thus the change of the signal is more taken into account, which is also evidenced by the deviation of signal parameters values.

At the same time, an analysis of the time spent on measurements is also performed in the chapter (Table 5) – the time needed to perform the above-described measurements and the time required for 100 measurements.

Table 5

Comparison of Static and Drive Tests Measurement Time

	City		Village	
	Static (HH:MM)	Drive-test (HH:MM)	Static (HH:MM	Drive-test (HH:MM)
Measurement time consumption	01:37	00:29	01:40	00:17
Time consumption for 100 measurements	01:28	00:58	01:31	00:57

The obtained measurement results show that in terms of time consumption the drive test measurements are more efficient and allow, if necessary for distance or measurement time correction, to define the delay between measurements, as it takes a shorter time in comparison to unattended probe static measurements. In the case of unattended probe measurements at a static location, by increasing the number of measurement locations and reducing the number of measurements performed at one location, the time required to perform one measurement may vary, but considering that a large part of the time is spend by moving between static measurement locations, the time required in this case can be expected to be even longer, because the time for one measurement, although it also varies within the error limits, is almost constant.

Chapter 3

In Chapter 3 of the Thesis, based on international standards, the criteria for determining the amount of Internet QoS measurements and the principles of choosing the measurement time depending on the type of measurements [30]–[33] are defined, which is necessary to ensure that the measurements are carried out according to a certain level of reliability degree, and the summary of measurement results allows to determine the QoS actually available to end-users at specific location. Taking into account the defined method of calculating the number of measurements [33], the models for determining measurement location in the territories of the country and individual municipalities are analysed and proposed. Certain factors affecting the measurements, including the human factor, which should be taken into account when performing the QoS measurements, processing, and analysing the obtained data, are also defined.

The chapter analyses the results of measurements made in several municipalities during several days, summarizing the measurements made over several years. It was determined that peak hours are observed in the evening hours, approximately from 9:00 p.m. to 11:00 p.m., however, the hours may differ depending on the area.

Taking into account the BEREC guidelines [6], [8], [10], which foresee the need for measurements during peak hours, the measurement results and practical considerations for measurement performance, including the fact that unattended probe and drive test measurements require human resources foreseeing normal working hours [34], the chapter analyses the possibility of determining the time range in which the difference between the obtained QoS parameter measurement results and the 24-hour measurement results would be as small as possible. For this purpose, the results of practical unattended probe measurements are analysed with respect to parameter values obtained in different time ranges and the deviation of the results from the results of 24-hour measurements is determined (Table 6).

Table 6

QoS Parameter Measurement Results in Different Time Ranges Relative to the 24-hour Measurement Results

	City								Countryside							
Time period	Download speed, Mbps	Difference, %	Upload speed, Mbps	Difference, %	Latency, ms	Difference, %	Jitter, ms	Difference, %	Download speed, Mbps	Difference, %	Upload speed, Mbps	Difference, %	Latency, ms	Difference, %	Jitter, ms	Difference, %
00:00 – 24:00	45.18		22.29		25.78		2.41		29.28		12.75		16.44		2.37	
09:00 – 15:00	44.78	1 %	22.07	1 %	25.99	1 %	2.42	1 %	29.32	0 %	13.06	2 %	16.48	0 %	2.31	2 %
09:00 – 17:00	43.95	3 %	22.09	1 %	25.76	0 %	2.43	1 %	28.33	3 %	13.07	3 %	16.48	0 %	2.36	0 %
00:00 – 09:00	51.71	14 %	22.48	1 %	26.61	3 %	2.30	5 %	37.55	28 %	12.89	1 %	16.22	1 %	2.21	6 %
15:00 – 23:59	39.36	13 %	22.28	0 %	24.96	3 %	2.50	4 %	21.57	26 %	12.39	3 %	16.61	1 %	2.55	8 %
17:00 – 23:59	38.64	14 %	22.32	0 %	24.91	3 %	2.51	4 %	20.38	30 %	12.19	4 %	16.65	1 %	2.57	8 %

Considering the results of the data analysis, it was concluded that the results, which are closer to the average value of the measurement results obtained during the 24-hour long measurements, are achieved in the time period from 9:00 to 15:00, when the deviation from the standard value in the case of 79 % of the results shown in the table did not exceed 4 %, which is within the measurement error. The values may differ depending on the configurations of the operators' electronic communication network, however, it can be concluded that the average values of the measurement results in certain hours of the day are close enough to the average value of the results of measurements made in 24-hour measurements. Therefore, it follows that unattended probe measurements and drive test measurements, for which it is not possible to obtain 24-hour results and where there is a possibility that there will be peak load hours or hours with very low load, which are usually night hours, are recommended to be carried out at a certain period of time during which the values of the measurement results are closer to the average value of the 24-hour measurement results.

The chapter also includes a list of measures that must be taken to ensure a 95 % degree of reliability of the measurements when only a certain number of measurements may be provided. Several standards, including ETSI EG 202 057-4, suggest the use of classical statistical formulas of normal distributions for calculating the number of necessary measurements, which can be expressed according to the specifics of Internet QoS parameter measurements as follows [33]:

$$n = \frac{z_{1-\alpha/2}^2}{a^2} \times \left(\frac{s}{mean(x)}\right)^2, \quad (2)$$

where

n – minimal necessary number of measurements;

a – relative accuracy, %;

$z_{1-\alpha/2}^2$ – normal distribution coefficient for chosen confidence level;

s – standard deviation of test measurement results;

mean(x) – average value of test measurement results.

Therefore, it can be concluded that in order to be able to guarantee that the results of Internet QoS measurements of all QoS parameters are able to meet the set accuracy requirements, it is necessary to determine the number of measurements according to the calculations mentioned in Formula (2), defining the necessary number of measurements based on the parameter where the calculation result shows the largest number of necessary measurements (Table 7).

Table 7

Example of the Results of Calculation of Necessary Number of Measurements at Different Relative Accuracies

Parameter	Normal distribution coefficient at 95 % confidence level	Standard deviation of a set of measurement results	Average value of a set of measurement results	Required minimum number of measurements at a relative accuracy of 5 %	Required minimum number of measurements at a relative accuracy of 2 %
Download speed, Mbps	1.96	18.46	32.80	487	3043
Upload speed, Mbps	1.96	13.38	26.54	391	2441
Latency, ms	1.96	5.77	25.31	80	500
Jitter, ms	1.96	81.21	19.90	25581	159882
Packet loss ratio	1.96	1.13	0.05	685258	4282865

It can be concluded that the number of measurements is also highly dependent on the measurement locations where the control measurements are carried out, based on which the planned number of measurements is calculated. Therefore, especially in the case when requirements for the accuracy of the measurements are defined at a national level, it is important to monitor the measurement results during the year, because additional measurements may be required to achieve the desired accuracy.

In addition, the chapter examines the possible distribution of municipalities and the distribution of the number of measurements and concludes that the distribution of municipalities proposed in international standards and recommendation [32] is not suitable for the territory of the Republic of Latvia, therefore it is recommended to ensure the distribution of measurement locations by municipalities in accordance with national regulations [35], not taking into account the smallest municipality units.

The chapter examines different options for the distribution of measurement sites, their advantages and disadvantages in relation to different types of measurements and measurement influencing factors, therefore, it is concluded that in order to distribute measurements in the territory of a country, a combined solution is needed, which will allow to ensure the amount of measurements execution with the existing number of resources, simultaneously supporting the possibility to perform high-quality monitoring of the quality of the service, ensuring the 24-hour measurements. It is not possible to cover every place in the country, both in the context of municipalities and in the context of the grid, so it is necessary to ensure that the measurements are evenly distributed within the borders of the country and their number is proportional to the population. In addition, it is recommended to provide measurements using a drive test, because only drive test measurements can ensure the performance of measurements within the road sections and at least partially ensure the measurement in small villages and homesteads.

Chapter 4

Chapter 4 of the Doctoral Thesis examines and, using mathematical and statistical methods, analyses and determines the relationships between the radio frequency spectrum, signal parameter values and QoS parameter values, based on practically obtained measurement results [16]. The chapter determines the correlation between the QoS parameters and signal parameters and analyses the measurement results depending on the measurement place. Taking into account the obtained results, it was concluded that it is necessary to use the obtained values of the signal parameters in the analysis of the measurement data to ensure that the reflected measurement results are transparent, justified and comparable [36], [37], as well as to make it possible to make a forecast of the quality of the internet service available in the entire municipality, depending on location and time [38]–[41].

In the research described in the chapter, it was observed that the dependence between the signal and QoS parameter measurement results appears in the case of large-scale measurement data within which measurements were made in several places. This observation reflects in the values of all QoS parameters but is especially noticeable in the example of the packet loss ratio (Fig. 5). It has been observed that the signal strength, which usually varies depending on the location, is much weaker in rural regions, and therefore, due to the influence of other signal parameters, the dispersion of values of the data can be greater compared to the measurement results where measurements were made in the city or other more populated areas [38]–[41].

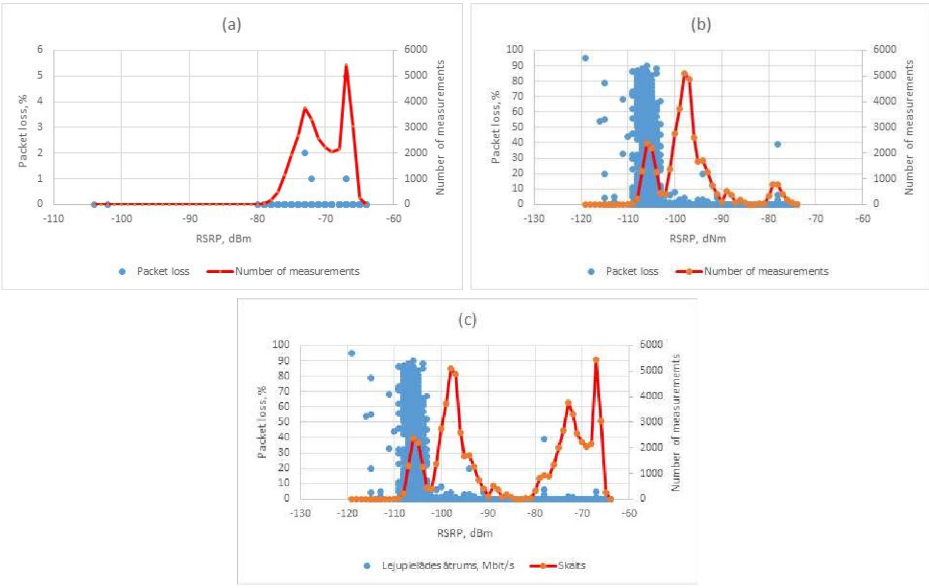

Fig. 5. The graphical relationship between the measurement results and the number of measurements for the packet loss ratio and RSRP, where the measurements are summarised for (a) the city, (b) the rural region, and (c) the summarised data.

Taking into account the theoretical data and the results of the data obtained in the study, it is concluded that the results of the QoS measurements in rural regions are usually lower, as well as the signal quality is lower, thus the QoS in rural regions and cities can significantly differ. In addition, at lower signal quality, the QoS parameter values are more scattered, especially if RSRP values they are below 100dBm, which repeatedly proves that performing regulatory measurements when RSRP value range is below this value is not recommended, because the results will not allow to unambiguously judge either the changes in parameters over time or forecast possible QoS parameter values in the coverage area of the base station transmitter.

In relation to the distribution of results of Internet QoS measurements depending on the measurement location and the use of signal parameters as a criterion for the placement of measurement equipment, the correlation between the values of the signal and QoS parameters was examined based on the experimental measurements carried out in the mobile electronic communication networks of three mobile operators (Table 8).

Table 8

Correlation Coefficients Between QoS and Signal Parameter Values

	Operator 1				Operator 2				Operator 3			
Signal parameters	RSRP, dBm	RSSI, dBm	RSRQ, dB	SINR, dB	RSRP, dBm	RSSI, dBm	RSRQ, dB	SINR, dB	RSRP, dBm	RSSI, dBm	RSRQ, dB	SINR, dB
QoS parameters	All results				All results				All results			
Download speed, Mbps	0.29	0.23	0.57	0.47	0.12	0.10	0.52	0.53	0.55	0.50	0.20	0.59
Upload speed, Mbps	0.74	0.69	0.46	0.33	0.92	0.91	0.25	0.26	0.77	0.69	0.00	0.61
Latency, ms	–0.72	–0.69	–0.53	–0.45	–0.27	–0.26	–0.06	0.01	–0.37	–0.35	–0.09	–0.41
Jitter, ms	–0.24	–0.28	–0.21	–0.31	–0.29	–0.34	–0.25	–0.39	–0.06	–0.05	–0.09	–0.08
Packet loss ratio, %	–0.16	–0.18	–0.15	–0.23	–0.23	–0.27	–0.27	–0.36	–0.05	–0.04	–0.07	–0.06
	The capital				The capital				The capital			
Download speed, Mbps	–0.14	–0.12	0.24	0.31	0.16	0.16	0.41	0.34	0.10	0.06	–0.01	0.10
Upload speed, Mbps	0.65	0.33	–0.02	-0.10	0.50	0.61	0.20	0.32	0.29	–0.02	–0.31	–0.18
Latency, ms	0.13	0.09	–0.15	–0.25	–0.05	–0.06	0.12	0.09	0.04	–0.07	–0.16	–0.04
Jitter, ms	0.16	0.10	–0.03	–0.06	–0.49	–0.54	–0.04	–0.15	–0.17	–0.15	–0.11	–0.22
Packet loss ratio, %	0.01	0.00	0.00	0.00	–0.18	–0.21	–0.02	–0.06	–0.19	–0.16	–0.10	–0.21
	Territory of the country, excluding the capital				Territory of the country, excluding the capital				Territory of the country, excluding the capital			
Download speed, Mbps	0.05	–0.09	0.59	0.46	0.32	0.14	0.58	0.63	0.04	0.08	0.45	0.41
Upload speed, Mbps	0.50	0.49	0.35	0.32	0.75	0.61	0.32	0.53	0.81	0.83	0.37	0.78
Latency, ms	0.06	0.02	–0.20	–0.25	–0.13	–0.11	–0.10	–0.01	0.25	0.18	–0.01	–0.02
Jitter, ms	–0.25	–0.29	–0.17	–0.37	–0.42	–0.43	–0.29	–0.47	–0.03	–0.01	–0.08	–0.04
Packet loss ratio, %	–0.19	–0.20	–0.13	–0.28	–0.36	–0.34	–0.32	–0.44	–0.02	0.00	–0.05	–0.02

In regard to the results of calculations, it can be concluded that regardless of the measurement location there is a strong positive correlation between the upload speed and RSRP and RSSI parameter values in the LTE mobile electronic communication networks of different operators. A strong positive correlation is also observed between the download speed and RSRQ parameter values in the networks of two mobile operators at a large measurement volume. For the rest of the QoS parameters, positive and negative correlation has been observed, from which it follows that there is a direct correlation between the QoS and signal parameter values, but it is mainly observed between the download and upload speed values and the RSRP, RSSI and RSRQ parameter values. Therefore, in can be assumed that based on the signal parameter values it is possible to predict the signal parameter values in the coverage area of the mobile cell, however, specific QoS parameter values are predictable only in relation to the network of a specific operator.

RESULTS OF THE DOCTORAL THESIS

In the course of carrying out the defined tasks, several main results and conclusions of the Doctoral Thesis have been obtained.

By analysing the electronic communications merchants, their electronic communications networks, autonomous systems, interconnections, and traffic related to these autonomous systems, the interconnection schemes of the autonomous systems used for the routing of the national Internet for IPv4 and IPv6 traffic are defined. It can be concluded that in the Republic of Latvia it is possible to meet the requirements of BEREC network neutrality and high-capacity network guidelines at the same time by providing an internet access measurement server in only one autonomous system, allowing to save the resources needed for internet access service measurements. This aspect is especially important when choosing or developing an Internet access service quality measurement tool, as well as performing measurements in case several measurement servers are available. Therefore, the conclusion put forward in the Thesis allows to use it practically by defining specific locations of measurement servers in regulatory acts and by allowing to develop or choose a measurement tool knowing the specific place in the electronic communication network where the measurement server should be installed, thus ensuring the acquisition of comparable and foreseeable measurement results.

At the same time, it is determined that in order to ensure actual and justified measurement results for regulatory purposes, it is necessary to ensure that the terminal equipment used for the measurement is not older than three years and supports all the technologies used in the mobile electronic communication networks. Determining the cycle of replacement of terminal equipment used for Internet access service measurements by NRA allows to foresee planned investments and ensures that the measurements made by the NRA reflect the quality of the service actually available on the market. Information on the cycle of equipment replacement can be also included in national regulatory acts to ensure transparency of the measurement process.

Considering the conducted studies, it has been ascertained that signal parameter measurements performed in addition to QoS parameter measurements are necessary to choose a measurement location that would ensure the most equal conditions possible for the QoS measurements of mobile Internet access service provided by various mobile operators. When performing in-depth analysis of results of signal parameter and QoS parameter measurements made under various measurement conditions, optimal signal parameter values were determined, which are recommended, if technically possible, to be taken into account when placing measurement equipment, and application of which will ensure the comparability and validity of the obtained measurement results. If it is not possible to evaluate the signal parameters indoors or in the vehicle, based on the results of practical measurements, optimal locations of measurement equipment for various types of measurements have been determined. The need to use signal parameter measurements in the process of Internet QoS measurement was also confirmed by determining that there is a strong correlation between the signal parameter values and QoS parameter values, therefore, signal parameter measurements can be used as a factor for choosing a measurement location.

Based on international standards and recommendations, as well as national regulatory legal acts, the criteria for planning and validating the number of measurements, as well as the principles of determining the geographical distribution of measurement sites based on the purposes of processing the obtained data, were determined.

Taking into account the results of the analysis and theoretical and practical research conducted throughout the research the guidelines for measurement process of the quality of Internet access service have been developed, which determine the requirements for the measurement procedure ensuring its openness, transparency, objectivity, and comparability of measurement results, as required by the European Union, national regulations and recommendations.

In addition, the Thesis examines the possibilities of automation of Internet service measurements and measurement data collection, as a result of which a program script has been developed that can be adjusted according to the measurement system, which can be used for automation of the regulatory measurement process.

The Doctoral Thesis summarises the results of completed research and defines possible further research directions:

1. To evaluate in practice the application of the principles of Internet access service quality measurement performance defined in the Thesis and to determine the possible improvements that would be necessary when monitoring the quality of the Internet access service in standalone NR mobile networks after independently functioning NR standalone technology in mobile electronic communication networks for the provision of Internet access service is implemented.
2. To develop and evaluate the measurement data analysis algorithms within the framework of which the distribution of the theoretical QoS parameter values within the coverage limits of the mobile cell could be determined based on the obtained signal and QoS parameter values.

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